PLASTICS AND THE OCEAN

ORIGIN, CHARACTERIZATION, FATE, AND IMPACTS

EDITED BY **ANTHONY L. ANDRADY**

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Edited by

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This work is dedicated with gratitude to my two mentors- Dr. R.O.B. Wijesekera (Ceylon Institute for Scientific Research, Colombo, Sri Lanka) and Professor Jim Harwood (University of Akron, Akron, OH, USA), both exceptionally talented teachers as well as accomplished researchers, under whose able guidance I was fortunate enough to receive my own training in scientific research.

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Preface

Interestingly, the invention of the first plastic was closely linked to the conservation of the African elephant. The material was invented as a low-cost replacement for ivory used to make Billiard balls back in the 1800s. With a single elephant tusk yielding just three balls, the expense, difficulty, and perhaps even the brutality of securing ivory, drove Michael Phelan, a star player of the game and an entrepreneur of his day, to announce a prize for anyone with an apt substitute for the unique ivory. That led the US inventor Wesley Hyatt, in 1869, to come up with hardened nitrocellulose (which he called celluloid) as a good substitute. Though he did not receive the prize, his efforts ushered in an era of plastics, a defining feature of the anthropocene epoch. It was soon followed by Bakelite in 1907 and then by a series of other plastics that continue to serve us even today. In fact, all the common plastics in use today were discovered by the early 1950s. An early success was nylon (invented by Carothers at Du Pont) introduced to the consumer at the 1939 World Fair, causing a sensation with 64 million pairs of stockings sold in a year. As nylon was a replacement the natural silk used in hosiery, the discovery of this first synthetic textile fiber saved millions of silkworms from an early demise as the demand for fine natural silk leggings dropped.

Plastics captured the imagination of the public and much was expected of this miraculous material which lived up to public expectations, quickly finding applications in fabric, packaging as well as in numerous other consumer products. The August 1955 issue of the *Life* magazine proudly announced the dawn of a plastic era with "throwaway living," where housewives would finally be relieved of having to clean utensils after each meal. Not only did this ominous claim come true with every single item in the Life magazine illustration becoming a common household product, but also introducing a host of innovative single-use plastics products widely used today. With nearly half the commodity plastics produced today devoted to disposable products, the unmanaged or carelessly disposed post-use plastics have now ended up in our environment, ironically harming wildlife, especially marine organisms. Today every aquatic system including the Marianna trench, the Arctic ice masses, and rivers on even uninhabited islands around the world are contaminated with post-use plastics. Marine convergence zones, like those in the Northern Pacific, concentrate small fragments of plastics, the microplastics, counted in the trillions in the upper ocean. As some plastics in the ocean sink to the sediment, what is sampled in surface water is only the tip of the proverbial iceberg. Their abundance in the water column, especially the bottom sediment, is reported to be much larger than in either surface water or the dry beach sediment. How much plastic enters the oceans is not precisely known. An estimate places the influx in 2010 at 4.8–12.7 MMT but it keeps growing each year.

An Already Stressed Ocean

The ocean that ends up receiving an annual increment of plastic waste from both land-generated debris *via* riverine transport and also directly from coastal areas, is already under stress. The burning of fossil fuels over the past several hundred years has already increased the acidity of surface waters by 30% threatening the survival of hard-shelled species; it's impact on the global fishery is not reliably known. Rampant unsustainable overfishing depleting the fishery, also leaves behind enormous amounts of derelict plastic gear each year, to continue on wasteful "ghost fishing" into the next generations. Ocean also has to contend with industrial or medical wastes that introduce either pathogens or toxic chemicals into the water, creating dead zones at sea. Over-enriching local patches of the sea by excess nutrients cause eutrophication, toxic algal blooms or fish kills. More than half the coastal and estuarine waters in the contiguous US are already affected by one or more of these phenomena to some extent.

To this already stressed ecosystem, human activity now introduces an annual load of at the very least, 8 MMT of plastic (even not counting ocean-generated plastic debris) with no known mechanism that can remove these plastics even in the long term. All the plastic debris discharged into the ocean, except for what gets washed ashore, accumulates in the bottom sediment, but little is known about how these plastics affect the benthic ecology. Recent studies estimate the floating plastics in the ocean in 2010 at 0.5 MMT; but this is only what can be sampled by plankton nets (mesh size 300 μm) and most of the plastic debris might be smaller, below the threshold size for plankton nets. Also, net-sampling of floating plastics excludes the majority of the plastic debris that resides in the water column or the benthos. Not surprisingly, what is counted is therefore far less than one might expect based on global plastic production.

Is it a Cause for Concern?

In common with all highly visible environmental problems with potential human health impacts, microplastics in the ocean has also been subject to media hype and exaggeration. But beyond the hyperbole, there lies a very real emerging problem that deserves the prompt attention of the research community. Exponentially growing research literature on the topic and many international professional forums addressing microplastics demonstrate some level of public commitment to the quest. Again, as with all environmental issues, some researchers do not agree that a serious problem does exist. Some point out that oceans are rich in natural micro-and nanoparticles in any event and the impact of the small fraction of microplastics would be minimal. Others cite the much higher microplastics concentrations (compared to levels likely to be present in the ocean), used in toxicology studies that show adverse impacts, to justify their stance. However, given that plastic waste will continue to be emptied into the ocean year after year, at the rate of about a garbage truck load a minute, (that will increase to four per minute by 2050), these arguments are not particularly persuasive. In fact, these are reminiscent of the complacency in the days before the Minamata tragedy in Japan in 1950s, where organic mercury was emptied into that river (coincidentally by a plastic manufacturer) on the expectation that the water concentrations would be far too low to cause any adverse health impact. Microplastics unlike the inorganic fines in the ocean are continually fragmenting organic particles that also absorb and concentrate persistent organic pollutants (POPs) dissolved in seawater. At least in some species ingesting them, POPs bio-accumulate and bio-magnify along the marine trophic chain, delivering progressively higher doses of the POPs, pharmaceuticals, metals, and enzyme-mimicking endocrine disruptor compounds to a range of marine organisms. With nanoplastics that can permeate the gut wall, these compounds can be delivered systemically. Microplastics present a threat that is very different from that of common toxicants and may well require criteria and methodologies beyond those in classical toxicology in their study. Even the toxicological data on the effects of microplastics ingestion often pertain to short-term studies and provide limited information. Virtually nothing is known of dose-response curves, long-term effects, embryonic toxicity, and intergenerational effects or their potential synergy with conventional toxic compounds. Not only do they have direct effects on the ingesting organisms but also indirect effects such as changing local marine biota by introducing rafter species, especially antibiotic-resistant bacteria developing on their surface biofilms.

How Much of a Threat do Plastics in the Ocean Pose?

MPs are ubiquitous in aquatic environments with about the same surface concentrations (from 0.01 to 1000 particles/m^3 of surface water) in the ocean and rivers around the globe. Over 50 trillion MPs were estimated as merely the floating stock in the ocean in 2017. Plastics are persistent and do not mineralize in an observable timescale, especially in the ocean. The threat of microplastics in the ocean persists beyond the present generation as their levels will keep increasing in future years and their ecological effects are likely to be irreversible. Available data show bioaccumulation of microplastics in several species and biomagnification by predation, while moving along the marine food web to reach the human consumer. For instance, some bivalves as well as commercial fish species are already reported to be contaminated with microplastics. That only two to three microplastics (discernible by eye or low power microscope) are found in a sample of fish or seafood species is not reassuring, because the fish could have been ingesting that amount of microplastics routinely and potentially bioaccumulating POPs sorbed by these in its tissue.

Their growing abundance indicated by an expanding body of research findings on microplastics in the ocean raises the question of their wider impacts on the ecosystem as a whole. Has the impact of microplatics now evolved beyond that of a mere pollutant, challenging planetary sustainability to exert a systemic influence on Earth's resilience? While they do not satisfy all criteria presently used to qualify as a planetary boundary threat, some have suggested that they would be a serious candidate phenomenon. There are, of course, many unknowns and the research that would address these gaps in knowledge needs to be undertaken without delay. The magnitude of microplastic-related impacts at the population level and how seriously they might impact the functioning of the physical and biological cycles in the ocean, remain unclear. So is the ingestion-related distress across the spectrum of marine organisms. Valid methodologies to allow decisions making despite these limitations need to be developed. Inadequate funding, especially in the US, to study such impacts especially at global hot-spots for plastic pollution, holds back this important task. Of the reviews on the topic published over the last few years, less than half are by scientists in Asia, the prime hotspot for plastic pollution. Also, a great majority of the research reports tend to be qualitative and the scarcity of relevant hard numbers to gauge the impacts, impedes this assessment.

Plastics in the ocean is a serious man-made problem that affects the present as well as future generations. A few decades from now, it may assume proportions that complicate or even defy any reasonable efforts at mitigation or containment. That the threat of plastic pollution of the ocean environment is serious and its effects irreversible are well established. Consistent with the precautionary principle, despite the scientific uncertainty of their full impact, adopting measures to curb the problem is prudent.

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Foreword

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As I began writing this Foreword in the waning days of 2020, the media was replete with reviews of the year soon to be thankfully gone. Besides 2020 being one long battle against COVID-19, the narrator of the Columbia Broadcasting System's (CBS) year in review made the following statement: "2020 was the year the plastic pollution problem got the world's attention." Apparently, the problem was baking in the world oven for a good half-century and finally came out in a form that caught "the world's attention." For those of us working for decades to draw back the plastic curtain of ignorance that has kept the public from a general understanding of the material that characterizes the modern era, this was a belated yet welcome assertion.

The study of marine plastics arose before plastics were acknowledged to be problematic for the ocean. At first, marine scientists were simply noting that plastics had been found in birds and on the sea surface and were unsure of what this meant. The problematic nature of synthetic polymers in our water world could have been inferred from the fact there is no background or natural level of these persistent anthropogenic compounds anywhere. This makes them a priori a pollutant; they do not belong in or to any natural system. Small amounts of synthetic polymers in the environment might have been ignored by science, but the quantities rapidly increased and became impossible to ignore. Sadly, it is because of plastic pollution that we study ocean plastics. In this volume, an esteemed publisher of scientific literature and a world-renowned expert on environmental plastics have teamed up to give you widely varied perspectives that together demonstrate clearly that marine plastic pollution its own field of science. If science can be characterized as a branch of knowledge that provides answers by carefully studying a phenomenon from as many areas of expertise as possible, then the study of plastic pollution of the marine environment has surely become its own field of scientific inquiry. For a deep and broad understanding of the issues surrounding ocean plastics, Wiley could not have found a better editor for this volume than Dr. Anthony Andrady. His 2003 volume *Plastics and the Environment*, was the most comprehensive treatment of the subject ever written with contributions from twenty-two authors.

No scientists are exempt from the world views known as paradigms that reign in their historical milieu. Scientists are slow to acknowledge the need for a completely new field of research, and academic institutions and their funders are slow to divert resources to a new scientific discipline, so it has taken over half a century to create awareness and a consensus so that institutions can seek and give funding that opens wide the doors to plastic pollution research. The production of 1000's of peer-reviewed studies and several textbooks over the last quarter-century is strong evidence that plastics and the ocean are now linked in a novel, though highly undesirable marriage for the foreseeable future; an unhappy union whose dissolution will be messy and unknowably prolonged. A world polluted by plastic is indeed a new world, and its discovery and elucidation could be described as a scientific revolution.

Thomas Kuhn stated in *The Structure of Scientific Revolutions*, “Though the world does not change with a change of paradigm, the scientist afterward works in a different world. . .” May we not take exception to this dictum in the case of plastic pollution? The world has changed, since its water, air and soil, as well as the space around it, are infected with synthetic polymers never before seen in its long history. The contemporary scientific paradigm is an anthropogenic one, and the modern scientist works in a world, in many ways, made by humans.

The field of marine plastic research may conveniently be divided into three chronological phases:

1) The Discovery Phase, 1960–1999, when the phenomenon of ocean plastic was first reported and confirmed.
2) The Consolidation Phase, 2000–2014, when ocean plastic research produced considerable quan- titative data and highlighted areas of concern, mainly entanglement and ingestion. Other areas considered collateral were aesthetics, increasing international production of plastic consumer goods leading to increasing ocean plastics, biofouling, three-dimensional movement in the water column, transport of exotics and effects on the health of marine species.
3) The Rapid Growth Phase, 2015-present, when large institutions and governmental organizations began to see ocean plastics as worthy of high-level research and remedial action, and nongovernmental organizations focusing on plastic pollution worldwide.

The dawn of the Age of Plastic can be traced to its increased development and use in WWII. During the Pax Americana that followed, synthetic polymers spread rapidly from wartime to peacetime consumer and industrial applications. The famous LIFE Magazine article entitled “Throwaway Living,” made single-use foodservice “modern” in 1955, but never addressed the after- life of the items thrown away. Away was far, not near. After three decades of this growing single-use lifestyle, the public became aware of problems with finding a faraway place for waste. This was highlighted by the long but circular voyage of the barge *Mobro 4000* from New York to Belize and back, when despite repeated attempts, no U. S. state, territory, or foreign country would accept 3000 tons of New York’s garbage. Upon the barge’s return to New York, symbolizing a very expensive and failed attempt to find “away,” the refuse was burned and the ash buried in a landfill. To this day, many forms of burning and burying continue to dominate plastic disposal, both of which are polluting “solutions” that waste the energy and resources used to make the original products.

The question of what happens to trash in a landfill was explored in the 1970s by William Rathje, a professor of anthropology at the University of Arizona. He found that when buried deep in a landfill, common biodegradable items, such as carrots, hot dogs, and newspapers did not biodegrade. A similar result for the ocean was observed after the sinking of the deep submergence vehicle Alvin, operated by Woods Hole Oceanographic Institution. Carl Wirsen and Holger Jannasch recovered the soup, sandwich, and apple lunch that sank to a depth of 1500 meters when Alvin’s lowering cable broke during surface launching. After 11 months of inoculation with seawater, “The apples were in a condition equal to that of conventional careful storage, and the bread, may onnaise, ham, and bouillon appeared to fare considerably better than they would have under normal conditions of refrigeration.” Jannasch and Wirsen conducted subsequent experiments, using specially designed vessels lowered to great depths with biodegradable materials inside and then inoculated with seawater. They concluded that, “if the true removal of pollutants is intended, then the slow rates of microbial degradation argue clearly against deep ocean disposal.” (Oceanus)

Seventeen years after the end of World War II, Steve Rothstein was studying seabirds and found certain petrel species (collected in 1962) had eaten plastic. As he told an interviewer compiling the early history of plastic pollution: "I didn't quite realize the significance of things. I figured, well, there's probably, maybe some plastic out there in the ocean and the birds are swallowing it. And I assumed that maybe everyone knows this, or it's not that worth reporting that much" (Plastisphere). As it turned out, it was indeed "worth reporting," but it would take two decades of such reports, mostly in journals and reviews characterized by Peter Ryan in "A Brief History of Marine Litter Research" as "not such good places," before the First International Marine Debris Conference was convened by the Southwest Fisheries Science Center in Honolulu in 1984.

Ed Carpenter, the first scholar to characterize floating marine plastics in the "good" peer-reviewed literature, (Science 1972), recognized potential problems associated with plastics in the ocean, such as their ability to sorb PCBs, and then be ingested by marine animals due to their ability to mimic natural prey, but he let the subject lapse after getting pressure from the Society of the Plastics Industry, leading him to wonder if his position as a marine biologist at Woods Hole might be placed in jeopardy by the industry complaining to his superiors. (Plastisphere Interview) Another paper published in a "good" journal, Nature, in 1974 by Wong et al. looked at "Quantitative Tar and Plastic Waste Distributions in the Pacific Ocean." The surface tows done for this study were conducted during the 1972 San Francisco to Honolulu Transpac sail race and would have avoided areas of light winds where debris concentrations may have been higher.

The initial response of the plastic industry to environmental plastic pollution was to consider plastic "litter" merely an aesthetic problem. After Carpenter's papers were published in *Science,* and Wong's in Nature, W.C. Ferguson, a member of the Council of the British Plastics Federation and a fellow of the Plastics Institute stated that "Plastics litter is a very small proportion of all litter and causes no harm to the environment except as an eyesore." This may still be the general public's attitude. Their nearly constant contact with the material, its lack of taste, smell, and obvious physical effects, have led most people to consider consumer plastics inert. If it were harmful in any way, why would it be used for our clothing, our home furnishings, and to serve and contain our food?

The need for a volume on plastics and the ocean before a volume on plastics in the soil or the air, or even in earth orbit, arises from the fact that the land we live on slopes down to the sea and gravity, coupled with wind and rain results in the ocean being the first receiving body to absorb massive amounts of vagrant plastics. The first plastics found by ocean scientists were a mix of discarded plastic consumer objects, but also pre-production plastic resin beads that came to be known as *nurdles*, the form that thermoplastic resin raw material is shipped to "converters," as the fabricators of plastic objects for the marketplace are known. These pellets showed up in the bellies of seabirds and in small mesh nets towed mostly at the ocean surface. In the decade following Carpenter's paper, larger objects came to be noticed and spawned the National Atmospheric and Oceanographic Administration (NOAA) international marine debris conferences. The early conferences focused primarily on derelict fishing gear as indisputable harm was being done to ships by blockage of intake ports and entanglement around propellers and drive shafts. To try to stop derelict nets and lines from being caught in propellers, several companies developed knives that could be attached to driveshafts to cut these lines as they wound around them. This fouling with debris had been a rare problem for vessels before the age of plastic, but as the age progressed, and less expensive and more persistent plastic fishing nets and lines proliferated, entanglement increased, and with its high cost to remedy, interest in tracking concentrations of this material became a new focus. Increasing reports appeared on derelict nets and fishing gear killing thousands of marine mammals through entanglement. This led to an interest in observing and recording the occurrence of floating marine debris. In 1987, two NOAA scientists at the National Marine Fisheries Service

Auke Bay Laboratory, Steve Ignell and James Seger, prepared a paper on methods for observing debris using line transects of vessels in transit. It was apparent to the authors that sunlight reflected by wavelets or "glare" would be "the most important single environmental factor affecting the sighting probability. . ." The paper was never submitted, probably because "Extensive analyses of sighting probabilities relating distance, wave height, and light conditions to type, sizes, and colors of marine debris will be needed to incorporate these data into debris estimation procedures." (Manuscript provided by Steve Ignell). The year before, Ignell had written another paper with Day and Clausen that emanated from the Auke Bay, AK laboratory entitled: "Distribution and Density of Plastic Particulates in the North Pacific Ocean in 1986." This paper preceded a more comprehensive study by Day, Shaw, and Ignell in 1990, "The quantitative distribution and characteristics of neuston plastic in the North Pacific Ocean, 1985–1989," published in the proceedings of the Second International Conference on Marine Debris in 1989. Plastic particulates were becoming more interesting, but the term "microplastics" was not yet used.

Surface drift up to this time had been in large part focused on the transport of fish eggs and larvae, especially those of commercially important species like salmon. James Ingraham Jr. had developed the Ocean Surface Current Simulator (OSCURS) for this purpose while working for NOAA in the Pacific Northwest. Collaborating with oceanographer Curtis Ebbesmeyer, he was able to adapt this simulator to track a container spill of Nike sneakers and predict where they would wash ashore on the West Coast. He expanded on this work to focus on North Pacific accumulation zones and presented his findings in the year 2000 at the 4th International Marine Debris Conference in Honolulu. The results showed two major areas of drifter accumulation: (i) off southern Japan, which has come to be known as the Western Garbage Patch and (ii) the middle of the eastern North Pacific which has come to be known as the Great Pacific Garbage Patch. The work by Day and colleagues never focused on the east-central North Pacific. When I crossed the area in 1997, I was impressed by the abundance of floating plastics. Two years later, I returned and sampled the area, finding three times the abundance and seven times the weight of the highest concentrations per km^2 found by Day a decade earlier in the western Pacific. In order to assess the potential for ingestion of plastics by open ocean filter feeders, we compared the abundance and mass of the zooplankton caught to that of the plastic in our manta trawls. We found the number of zooplankton was five times greater than the number of plastic pieces >0.3mm in diameter, but the weight of the plastic was six times greater than the zooplankton. We published our findings in *Marine Pollution Bulletin* (42,12, 2001). This finding was shocking and controversial, but to have more plastic than life anywhere in the ocean, no matter how you look at it, was explosive. Another important paper linking floating plastics to absorption of persistent organic pollutants was published the same year by Mato and Takada et al., "Plastic resin pellets as a transport medium for toxic chemicals in the marine environment." They found the pellets could sorb hydrophobic pollutants up to one million times their level in the surrounding seawater. This gave credence to the description of small ocean plastics as "poison pills" for marine creatures.

Of course, during these developments, the plastic industry and its professional organizations were becoming aware of calls to label plastic waste in the environment as pollution. I was invited to speak at a meeting of the Southern California Film Extruders and Converters Association and was introduced to an industry response that focused on making plastic waste "disappear" using an "OxoDegradable" plastic additive. There were two benefits promoted by the producer of the OxoDegradable additive. The first was that it would accelerate the breakdown of the polymer chain, minimizing the risk of entanglement, such as was seen to occur with plastic six-pack rings used to hold canned beverages. When discarded into the marine environment, they had been photographed choking several species. The second supposed benefit of the additive was more rapid biodegradation. The idea was that no matter how slowly, plastic polymers will undergo some biodegradation in the environment, and this process could be accelerated by mixing fragmenting agents into plastics to make them smaller. Although oxo additives did not themselves improve biodegradation, the fact that they produced smaller pieces of plastic suggested that they would disappear sooner through greater exposure per unit of mass to biodegradation organisms. A representative of the company was showing a jar of soil with fragmented plastics to make his point. However, when asked to produce proof of final degradation, none was forthcoming. This did not stop the company from telling its customers to label their plastic products biodegradable if they contained oxo-degradable additives. Experiments with the six-pack rings showed OxoDegradable additives to be ineffective in the cold, wet environment of the ocean, making their effectiveness in preventing entanglement questionable.

So, if you are the plastic industry, and you can't show that vagrant plastic waste will go "away," you might find it advantageous to blame consumers of plastic products for their failure to properly dispose of plastic waste. An extremely effective campaign was mounted by an industry- sponsored organization in the US called "Keep America Beautiful." Its focus was the "litterbug," who did not properly dispose of their used products. If only people would not litter, the problem of plastics in the ocean would go away. Even scientists studying the problem of ocean plastics believed this theory. After listing potential (though not actual) solutions in their paper: "Global research priorities to mitigate plastic pollution impacts on marine wildlife," Vegter and 26 co-authors con cluded that, if their potential solutions were implemented ". . .it would be feasible to deal with what is ultimately an entirely avoidable problem." It seems at just this point; the scientists stop being objective, and revert to fantasy. There is no avoiding the problem of ocean plastic pollution in any sense, nor is there any way for it to reach some sort of equilibrium or begin to diminish in any realistic near-term scenario. Plastic use will surge with the conversion of oil for fuel to oil for plastic. 3-D printing of everything imaginable with plastic feedstocks along with plastic packaging for nearly every manufactured product and many fruits and vegetables will contribute to the projected doubling or tripling of plastic production by mid-century. Therefore, it is very important to have a broad view of the resulting issues that you will get from studying the subjects covered in this volume. Plastic pollution and its effects will continue to plague the ocean for many future generations of scientists.

After my discovery or, more accurately, my confirmation of the existence of the "Great Pacific Garbage Patch," and publication of my findings in *Marine Pollution Bulletin* 42:12 (2001), I resolved to work diligently to highlight the issue of ocean plastic pollution, not only with the public but also with industry and the scientific community. I believed the role of "popularizer" of scientific findings to be an important one, and that I had sufficient speaking and writing skills to fill that role successfully. The most widely read article I wrote appeared in *Natural History* magazine. The article titled "Trashed, *Across the Pacific Ocean, plastics, plastics, everywhere*," appeared in November, 2003. After this article, I was besieged with requests for interviews with writers for many different publications from "Best Life, *Our oceans are turning into plastic . . . are we*," to "US News and World Report," and "Rolling Stone." Audio-visual media were also interested and I never turned down a single interview, from a student classroom to Late Night with David Letterman. Documentaries were made by the likes of Academy Award winner Jeremy Irons, who sailed aboard my research vessel to do the film, *Trashed*. Also sailing with me were the crews of Nightline and CBS Sunday Morning, among many others. I even took a public television film crew from the Korean Broadcasting System out to the Great Pacific Garbage Patch to film our research As the media began to produce more content on the issue of ocean plastics, the scientific community also began to show greater interest in the topic. A little-known Italian scientific organization, The World

Federation of Scientists, started by a physicist and scientific advisor to the Pope, had been holding annual conferences to discuss what they considered "planetary emergencies," such as climate change and pollution. For their 2006 meeting at their headquarters in Erice, Sicily, they wanted to include "Pollution of water by plastic" as a new planetary emergency. They reached out to Jean Michele Cousteau, President of the Ocean Futures Society, who had given a keynote address, "Trashing the Sea" at the 3rd International Marine Debris Conference in 2000. The organizers wanted him to present data on ocean plastic pollution, but his group had done no studies of the subject and had no data to present. They then contacted me to see if I would be willing to present my data at the conference, and I agreed. This meeting of top scientists was to become more productive than I could have imagined. There was a small press room, and a past editor of the Transactions of the Royal Society overheard me talking to someone about plas tic pollution. He approached me and offered to create a dedicated issue on the topic in one of the oldest and most prestigious scientific journals. Up to this time, no researcher had published on the transmission of chemicals sorbed to plastic into wildlife. Several papers were presented at the conference in Erice on the endocrine-disrupting effects of compounds in plastics such as BPA and phthalates, but the connection had never been established linking them directly to wildlife through plastic ingestion. The Theme Issue was edited by Richard Thompson, author of the paper "Lost at Sea: Where is all the plastic?," Shanna Swan, a researcher on phthalates at the USEPA and author of Countdown, Fred vom Saal, a pioneering researcher on the effects of BPA, and myself. The theme issue in *Transactions of the Royal Society B*, was titled "Plastics, the environment and human health." It contained the article by Teuten et al., "Transport and release of chemicals from plastics to the environment and to wildlife," which was an important milestone in the field of ocean plastic research. I bring up these personal experiences for two reasons: (i) some of these aspects of the history of plastic pollution research have not before been reported and (ii) to show how scientific progress may in some cases be advanced by individuals who straddle the line between research and activism.

After the Royal Society publication in 2009, research papers on the effects of chemicals associated with plastics became commonplace and we began to enter the rapid growth phase of ocean plastic research. The paper that created the most interest in ocean plastics after my actively promulgated finding that plastic outweighed zooplankton in the central Pacific was Jenna Jambeck's paper published in *Science* in 2015 titled "Plastic waste inputs from land into the ocean." The editor of this volume and the author of chapter 12 were co-authors. Both the scientific community and the public were shocked at the median figure of eight million tons of plastic waste per year enter ing the ocean, and that this amount would be likely to grow into the next century, since "peak waste" would not be reached before 2100. In 2016, based on this paper, the Ellen MacArthur Foundation predicted that there would be more plastic than fish in the ocean by 2050 and that one refuse truck's worth of plastic is dumped into the sea every minute. I would speculate that few major newspapers or online news platforms failed to mention one or both of these estimates. Images that showed the sea surface covered with plastic in near coastal areas became more com mon. Many had requested similar images of the "trash island" because of my work in the Great Pacific Garbage Patch. However, because debris there occurs in Langmuir windrows (long lines) that can stretch for more than 50 miles, and the debris is rarely touching, no areas covered in debris existed in the gyre, even in the areas with the highest concentrations of surface plastic. I have emphasized the point that plastics in the ocean are pollutants, but there is still considerable debate concerning their harmfulness. A milestone 2013 paper linking plastic ingestion in fish to negative physiological outcomes was by Chelsea Rochman and colleagues, "Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress." Consumption of plastic particles that had sorbed pollutants while floating in San Diego Bay resulted in liver abnormalities in fish.

There remained what many considered the most important aspect of plastic pollution, its effect on human health, as papers quantifying the plastics consumed in seafood were becoming common. In 2017, Fred vom Saal and Aly Cohen edited an Oxford University Press Publication titled Integrative Environmental Medicine intended for medical practitioners. Their goal was to mainstream cutting- edge concepts that were not taught in traditional medical courses. Sara Mosko, a physician and I contributed a chapter: “The Plastic Age: Worldwide Contamination, Sources of Exposure and Human Health Consequences.” The Key Concepts included this provocative statement: “The list of human health problems that correlate with exposure to chemicals in plastics reads like a catalog of modern Western diseases.” Although correlation is not causation, correlations do merit further investigation. We are now in the phase of plastic pollution research where the dividing line between environmental effects and medical research has been breached and medical researchers are looking seriously at potential human health effects. While at first, concerns about eating fish that had consumed plastic were paramount, we now have ample evidence that exposure through respiration is a greater threat, and that plastics at the nanoscale have invaded consumables of all kinds.

An implication of the dictum that the dose makes the poison is that as the dose of a substance increases, so does its potential toxicity. There are certain substances in plastics that contradict this. I imagine a crowd unable to get through a door when an individual could. Binding to receptors can exhibit a U-shaped curve where a very low dose given at the right time binds to a receptor and larger doses have less effect until the system is eventually overwhelmed at very high doses. Future ocean plastic research will examine such questions and others as they relate to population-level effects.

This volume concludes with two chapters on behavior change and legal remedies, which are certainly important in stemming the tide of vagrant plastics invading the ocean and the entire biosphere. However, the economic drivers of plastic pollution are in the ascendant, and until the worldwide growth of infinitely variable plastic products is redirected by a major paradigm shift, scientists will continue to work in a “different” plastic world.

1

Plastics in the Anthropocene

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We live in an era where human beings dominate and control most geochemical processes on Earth's surface, including some aspects of the ocean system. It is impressive that *Homo sapiens* accounting for a mere 0.01% of the biomass on Earth, can exert such control; the mass of structures built on Earth by man now exceeds the total biomass on the planet (Elhacham et al. 2020). The present epoch of man deserves to be formalized a distinct period, the Anthropocene, within the geological time scale (Crutzen and Stoermer 2000). This era started in the post-World War II (WWII) years (Steffen et al. 2015; Zalasiewicz et al. 2016) and is ongoing. Plastics, a unique identifier of the Anthropocene, survives as stratigraphic markers in the soil to guide future archeologists exploring our era. Historical origins of plastics, however, can be traced further back in history, perhaps to 1869, when Wesley Hyatt invented nitrocellulose as a potential substitute for elephant ivory that was used to make billiard balls at that time. Even though Wyeth's celluloid billiard balls were a failure (as some of them exploded on impact), this unique product opened the floodgate for synthetic plastic products in to the consumer world. But, the commodity plastics we are familiar with today, came of age much later when the War effort spurned a rapid expansion of the materials industry in the US with public funding allowing new plastic resin plants to be built to produce vital plastics for the military supply chain.

Postwar years saw the enthusiastic acceptance of plastics by consumers worldwide, thanks mostly to the efforts of industry to promote plastics as a unique "wonder material," and much was expected of this novel semi-utopian material that promised a wide range of affordable products. Today, plastics have emerged as the material of choice in a variety of applications ranging from food packaging to spacecraft design. The abundant societal benefits of plastics (Andrady and Neal 2009) are evidenced by the rapid substitution of conventional materials used in packaging, building, transportation, and medicine, with plastics. Plastics have, by now, become indispensable to the modern lifestyle, with their *per capita* consumption governed generally by the affluence of the country. While the US, Canada, and Japan, for instance, use over 100 kg *per capita* of plastics annually, India and some countries in Africa or Central Europe, use less than 50 kg *per capita* (e-Marketer 2021). To meet this steadily increasing global *per capita* demand of an average ~46 kg annually, plastic resin production had grown to 359 million metric tons (MMT); 432 MMT inclusive of the polymer used in synthetic textile fibers) in 2019. China accounted for about 30% of the production, and with ~50% of the global resin demand in Asia, the country is well poised to remain as the leading resin manufacturer in the world. The annual global production of plastics in the year

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2015 alone, if processed into a thin plastic "cling film," was estimated to be large enough to wrap the entire earth in plastic wrap (Zalasiewicz et al. 2016).

An estimated (Geyer et al. 2017) 7300 MMT of plastic resin and fiber was manufactured globally from just after WWII until the year 2015. By 2020, this figure rose to 8717 MMT. More than half of this was either PE (~36%) or PP (~21%). In addition, the thermoplastic polyester (e.g., poly(ethylene terephthalate) [PET]) used in beverage bottles, polystyrene (PS) in packaging, and poly(vinyl chloride) (PVC) as a building material, were also produced. Reflecting their high-volume use, these same 4–5 classes of plastics typically dominate the plastic content in the municipal solid waste stream (MSW), in urban litter, as well as plastic debris in the marine environment. The current discussion is therefore focused on this limited set of plastic types: PE, PP, and PS foam that dominates floating plastic debris in surface waters of the ocean and nylons or polyamide (PA). PET, PS, and PVC, mostly found in the deep sediment. Deep-sea sediment is the most important sink or repository of waste plastics that enter the ocean every year. While no systematic quantitative assessment is available, there is little doubt that plastics accumulate in the benthic sediment and a recent estimate places it conservatively at about 14 MMT (Barett et al. 2020).

1.1 What Are Plastics?

The term "plastic" is used in common parlance as if it is a single material. But it is, in fact a broad category of materials that include hundreds of different types. Plastics are a sub-class of an even larger group of materials called the polymers, characterized by their unique long chain-like molecular architecture, made up of repeating structural units. They tend to be giant molecules with average molecular weights (g/mol) in the range of 10^5–10^6 (g/mol). Being a subset of polymers that can be melted and re-formed into different shapes repeatedly, they are therefore called thermoplastics. The word "plastic" is derived from 'thermoplastic [See Box 1.1]. Hundreds of chemically distinct types of thermoplastics exist, even though only a few are used in most consumer plastic products.

This is somewhat analogous to the about 95 elemental examples in the group 'metals' and their numerous commercially available blends, even though only a few common ones such as copper or aluminum are extensively used. The same is true of plastics, but even within a single type of plastic such as polyethylene (PE)[1] several different varieties of resins with different characteristics are available. For instance, the common varieties of PE are low-density polyethylene (LDPE), high-density polyethylene (HDPE), medium-density polyethylene (MDPE), and linear low-density polyethylene (LLDPE) resins. Each of these varieties includes different grades of that plastic with range of properties despite their identical repeat-unit chemical structure. For instance, one grade of LDPE (low molecular weight grade) is a soft wax used as a lubricant, while another (ultra-high molecular weight grade) of PE, is spun into fibers so strong that they are used as an antiballistic material in military hardware. Therefore, in research reports, identifying a material just as a "plastic" or even as "polyethylene" is not particularly informative; details of at least the type, if available the grade, and its basic properties should be mentioned in order to compare data across publications.

1 The term should really be "polyethylenes" because any given class of plastic such as PE includes many different grades of the same polymer that differ in their average molecular weight, molecular weight distribution, and polymer chain architecture such as the degree of branching. Despite the identical chemical structure, their key properties including strength, melting point and levels of crystallinity are very different.

Box 1.1 Thermoplastics and Thermosets

All plastics are polymers but not *vice versa*; plastics or thermoplastics include only those types of polymer that can be melted and re-formed into different shapes repeatedly. Therefore, polymers such as tire rubber, polyurethane foam, or epoxy resin as well as cellulose or proteins, that do not melt on heating by virtue of their molecular architecture, are not thermoplastics but are thermosets. What is commonly described under "plastic debris" or "microplastics" in marine debris literature, however, often includes some thermosets such as epoxy resin, reinforced polyester (e.g., glass-reinforced plastic (GRP)) and tire rubber particles. In this chapter, we will use the term "polymer" interchangeably with "plastic" for convenience of discussion.

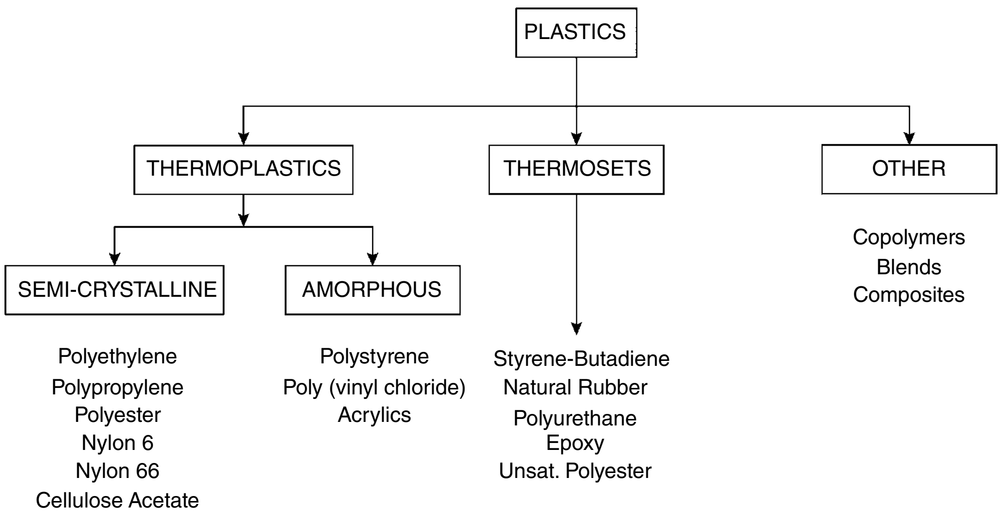

Figure 1.1 Classification of plastic types commonly found in the marine environment.

Plastics owe their impressive success as a material to their unusual molecular structure that obtains a unique combination of advantages (Singh and Sharma 2008). Very long, chain-like molecules in polymers result in strong attractive forces between them that allow for the development of unusual strength in the material. If the long-chain molecules are flexible enough, they can also profusely entangle with each other, resulting in resistance to deformation, contributing to the strength of plastics. Thermoplastics can easily be formed into different shapes at relatively low temperatures to obtain lightweight (low density) products that are strong, transparent, bio-inert, and gas-impermeable, thereby making them ideal as packaging materials. Thermosets, especially polymer composites reinforced with fillers or carbon fibers, serve as a durable, high-strength, and corrosion-resistant material that allows a new degree of design freedom that is exploited in building design and transport applications. It is this combination of characteristics that impart the versatility of plastics in numerous applications. No wonder we now annually produce enough plastics that exceed the global biomass of human beings. Figure 1.1 shows the classification of common plastics in the marine environment.

Figure 1.2 shows a breakdown of the mix of plastic resins manufactured worldwide along with the main application sectors for different resin types. PE is the resin produced in the highest volume(~50%) followed by PP and PET. The figure shows that over 35% of resins produced are

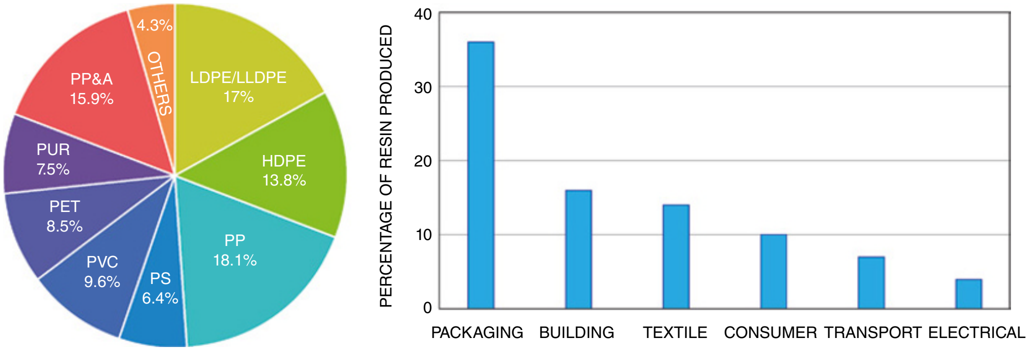

Figure 1.2 Left: Global plastic resin production (2015 data), Right: Percentage use of the production in different application sectors (miscellaneous categories not shown). *Source:* Redrawn from data in Geyer et al. (2017)

used in packaging where products are expected to have the shortest service life and are particularly likely to end up as urban or beach litter.

1.2 Plastics at Present and in the Future

At present, plastic production is a relatively energy-efficient operation supporting a vast global manufacturing industry providing an array of useful products at a resource cost of only about 4–6% of the annual global petrochemical demand (compared to the ~50% used for transportation). The embodied energy[2] EE (MJ/kg) of a material is a useful measure of how "energy-expensive" a given material might be and is the sum of all energy expenditure associated with producing a unit mass of the material or a functional unit of a product. This energy is not "embodied" in a product in the sense that all such energy can be recovered from the material. Market cost, however, is an unreliable guide to the EE of a material or product. Common plastics generally have a lower EE compared to metal, close to that of glass, but higher than that of wood. Most of this energy is typically derived from fossil fuel, a dwindling non-renewable resource that should invariably constrain global plastics production. But, a shortage of feedstock is not expected, especially in the US, at least in the foreseeable future; the boom in natural gas in the US (with about 500 trillion ft^3 of proven gas reserves) guarantees the availability of low-cost feedstock for plastics at least the next couple of centuries. Also widely anticipated is the freeing up of about 45% of the demand on global crude oil for gasoline production because of the expected growth in electric vehicles worldwide (CIEL 2021). The petrochemicals sector, including plastics, will then become the major driver for the petroleum industry, accounting for about a third of the future oil demand (IEA 2020).

As shown in Figure 1.3, manufacturing plastic resin requires a regular supply of fossil-fuel feedstock, a source of processing energy, as well as commons resources such as air or water, a category often either overlooked or incompletely accounted for in calculating the cost of the product, shown on the left side of the figure. In the process, the carbon in the feedstock is sequestered in the plastic resin, while that used as fuel to generate energy for the operation is released as CO_2. A suite of externalities that impact air, water, and the generation of solid waste accompany the manufacturing process. The result of this

2 Embodied Energy (EE) is the energy expended in making a unit mass of the material from feedstock or the ore and includes energy used in raw material extraction, product processing, transportation, construction, use/maintenance, and disposal or reuse.