Microplastic: What Are the Solutions?

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Abstract The plastic that pollutes our waterways and the ocean gyres is a symptom of upstream material mismanagement, resulting in its ubiquity throughout the biosphere in both aquatic and terrestrial environments. While environmental contamination is widespread, there are several reasonable intervention points present as the material flows through society and the environment, from initial production to deep-sea microplastic sedimentation. Plastic passes through the hands of many stakeholders, with responsibility for environmental contamination owned, shared, or rejected by plastic producers, product/packaging manufacturers, government, consumers, and waste handlers.

The contemporary debate about solutions, in a broad sense, largely contrasts the circular economy with the current linear economic model. While there is a wide agreement that improved waste recovery is essential, how that waste is managed is a different story. The subjective positions of stakeholders illuminate their economic philosophy, whether it is to maintain demand for new plastic by incinerating

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postconsumer material or maintain material efficacy through recycling, regulated design, and producer responsibility; many proposed solutions fall under linear or circular economic models. Recent efforts to bring often unheard stakeholders to the table, including waste pickers in developing countries, have shed new light on the life cycle of plastic in a social justice context, in response to the growing economic and human health concerns.

In this chapter we discuss the main solutions, stakeholder costs, and benefits. We emphasize the role of the "honest broker" in science, to present the best analysis possible to create the most viable solutions to plastic pollution for public and private leadership to utilize.

Keywords Extended producer responsibility, Marine debris solutions, Microplastic, Plastic marine pollution, Recycling, Reuse

1 Research Conclusions Guide Solutions

Since 2010 there have been more research publications about plastic marine pollution than in the previous four decades, bringing the issue mainstream as a robust field of science and in public discourse. Much of what we know can be summarized in three conclusions: fragmented plastic is globally distributed, it is associated with a cocktail of hazardous chemicals and thus is another source of hazardous chemicals to aquatic habitats and animals, and it entangles and is ingested by hundreds of species of wildlife at every level of the food chain including animals we consider seafood [1].

Global Distribution of Microplastics The global distribution of plastics is a result of the fragmentation and transportation by wind and currents to the aquatic environment, from inland lakes and rivers to the open ocean and likely deposition to coastlines or the seafloor [2]. New studies are showing increasing abundances of microplastic upstream, showing that microplastic formation is not limited to the sea, though it was discovered there.

The first observations of plastic in the ocean were made in 1972 in the western North Atlantic consisting of preproduction pellets and degraded fragments found in plankton tows [3]. Studies in the North Pacific [4, 5], and South Atlantic followed [6]. Scientists were beginning to understand the global implications of fragmented plastics traveling long distances. "Data from our oceanic survey suggests that plastic from both intra- and extra-gyral sources becomes concentrated in the center of the gyre, in much the same fashion that *Sargassum* does [7]."

In 2001 Captain Charles Moore published his discovery of an accumulation of microplastics in the North Pacific Subtropical Gyre [8]. This finding might have joined the trickle of research that had been published in the previous quarter century, but sensationalized media stories reported fictional islands of trash converging in the ocean that were forming garbage patches twice the size of Texas.

This subsequently catalyzed the attention, interest, and concern of the public, policymakers, industry, and science.

Regional and global estimates of floating debris have come forth [9, 10]. Estimates of environmental concentrations have ranged from 8 million tons of plastic leaving shorelines globally each year [11], compared to one estimate of a quarter million tons drifting at sea [12]. This represents a huge disparity suggesting that plastics sink, wash back ashore, or fragment long before they arrive in the subtropical gyres. Analysis of the size distribution of plastic in the oceans has found hundred times less microplastics than expected [10, 12], supporting the suggestion that fragmented microplastics do not survive at the sea surface indefinitely and likely invade marine food chains before moving subsurface to be captured by deeper circulating currents and ultimately deposited as sediment. Recent studies have unveiled microplastics frozen in sea ice [13] and deposited on shorelines worldwide [14] and across the sea floor [15, 16], even the precipitation of synthetic fibers as fallout from the skies [17]. Collectively, these observations suggest widespread contamination in all environments.

Inherent Toxicity and the Sorption of Pollutants While plastic products entering the ocean represent a range of varied polymers and plasticizers, many absorb (taking in) and adsorb (sticking to) other persistent organic pollutants and metals lost to the environment, resulting in a long list of toxicants associated with plastic debris [18]. Gas stations will sometimes use giant mesh socks full of polyethylene pellets draped around storm drains to absorb hazardous chemicals before they reach the watershed. In the aquatic environment, plastic behaves similarly, mopping up chemicals in surrounding water. Several persistent organic pollutants (POPs) bind to plastic as it is transported through the watershed, buried in sediment, or floating in the ocean [19, 20]. A single pellet may attract up to one million times the concentration of some pollutants in ambient seawater [21], and these chemicals may be available to marine life upon ingestion.

The chemistry of plastic in consumer products raises human health as well as ecological concerns. For example, they include polyfluorinated compounds ("PFCs") [22–24] and the pesticide/sanitizer triclosan [25, 26], also used in over-the-counter drugs, antimicrobial hand soaps and some toothpaste brands, flame retardants, particularly PBDEs [27, 28], and nonylphenols. Bisphenol A (BPA), the building block of polycarbonates, and phthalates – the plastic additive that turns hardened PVC into pliable vinyl – are both known endocrine disruptors [29, 30].

This is not surprising in the case of BPA, which was invented as a synthetic estrogen [31], yet proved to be a usable form of plastic. Exposure may come from the lining of metal cans for food storage [32], CDs, DVDs, polycarbonate dishware, and receipt paper from cash registers. BPA has been linked to many developmental disruptions, including early puberty, increased prostate size, obesity, insulin inhibition, hyperactivity, and learning disabilities [33]. Phthalates are similarly problematic as endocrine disruptors [34], with effects including early puberty in females, feminization in males, and insulin resistance [35]. Different phthalates are found in paints, toys, cosmetics and food packaging, added for the purpose of increasing durability, elasticity, and pliability. In medical applications, such as IV bags and tubes, phthalates are prone to leaching after long storage, exposure to elevated temperatures, and as a result of the high concentration present – up to 40% by weight [36]. Although phthalates metabolize quickly, in a week or less, we are exposed continuously through contact with associated products.

Widespread Effects on Marine Life Of the 557 species documented to ingest or entangle in our trash, at least 203 [1] of them are also ingesting microplastic in the wild, of which many are fish [37] and other vertebrates [38, 39]. In addition, laboratory data suggest a growing list of zooplankton [40], arthropods [41], mollusks [42], and sediment worms [43] is also susceptible, along with phytoplankton interactions that may affect sedimentation rates [44]. In addition, examples of clams [45] and fish [46] recovered from fish markets have been found with abundant microplastics in the gut. A study of mussels in the lab demonstrated that 10 μm microplastics were translocated to the circulatory system [47], leading to studies that now demonstrate evidence that micro- and nanoplastics can bridge trophic levels into crustaceans and other secondary consumers [48, 49]. Ingested microplastic laden with polybrominated diphenyls (PBDEs) may transfer to birds [50, 51] and to lugworms [52]. The evidence is growing that there are impacts on individual animals including cancers in fish [53] and lower reproductive success and shorter lifespan in marine worms [43]. Some studies even show impacts to laboratory populations: one study of oysters concludes that there is "evidence that micro-PS (polystyrene) cause feeding modifications and reproductive disruption [. . .] with significant impacts on offspring" [54].

While some research shows that plastic can be a vector, or entry point, for these toxicants to enter food webs, others do not. Some studies of microplastic ingestion have shown that complete egestion follows, as in the marine isopod *Idotea emarginata* [55], or ingestion of non-buoyant microplastics by the mud snail *Potampoyrgus antipodarum*, which showed no deleterious effects in development during the entire larval stage [56]. A recent review concluded that hydrophobic chemicals bioaccumulated from natural prey overwhelm the flux from ingested microplastic for most habitats, implying that microplastic in the environment is not likely to increase exposure [57].

Section Summary These three themes dominate the literature today, with an increasing resolution on ecotoxicology and human health. Understanding the fate of micro- and nanoplastics is necessary for a better understanding of the distribution and disposition of plastic pollution. These themes collectively imply microplastic is hazardous to the aquatic environment in the broadest sense. As the literature expands, these themes become benchmarks, tools for policymakers, to mitigate foreseen problems of microplastic contamination of all environments and the social impacts they have on communities worldwide.

2 Mitigation Where There Is Harm

Demonstrated harm to wildlife from plastic is documented from entanglement and macrodebris ingestion, and ingestion of microplastics have shown negative impacts on individual organisms, but demonstrating that microplastics cause harm to the whole ecosystems is unclear [58]. In a recent meta-analysis of available research demonstrating impacts on wildlife from marine debris, 82% of 296 demonstrated impacts were caused by plastic [59]. Interestingly, the vast majority of those (89%) were impacts at suborganismal levels from micro- and nanoplastics, including damages to tissues or organ function, with only 11% due to impacts from large debris, such as entanglement in ropes and netting or death from ingestion of larger items.

According to Rochman et al. [59] there are many cases of suborganismal level impacts, like the ingestion of 20 μm microplastic particles by the copepod *Calanus helgolandicus* affecting survival and fecundity [60], toxic effects on the embryonic development of the sea urchin *Lytechinus variegatus* [61], and reduced feeding in the annelid worm *Arenicola marina* after ingesting 400 μm particles [43]. What these studies and others have in common is that they are limited to laboratory settings, often using PS microspheres only, and use a narrow scale of particle size, shape, and duration of exposure [62]. This criticism was also pointed out in a recent study of the freshwater mud snail *Potamopyrgus antipodarum*, whereby five common and environmentally relevant non-buoyant polymers were introduced in a range of sizes and high concentrations in their food, resulting in no observed effects [56], suggesting that more work in real settings with environmentally relevant microplastic particle size, shape, and polymer type is needed to better understand ecological harm.

Can we say ecological harm exists without the weight of evidence in the literature to say so? One could argue that the volume of research published lately, especially the proposal from Rochman and others to classify plastic marine debris as a hazardous substance [63], indicates substantial concern from the scientific community. That classification would meet criteria for mitigation from policymakers in terms of shifting the burden of proof that plastic is safe to the producer [64]. While further studies of ecological impacts are needed, it is reasonable to employ the precautionary principle considering the risk of widespread and irreversible harm.

Equally, we must not forget the harm to society from plastic pollution. The flow of the material from plastic production to waste management and environmental pollution affects societies in ways that are often difficult to quantify and are often ignored. For example, plastic waste has been shown to incubate water-borne insects and act as a vector for dengue fever in the Philippines [65]. The industry of waste-picking in developing countries is plagued with substantial human health costs from illness and injury from collecting and handling plastics. Open-pit and low-tech incineration is correlated with respiratory illness and cancer clusters among the populations that live near them [66]. While this book aims to understand the impacts of freshwater microplastics, in this chapter we aim to understand and include the upstream social costs in our assessment of the sources and true costs associated with micro- and nanoplastics.

3 Downstream (Ocean Recovery) Versus Upstream Intervention

Then where do our actions to prevent the potential of irreversible harm begin? The three research themes (global distribution, toxicity, marine life impacts) guide mitigation upstream, but it did not begin that way.

The sensationalized mythology of trash islands and garbage patches that had dominated the public conversation about plastic marine pollution in the mid-2000s invoked well-intentioned schemes to recover plastic from the ocean gyres, like giant floating nets to capture debris and plastic-to-fuel pyrolysis machines on ocean-going barges, to seeding the seas with bacteria that consume PET, polyethylene, and polypropylene (which, if this could work, would have the unintended consequence of consuming fishing nets, buoys, docks, and boat hulls). All of these schemes fail on several fronts: economics of cost-benefit, minimizing ecological impacts, and design and testing in real ocean conditions [67]. Recent analysis of debris hot spots and current modeling support the case for nearshore and riverine collection rather than mid-ocean cleanup [68].

This begs the question, “What should be done about what is out there now?” If we do nothing, the likely endgame for microplastic is sedimentation on shore [14] or the seafloor [16], as a dynamic ocean ejects floating debris. Consider the precedent of how tar balls plagued the open ocean and shorelines until MARPOL Annex V stopped oil tankers from rinsing their ship hulls of petroleum residue to the sea in the mid-1980s. A relatively rapid reduction in tar ball observations soon followed [69]. Though we will live with a defining stratigraphy of micro- and nanoplastic in sediments worldwide [70], the ocean can recover if we stop doing more harm.

Still, what can be done about macrodebris? In the 2015 G7 meeting in Germany, Fishing for Litter was presented as the only viable ocean cleanup program, and described as “a useful last option in the hierarchy, but can only address certain types of marine litter” [71]. While Fishing for Litter campaigns can be effective at capturing large persistent debris, like fishing nets, buoys, buckets, and crates before they fragment further, like the KIMO International efforts in North Sea and around Scotland [72], they do not address the source.

4 Upstream Interventions at the Sources of Freshwater Microplastic

Doing no more harm requires upstream intervention. The further upstream mitigation occurs, the greater the opportunity to collect more plastic with less degradation and fragmentation and identifying sources before environmental impacts occur. For most scientists and policymakers, ocean cleanup is not economically or logistically feasible, moving the debate to upstream efforts, like zero waste strategies, improving waste recovery, and management and mitigating point and nonpoint sources of microplastic creation and loss to the environment.

Measuring Microplastic Sources There is wide agreement that microplastic at sea is a case of the tragedy of the commons, whereby its abundance in international waters and untraceability makes it nearly impossible to source to the company or country of origin. In terrestrial environments, identification to source is easier due to less degradation, but capturing and quantifying microplastics in any environment is difficult and can easily be contaminated or misidentified [73], and in inland waterways there is the challenge of sorting debris from large amounts of biomass. In the United States provisions under the Clean Water Act and state TMDLs (Total Max Daily Loads) direct environmental agencies to regulate plastic waste in waterways, like California's TMDLs, though they are often limited to >5 mm and miss microplastic entirely.

While there are processes in the environment that degrade plastic into smaller particles (UV degradation, oxidation, embrittlement and breakage, biodegradation), there are other terrestrial activities and product/packaging designs that create microplastic (Table 1). These may include the mishandling of preproduction pellets at production and distribution sites, industrial abrasives, synthetic grass in sports arenas, torn corners of sauce packets, vehicle tire dust, tooled shavings from plastic product manufacture, road abrasion of plastic waste on roadsides, unfiltered dryer exhaust at laundry facilities losing microfibers to the air [17], or combined sewage overflow that discharges plastics from residential sewer lines, like personal care products, fibers from textiles, and cosmetics, into the aquatic environment. These many sources lack specific methods of measurement.

There are examples of observed microplastic abundance in terrestrial and freshwater environments leading to mitigations, such as the US Microbead-Free Waters Act of 2015 [74] and state laws on the best management practices on preproduction pellet loss [75]. Interestingly, these two examples share three common characteristics: (a) they are quantified by standard methods using nets to measure discharges in waterways, (b) they are found in high abundance, and (c) they are primary microplastics, making it easier to identify responsible sources. Considering the many terrestrial activities that create small amounts of difficult to quantify micro- and nanoplastics, often called secondary microplastics, there is a need for new methods to measure their significance.

Table 1 Sources, measurements, and strategies for upstream mitigation of microplastics

Tackling upstream microplastics		
Category	Source	Potential mitigation
Production	Microplastics in cosmetics	Removing them from products. Replace with benign alternatives
	Mismanaged preproduction pellets	Regulate pellet handling. Operation clean sweep
Commerce	Industrial abrasives	Improve containment and recovery and require alternatives
	Laundromat exhaust	Improved filtration
	Agriculture – degraded film, pots, and pipes	Improve recovery, biodegradable plastics
Consumer	Tire dust	Technological advances, road surface
	Littering of small plastic items (cigarette filters, torn corners of packaging, small film wrappers, etc.)	Enforcement of fines for littering, consumer education, EPR on design
	Domestic laundry. Waste water effluent	Wash with top-load machines. Wastewater containment, single-fiber woven textiles. Textile coatings
Waste management	Fragmentation by vehicles driving over unrecovered waste	Improved waste management
	UV and chemically degraded terrestrial plastic waste	Improved waste management
	Sewage effluent (synthetic fibers)	Laundry filtration, textile industry innovation
	Combined sewage overflow (large items)	Infrastructure improvement
	Mechanical shredding of roadside waste during regular cutting of vegetation (mostly grass)	Better legislation and law enforcement; valorization of waste products

Why wait until microplastic reaches water to quantify its existence? The current methods of storm drain catchment and waste characterization measure macroplastic only. Microplastics, such as synthetic grass, tooled shavings, road abrasion, etc., are sources of microplastic with unknown abundances, which could be measured by sampling surface areas on the ground nearby the activities that create them. Methodologies might include square meter sweeping of sidewalks and roadsides to quantify abundances. A recent study of microfiber fallout used containers on rooftops in Paris to capture airborne particles [17]. These micro- and nanoplastic fibers can be measured closer to the source. Surveying the surface of foliage near laundromats (Eriksen, unpublished data) recently discovered abundant microfibers. Other methods might employ footbaths outside hotels or shops with carpeted floors to measure the transport of fibers due to foot traffic. The production of household microplastics could be estimated from dust particles accumulated in the filter bags of vacuum cleaners. Quantifying the significance of these point and nonpoint sources might assist efforts to mitigate their contributions.

5 Competing Economic Models Impact Microplastic Generation

The contemporary debate about solutions largely contrasts the circular economy with the current linear economic model. These competing economic models reveal subjective stakeholder motives, whether it is a fiduciary responsibility to shareholders, an environmental or social justice mission, or an entrepreneurial opportunity. These economic models influence the design and utility of plastic and therefore the abundance and exposure of plastic waste to the environment, thus influencing the formation of microplastic.

Material Loss Along the Value Chain in the Linear and Circular Economic Models Given the many sources of microplastic, the different sectors of economy and society producing these and the relatively limited knowledge about them (Table 1), it becomes apparent how difficult it would be trying to "plug" leaks of microplastics to the environment. Some of the sources could be stopped by effective legislation (e.g., banning microbeads in cosmetic products), education and regulation enforcement (litter laws), and technological advancements (effluent filters, biodegradable polymers).

However, in the end it becomes increasingly difficult to mitigate these leak points the further from the source intervention begins. The closest point to the source is the choice of polymer and how it is managed throughout the supply chain and once it becomes waste. Some efforts have included an upfront tax to fund cleanup efforts or mitigate environmental impacts, but those appear impractical due to the diffusion and difficulty in collecting small microplastics. Given the low value of most postconsumer plastic products and lack of recovery incentives, the chances of downstream mitigation are extremely low.

Consequently, leaks of microplastics to the terrestrial and ultimately aquatic environment (primary or secondary by input in form of large objects which later degrade into microplastics) occur throughout the supply chain, e.g., in form of loss of preproduction pellets, littering, or irresponsible waste management (Fig. 1). Little material remains in the system, and most would not be fit for effective recycling (i.e., reusing) because of contamination or expensive recuperation schemes. Deposition in landfills or energy recovery through incineration therefore appears as the ultimate strategy to remove almost all material from the system, effectively creating a linear economic model. Energy recovery is not a form of recycling and does not break this linearity, because it essentially removes used plastics from the economic system through destruction, converting them into ashes and atmospheric CO_2 (Fig. 1).

A circular economic model on the other hand could address leaks of plastics at all life cycle stages. The reduction of leakage to the environment requires adaptation and consensus of all stakeholders, e.g., designing for reuse; discouraging littering, for example, by introducing deposit return schemes; and ensuring a high recycling quota during the waste stage (Fig. 2). Most likely one key to the

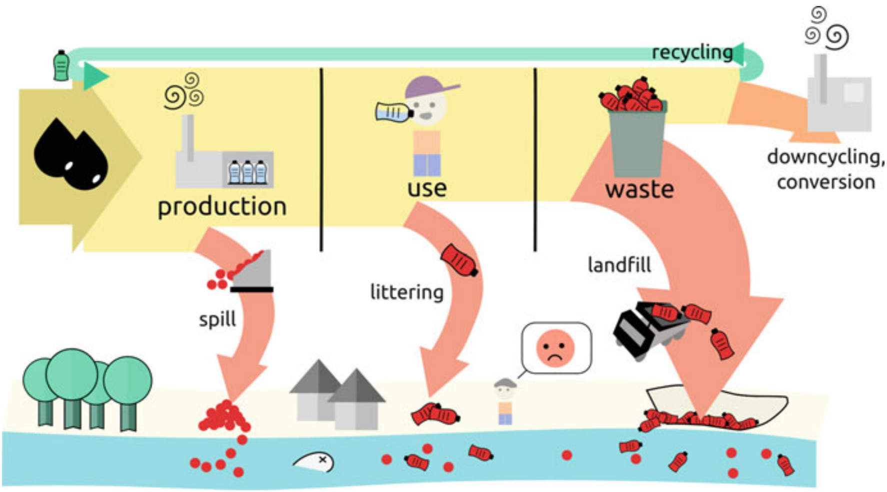

Fig. 1 Linear economy model for plastic products and packaging and system leaks. Product is manufactured using principally new resources, largely petroleum based. Most of the product's value is lost during its life cycle because of leakage along the entire value chain (*red arrows*), including pellet loss, littering, combined sewage overflow, loss during transport and improper storage of waste, and poorly designed products that are easily lost to the environment and difficult to recover (microbeads, small wrappers, torn corners of packaging). This leads to a contamination of the environment, affecting wildlife and human well-being. A small proportion is recycled (*green arrow*) for remanufacture, with the remainder utilized for energy recovery

implementation of this circular economic model is to modify the value chain of plastics throughout all phases of its functional life. A number of economic alternatives are already being implemented as will be described below. This model also puts emphasis on preventive measures when accounting for environmental problems caused by excessive leakage. Prevention is also much more cost-effective and environmentally friendly than postconsumer cleanup schemes, many of which are economically or technologically unfeasible.

Most stakeholders agree waste management must improve globally to prevent pollution of the aquatic environment, and that landfilling waste is not a viable strategy in the future. What some have called "uncontrolled biochemical reactors" [76] are landfills which are increasingly losing popularity as the costs and hazards outweigh the benefits. In "Zero Plastics to Landfill by 2020" [77], the European Union, and the trade organizations Plastics Europe and the American Chemistry Council [78], advocates ending landfill reliance. Where the circular and linear economies largely differ is the role of policy to drive design, and the end-of-life plan for recovered plastic.

Zero Waste vs. Waste-to-Energy This division could be considered the frontline where sharp divisions exist. Whether plastics are incinerated for energy recovery or sorted for recycling and remanufacture reflects stakeholder positions and influences

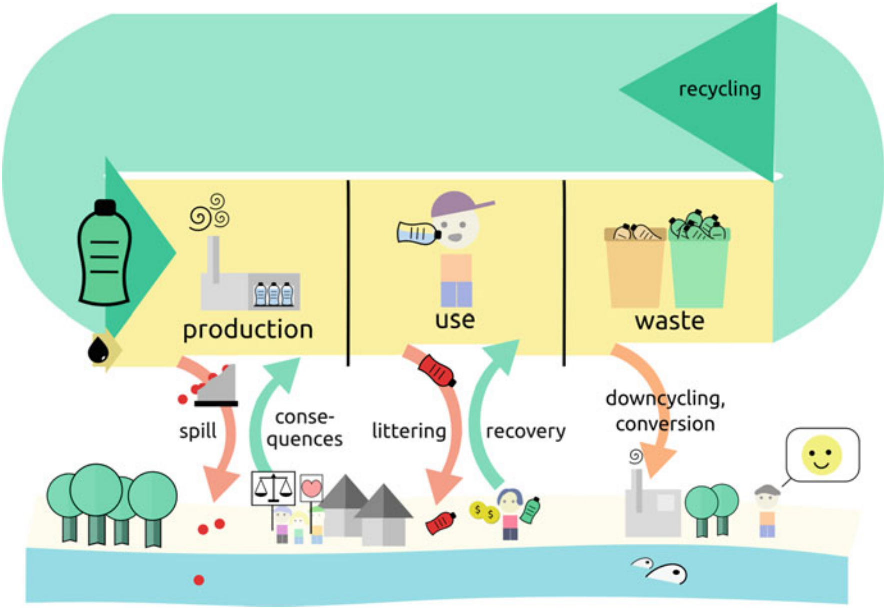

Fig. 2 Circular economy model for plastic products and packaging. A high percentage of recycled content is required as feedstock for new products, and the remainder from sustainable sources (potentially biopolymers). Poor practices (*red arrows*) throughout the life cycle are mitigated, for example, by proper legislative policy, public awareness that leads to proper consumer waste handling, and incentivized recovery systems (e.g., returnable bottles). Recovery is further improved by regulating end-of-life design in products and packaging. This leads to reduced leakage of plastic to the environment from all sectors of society, and significant improvements are social justice concerns for communities that manage waste. The small amount of residual plastic is then disposed of responsibly

decisions about product and packaging design and regulation far upstream. The end-of-life plan for plastic affects the entire value chain.

A recent document produced by the Ocean Conservancy (2015) titled "Stemming the Tide," with strong industry support, called for a $5 billion investment in waste management, with large-scale waste-to-energy incinerator plants targeting SE Asia, specifically China, Taiwan, Philippines, Indonesia, and Vietnam, based on a study reporting 4–12 million tons of waste entering the oceans annually, primarily from that region [11]. It was released 1 week prior to the October 2015 Our Ocean Conference. Within days, the organization Global Alliance for Incinerator Alternatives (GAIA) submitted a letter in response with 218 signatories, mostly environmental and social justice NGOs, arguing that incinerators historically exceed regulatory standards for emissions and subsequently cause harm to the environment and human health and that the financial cost to build infrastructure, maintenance, and management are typically underestimated [79]. In many cases, the financial structure includes long-term waste quotas that lock communities into mandatory waste generation [66]. For example, the $150 million cost to build the H-Power incinerator in Oahu, Hawaii, also comes with an 800,000 ton per year "put or pay" trash obligation. If they don't get their quota of waste, the city pays a portion of the revenue they would have earned burning the trash they didn't get. The public calls it "feeding the beast" [80], which had undermined recycling, waste diversion, and composting programs, for fear of fines.

Two earlier documents, "On the Road to Zero Waste" from GAIA [79] and "Waste and Opportunity," from As You Sow and the National Resources Defense Council (NRDC) [81], both lay out a framework for sustainable material management from resource extraction to recovery and remanufacture, without the need for incineration, or the legacy of associated toxicity and human health effects.

In the developing world, circular economic systems are expanding. There are material recovery facilities, or MRFs, sprouting up everywhere. Waste sorting and collection happens door to door, with the collector keeping the value of recyclables after delivering all materials to the local MRF. Organics are composted, recyclables are cashed in, and the rest is put on public display to show product/packaging design challenges. According to the Mother Earth Foundation, 279 communities in the Philippines have MRFs, and waste diversion from landfills and open-pit burning now exceeds 80%. The template for the community MRF is proving its scalability across Asia, India, Africa and South America.

Rationale of the Linear Economy In 2014 Plastics Europe released an annual report titled "Plastics – the facts 2013: An analysis of European latest plastics production, demand and waste data" [82], outlining the forecast for plastic demand and challenges in the years ahead. Worldwide, there has been a historical trend of a 4% increase of annual plastic production since the 1950s, with slight dips during the OPEC embargo in the 1970s and the 2008 economic downturn, but otherwise it's been steady growth from almost no domestic plastic produced post-WWII to 311 million tons of new plastic produced in 2013 alone. If this growth rate continues as anticipated worldwide, there will be close to 600 million tons produced annually by 2030 and over a billion tons a year by 2050.

This trajectory is partially based on rising demand from a growing global middle class and is coupled with the rising population. Yet, these demands will stabilize, leaving waste-to-energy through incineration a key driver in the security of demand for new plastic production. Recycled plastic is a direct competitor with new plastic production, being inversely proportional to the available supply. This has been largely acknowledged and has kept recycling rates generally very low worldwide. Consider recycle rates in the United States alone, with the highest recovery per product in 2013 won by PET bottles (31.3%) seconded by HDPE milk containers (28.2%), and national average for all plastic combined was 9.2% after 53 years of keeping score [83].

The industry transition in light of these trends is to advocate energy recovery after maximizing the utility of plastic, arguing that the cost vs. benefit of plastic favors unregulated design and improved waste management. A careful look at the life cycle of alternative materials (paper, metals, glass), from extraction to manufacture, transportation, and waste management, must be weighed against the benefits of plastic. Plastics make food last longer [84], offer more durable and lightweight packaging for transportation of goods, maintain clean pipes for drinking water distribution, and facilitate low-cost sterile supplies for hospitals, each having degrees of efficiency over alternative materials in terms of waste generation, water usage, and CO_2 emissions, like lightweighting cars with plastic resulting in lower fuel consumption [85].

For example, an industry analysis comparing the impacts of transportation, production, waste management, and material/energy recovery on the environment concluded that the upstream production and transportation phases of the value chain for plastics accounted for 87% of total costs [78], leaving 13% of the impacts on the environment caused downstream by how waste is managed. Plastic producers have suggested that some of these upstream production impacts could be further mitigated by sourcing low-carbon electricity that by doubling the current use of alternate energy for production could cut the plastics sector's own greenhouse gas emissions by 15% [78]. Mitigating the problems of microplastics requires understanding not only where waste is generated but also where other environmental harms can be avoided at all points along the value chain.

The Case for Bridge Technologies While large-scale incinerators are criticized for cost, waste quotas, emissions, and the effect of undermining zero waste strategies, is there a case for the temporary use of small-scale waste to energy until more efficient systems of material management evolve?

While the H-Power plant in Oahu, Hawaii has been criticized, alternatives have been proposed. One firm recently proposed gasification (high heat conversion of waste to a synthetic gas), submitting evidence that the initial cost of infrastructure is far less than the H-Power plant, pays for itself in 1.4 years with current waste input, is three times more efficient than incineration in terms of energy conversion, and has no long-term waste quota, allowing zero waste strategies to alleviate existing waste streams. The system could then be relocated to other waste hot spots to manage waste or reduce waste volumes in exposed landfills (Sierra Energy, personal communication).

Although volumes of waste reduced on land become volume of waste increased in the air (conservation of mass), any form of combustion (pyrolysis, gasification, incineration) to create energy results in greenhouse gas (GHG) emissions, a principle concern of any form of waste incineration.

A study of waste incineration and greenhouse gas (GHG) emissions found that once it came to energy recovery, "the content of fossil carbon in the input waste, for example, as plastic, was found to be critical for the overall level of the GHG emissions, but also the energy conversion efficiencies were essential" [86]. Increased plastic in the waste stream meant increased overall GHG emissions. Reliance on energy recovery from waste in the linear economic model will have a net balance of more GHG than upstream mitigation strategies in the circular economic model, though the linear vs. circular economy may not be so black and white. A combination of multiple end-of-life strategies could collectively manage the diversity of waste in both efficiency and economy.

Another analysis of GHG emissions compared the current strategy in Los Angeles of landfilling the vast majority of waste to a combination of three strategies in a modern MRF, namely, (a) anaerobic digestion of wet waste, (b) thermal gasification of dry waste, and (c) landfilling residuals [87]. Their analysis did not consider economic, environmental, or social parameters, only GHG emissions, and was based on an assumption of 1,000 ton of waste per day entering each scenario for 25 years; then they modeled the GHG emissions for the century that followed. In each scenario, the GHG emissions from transportation, operation, and avoided emissions by replacing fossil fuels were factored in. Results showed that continued landfilling resulted in a net increase of approximately 1.64 million metric tons of carbon dioxide equivalent (MTCO2E), while the MRF scenario results in a net avoided GHG emissions of (0.67) million MTCO2E, showing that a shift to a MRF where multiple waste management strategies are employed resulted in a total GHG reduction of approximately 2.31 million MTCO2E.

Those residuals that exist after diversion of waste to recycling and anaerobic digestion could be landfilled, and in some cases waste-to-energy could have a role. This would be appropriate only after diversion efforts of recyclables and compostables have been maximized. Also, building incinerator infrastructure could create tremendous debt or include a demand for large volumes of waste, also called a "waste quota" that could undermine local efforts to eliminate products and packaging that generate microplastics. Simultaneously, a market for recycled materials must be encouraged, while all environmental and worker health concerns are prioritized. Waste-to-energy could have a role, but long after all other efforts to manage waste have been employed.

Section Summary In the linear economy contrasted with the circular economy, we see two world views on how to solve the plastic pollution problem. While the linear economic system benefits production by eliminating competition from recycled material, it is more polluting than the circular system because of multiple points of leakage along the supply chain. Plastic pollution is lost at production as pellet spills, lost by the consumer as litter with no inherent value, and lost at collection and disposal as waste is transported. In the circular system these are mitigated when systems to focus on material control and capture are implemented. Zero waste is the ideal of the circular economy, where the need for destruction through energy capture, or landfill, are increasingly unnecessary.

6 Microplastic Mitigation Through a Circular Economy

In the emerging circular economy, the flow of technical materials through society returns to remanufacture, with products and packaging designed for material recovery, low toxicity, ease of dismantling, repair and reuse, and where this doesn't work, a biological material may substitute so circularity in a natural system can prevail. Shifting to a circular economy has prompted interest in a range of interventions, including bioplastics, extended producer responsibility, and novel business approaches.

Green Chemistry as a Biological Material Bioplastic has been in production since Henry Ford's soybean car in the 1930s, made from soy-based phenolic resin, which he bashed with a sledgehammer to demonstrate its resilience, but the WWII demand for a cheap, better-performing material induced him to chose petroleum-based plastic. Today, bioplastics are viewed with new interest. These plant-based plastics are considered a means to create a more reliable and consistently valued resource, decoupled from fossil fuels. The Bioplastic Feedstock Alliance, created with wide industry alliance and support from the World Wildlife Fund (WWF), intends to replace fossil fuels with renewable carbon from plants, representing no net increase in GHG emissions. Referred to as [the] "bioeconomy," these companies envision bioplastics as "reducing the carbon intensity of materials such as those used in packaging, textiles, automotive, sports equipment, and other industrial and consumer goods" [88].

It is important to distinguish biodegradable from bio-based plastics. Bioplastic is the loosely defined catch-all phrase that describes plastic from recent biological materials, which includes true biodegradable materials and nonbiodegradable polymers that are plant based. While the label "biodegradable" has a strict ASTM standard and strict guidelines for usage in advertising, the terms bioplastic, plant based, and bio based do not. Despite all of the leafy greenery in labeling for these bioplastics, it is still the same polymer that would otherwise have come from fossil fuels.

The biodegradability of bio-based and biodegradable plastics will vary widely based on the biological environment where degradation may occur. Poly-lactic acid (PLA) is a compostable consumer bio-based plastic requiring a large industrial composting facility that's hot, wet, and full of compost-eating microbes, unlike a backyard composting bin. Poly-hydroxy-alkanoate (PHA), made from the off-gassing of bacteria, is a marine-degradable polymer (ASTM 7081), but rates of degradation vary with temperature, depth, and available microbial communities [89].

PHA and PLA are both recyclable and compostable, but how these materials are managed depends on available infrastructure. While recycling could be energetically more favorable than composting, it may not be practical because of sorting and cleaning requirements. Kale et al. point out the lack of formal agreement between stakeholders (industry, waste management, government) about the utility of biodegradable plastics and their disposal [90], but the compostability of bioplastic packaging materials could become a viable alternative if society as a whole would be willing to address the challenges of cradle-to-grave life of compostable polymers in food, manure, or yard waste composting facilities. The industries that make bioplastic polymers recognize these challenges and therefore their limited applications. PHA is ideal to be used where you need functional biodegradation, such as some agriculture and aquaculture applications, where a part has a job to do in the environment but it would be either impractical or very costly to recover (Metabolix, personal communication). Also, many single-use throwaway applications may be replaced by PHA, including straws or the polyethylene lining on paper cups (Mango Materials, personal communication). Without the infrastructure widely available to recycle bio-based and biodegradable plastics, manufacturers are aiming for compostability in compliance with organic waste diversion initiatives.

Extended Producer Responsibility (EPR) There is a wide agreement that waste management must be improved, including public access to recycling, composting, and waste handling facilities. Equally, there is a need to improve the design of products and packaging to facilitate recovery in the first place. Regulating primary microplastics has been successful with microbeads and preproduction pellets, yet there are many characteristics of product and packaging design that could be improved to minimize the trickle of irrecoverable microplastics from terrestrial to aquatic environments.

Product and packaging design must move "beyond the baseline engineering quality and safety specifications to consider the environmental, economic and social factors," as explained in "Design through the 12 Principles of Green Engineering" [91]. When designing for the full life cycle of a product, manufactures and designers talk with recyclers to reduce environmental impacts by improving recovery, which may include avoiding mixed materials or laminates, reduced toxicity, and ease of repair, reuse, and disassembly, as well as the systems that move materials between consumer and the end-of-life plan. Reducing microplastic formation by design might also include eliminating tearaway packaging (opening chip/candy wrappers, individual straw/toothpick covers), small detached components (bottle caps and safety rings), or small single-use throw-away products (coffee stirrers, straws, bullets in toy air rifles). These mitigations can be voluntary, but are often policy-driven through fees or bans [92].

Extended producer responsibility is a public policy tool whereby producers are made legally and financially responsible for mitigating the environmental impacts of their products. When adopted through legislation, it codifies the requirement that the producer's responsibility for their product extends to postconsumer management of that product and its packaging. With EPR, the responsible legal party is usually the brand owner of the product.

EPR is closely related to the concept of "product stewardship," whereby producers take action to minimize the health, safety, environmental, and social impacts of a product throughout its life cycle stages. Producers' being required to take back and recycle electronic equipment through the EU's Waste of Electrical and Electronic Equipment (WEEE) Directive is an example of EPR. The Closed Loop Fund – which accepts corporate money to loan to US municipalities to boost packaging recycling – is an example of voluntary product stewardship [93]. Different schemes of EPR have been implemented [94], and even though some first success is achieved in recycling of plastics and other packaging products [95], these systems still require many improvements ranging from economic models [96] to logistic aspects [97].

While EPR has primarily been applied as a materials management strategy, the concept can also be applied to plastic pollution prevention and mitigation. In 2013, the Natural Resources Defense Council helped advance how EPR can more directly impact plastic pollution beyond boosting the collection and recycling of packaging [98]. NRDC developed policy concepts and legislation to make the producers of products which have a high tendency to end up as plastic pollution, responsible not just for recycling, but for litter prevention and mitigation as well. Legislation introduced in California would have (a) had State Agencies identify the major sources of plastic pollution in the environment and (b) required the producers of those products to reduce the total amount in the environment by 75% in 6 years and 95% in 11 years. While the legislation did not advance far in California, this was a significant development and provides an example of how to incorporate litter prevention and pollution mitigation in future EPR policy.

Section Summary The utility of green chemistry has led to public confusion over the biodegradability of polymers, stemming from an important differentiation between biopolymers and biodegradable polymers, as well as the true conditions where biodegradability occurs. While biopolymers offer a promising divestment from fossil fuel feedstocks, biodegradable plastics are challenged by the infrastructure requirements for identification, sorting, and degradability. In a circular economy, biopolymers and biodegradable polymers must exist in a system, either manufactured or natural, where the material is recovered and reprocessed. Extended producer responsibility is the policy mechanism that creates those systems, with the intention to mitigate the true economic, social, and environmental costs associated with waste.

7 Business Transformation Through Novel Policy and Design

The status quo for much of product and packaging manufacture is planned obsolescence, which drives cheap-as-possible chemistry and design and has been largely subsidized by municipalities that agree to manage all that waste at a limited cost to the manufacture and principal cost to the tax payer. With an abundance in the waste stream of plastics embedded in difficult-to-recover products and packaging (electronics, laminates, food-soiled packaging), energy recovery becomes a more attractive alternative.

The effort to rely on energy recovery through incineration is largely a perpetuation of the “planned obsolescence” strategy of securing demand for new products, employed historically since post-WWII manufacture. Planned obsolescence encourages material consumption in several ways: technological (software and upgrades overwhelming old hardware), psychological (fashion), and conventional (designed weakness and impractical repair).

The Ellen MacArthur Foundation [99] published in February 2016 “The New Plastics Economy” proposed business solutions that manage materials through the consumer, beyond planned obsolescence, where product designers talk to recyclers to create an end-of-life design, systems of “leasing” products over ownership, allowing product upgrades over planned obsolescence. By making a business case for managing the circular flow of technical materials, the status quo of cradle to grave can be put to rest.

The market dominance of poorly designed products will likely not self-regulate a transformation, requiring policy tools. EPR in some ways can be facilitated by novel policy tools. In London in 2015 a 5p fee on plastic bags, rather than a ban, resulted in an 85% reduction in their consumption. In areas where citizens "pay to pitch" the waste they generate, consumers commonly strip packaging at the point of purchase, which in turn is communicated to the distributor of goods to redesign the delivery of goods. This system of pay to pitch has been applied to some remote communities, such as islands, to require importers to export postconsumer materials.

Andrew Winston, author of *The Big Pivot*, suggests an alternate model of doing business, the Benefit Corporation, or "B-Corp," whereby corporations take on a mission statement of social or environmental justice that is on equal par with the profit motive. A rapidly changing consumer base that is more connected through communication is forcing corporations to be transparent, accountable, and behave ethically. The B-Corp is the bridge across the divide.

8 Reducing and Reusing Plastic Waste

Avoiding the production of new plastics altogether whenever possible is the most reliable way to avoid the generation of microplastics, whether primary microplastics (needed for the production of new plastic articles) or secondary (resulting during breakdown of larger plastic items).

As the market for ethically produced products is growing worldwide (e.g., Fairtrade [100], organic food produce [101, 102]), and consumers become aware of the possible impacts of marine pollution [103], several examples are demonstrating a successful reduction of plastic waste or the reuse of discarded plastics in order to create other products (upcycling), thereby saving natural resources and, in some cases, even removing ocean plastic pollution.

Among popular recent innovations are the production of clothes, shoes, skateboards, sun-glasses, and swimming gear from derelict fishing gear [104, 105]. Such lines of products, making a pro-environmental statement, are likely to be especially appealing to customers of the Generation Y/Millenials (see references in [106]). Another example for a consumer-driven desire to combat excessive plastic litter, this time in the form of packaging waste, is the recent development of zero waste stores, sprouting up in Europe and the United States (Fig. 3a) [107, 108]. Many of these stores are crowd funded [107] and require customers to bring their own food container which also avoids food waste by allowing customers to buy the quantities they consume. Many of those shops do not offer products from large brands to distance themselves from supermarket chains and emphasize a community-based economy model.

Fig. 3 Initiatives to reduce or recuperate packaging waste. (**a**) = "Unverpackt" store in Germany where customers can buy food in bulk, bringing their own containers. ©Martin Thiel. (**b**) = Reverse vending machines accepting glass and plastic bottles and aluminum cans in a supermarket in the United States. ©Alex Kirsch. (**c**) = Advertisement of the "Pfand gehört daneben"-campaign in Germany, advocating to leave deposit return bottles in Germany next to the garbage bin in order for easy pick up ©Pfand gehört daneben 2016. (**d**) = "Feria libre" in Chile, allowing customers to buy vegetables and fruits in bulk (public domain, Jorge Valdés R. Joval)

An example of a large retail store taking up waste reduction strategies is the Amazon.com, Inc., with its program "Frustration-Free Packaging," which aims to reduce packaging volume and complexity. The company claims to have saved 11,000 tons of packaging during 5 years, including reductions of styrofoam and thin plastic films [109].

Possibly the most established way of avoiding excessive waste and saving valuable resources is in the form of container deposit fees, especially for beverages (Fig. 3b). This has been shown as highly effective to reduce the amount of waste in the environment with return rates as high as 90% and higher in Sweden and Germany for several materials commonly used in beverage production (metal, glass, plastic) [110, 111]. Deposit return strategies are more efficient than curbside recycling programs [112], largely because of the monetary incentive for recovery ("One man's trash is another man's treasure"). For example, the "Pfand gehört daneben" campaign in Germany ("Deposit bottles belong next to it [the garbage bin]") encourages the public to leave unwanted deposit return bottles accessible for easy pick up by private waste collectors and not trashing them in a garbage bin

(Fig. 3c). However, a return deposit fee on food containers does not ensure that the container is reused as the large and growing proportion of returnable but single-use plastic bottles in Germany illustrate [113]; therefore, further incentives are necessary.

Another way to reduce plastics is prohibition or taxing of plastic products that can be easily replaced, such as microbeads in cosmetic and daily care products and plastic bags for groceries. A survey conducted in Ireland revealed that fees/taxes on plastic bags seem to be well received among customers [114].

Buying from local farmers' markets is another way for a customer to procure less packaging (Fig. 3d). While farmers' markets were replaced in most of Europe and North America by large supermarket chains, they are celebrating a comeback over the last two decades [115]. In other countries it is still normal to procure the majority of fresh foods from farmers' markets, despite the introduction of large supermarket chains. This is the case in Chile where "Ferias libres" (neighborhood outdoor markets) supply the population with 70% of its demand for fruit and vegetables and 30% of seafood products [116].

Collectively, all these strategies help reduce the leakage of low-value/single-use plastics into terrestrial and aquatic environments and subsequent formation of microplastics from their degradation. Regardless of the most modern waste management systems available, leakage of single-use throwaway products and packaging occurs. Their reduction is the most efficient mitigation effort to reduce microplastics in the environment.

9 Conclusion

An environmental movement may be defined as a loose, noninstitutionalized network of organizations of varying degrees of formality, as well as individuals and groups with no organizational affiliation, who are engaged in collective action motivated by shared identity or concern about environmental issues [117].

In July of 2016, the American Chemistry Council published "Plastics and Sustainability: A valuation of environmental benefits, costs and opportunities for continuous improvement," largely a comparison of life cycle analyses putting plastic in a positive light against alternative materials (glass, metal, paper). At the same time, the Plastic Pollution Policy Project convened 18 organizations focused on zero waste initiatives to align on policy and campaigns and to create common messaging to counter industry-dominated narratives. A movement has emerged, while stakeholder positions have dug in their heels.

Here we have discussed solutions to microplastics in freshwater ecosystems, which largely form in terrestrial environments from primary or secondary microplastics. We know that microplastics are global, increasingly toxic over time, and impacts to wildlife are pervasive, leading to the collective conclusion that plastic in the environment causes harm. We also know that capturing microplastic downstream is extremely difficult and requires upstream intervention.

Once in natural water bodies (rivers, lakes, oceans), recovery of microplastics is impossible. Therefore, one challenge is to identify and quantify the upstream sources – a prerequisite to mitigation. In the cases of microbeads and preproduction pellets, we witnessed the role of science to present observations of microplastic pollution, followed by a movement to pressure policymakers to regulate industry. The work of scientists continues to illuminate microplastic impacts, such as recent reports from the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) [118], a working group gathered by UNEP to synthesize and report on the state of the scientific evidence regarding the plastic pollution issue and distribute the information to the United Nations Environment Assembly.

There are four principal solutions that will have high impact on preventing terrestrial and freshwater microplastics from forming. They are: (1) identify and quantify terrestrial microplastic sources, (2) scale zero waste strategies, (3) pursue policy-driven EPR, and (4) develop novel business solutions. These solutions will bring greater alignment between stakeholders on the utility of plastic in society and a more equitable end-of-life, where environmental and social justice are integrated in the full cost of plastic. The bridge between the linear and circular economy is about material circularity coupled with a sincere investment in common decency and democracy, and corporate responsibility toward those ends, what Severyn Bruyn calls a Civil Economy, whereby government, business, nonprofits and civic groups "can develop an accountable, self-regulating, profitable, humane, and competitive system of markets" [119] (Bruyn 2000).

This a thoughtful approach that considers the chemistry of materials, the design of products, the processes required to make things, and finally the systems that manage how materials flow back into the production chain, all in the context of causing no harm to people and the environment, benign by design in its totality.

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