Research Topics

Emerging challenges and solutions for plastic pollution

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Emerging challenges and solutions for plastic pollution

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Editorial: Emerging challenges and solutions for plastic pollution

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Editorial on the Research Topic
Emerging challenges and solutions for plastic pollution

1 Introduction

Without a change in policy and management, plastic waste is modeled to triple by 2060 compared to 2019 (OECD, 2022). Even with far-reaching actions, 710 million metric tons of plastic waste will enter environments between 2016-2040 (Lau et al., 2020). In this special issue, “Emerging Challenges and Solutions for Plastic Pollution,” we invited articles exploring plastic pollution issues and hypothesizing solutions. The topic was broad to include diverse approaches as contributions from all stakeholders are needed to provide a full perspective on the plastic waste problem (Jambeck et al., 2015; Borrelle et al., 2020; Lau et al., 2020). The special issue is a transdisciplinary collection of articles from academia, nongovernmental organizations, and industry: (Diana et al., Fürst and Feng, Grabiel et al., Koongolla et al., Lauer and Nowlin, Morrison et al., Murphy et al., Stolte et al., 2022; and Alnahdi et al., Karasik et al., 2023).

2 Harm posed by plastic pollution to marine animals

Plastic pollution can harm marine animals through entanglement, ingestion, and additive leaching. For example, ninety-four percent of fish (n = 271) from the Beibu Gulf, South China Sea, had microplastics (< 5 mm) in the gill and gut (Koongolla et al., 2022). Microplastics may be consumed unintentionally as prey or intentionally *via* active feeding (Savoca et al., 2016; Allen et al., 2017; Savoca et al., 2017), exposing animals to plastic additives (Turner, 2018; Diana et al., 2020). Plastic exposure can induce the production of reactive oxygen species and result in gastrointestinal obstruction, translocation, and trophic transfer among marine animals (Morrison et al., 2022; Yip et al., 2022a). Plastic leachates can be acutely toxic to aquatic animals (*e.g.*, barnacle larvae, *Ceriodaphnia dubia*) (Li et al., 2016; Thaysen et al., 2018).

3 Does plastic pollution harm human health?

Human plastic exposure is ubiquitous; however, health effects are poorly understood. Laboratory and occupational epidemiology studies link plastic exposure to respiratory irritation, cardiovascular disease, gut disturbance, inflammation, oxidative stress, and cancer (Morrison et al., 2022; World Health Organization (WHO), 2022). Human cells exposed to nanoplastics showed significant toxicity (Yong et al., 2020; Danopoulos et al., 2021; Mahadevan and Valiyaveettil, 2021). However, microplastics are diverse in their polymer type, shape, source, and chemical composition (Rochman et al., 2019), so laboratory studies greatly simplify real-world exposures, often by testing only one polymer type (World Health Organization (WHO), 2022). Plastics are associated with over 10,000 compounds, at least 2,400 of which have known toxicity issues (Hahladakis et al., 2018; Groh et al., 2019; Wiesinger et al., 2021). Though endocrine-disrupting Bisphenol-A and phthalates are frequently studied (Morrison et al., 2022), the health impacts of other plastic additives/mixtures are not well understood.

Plastics inequitably impact marginalized, low-income communities worldwide (Karasik et al., 2023; UNEP, 2021a). Plastic creates economic benefits and human health burdens across all lifecycle stages (Karasik et al., 2023). Benefits and burdens are intertwined: petrochemical industries provide convenient lifestyle support, economic benefits, and air and environmental pollution (Karasik et al., 2023). Diana et al. (2022) support Persson et al. (2022)'s assessment that plastics have crossed planetary boundaries; thus, society is beyond the "safe operating space" in which human activities can occur (Steffen et al., 2015; Persson et al., 2022).

4 Solutions

To address the harms to human and environmental health posed by plastic pollution (*e.g.*, Yong et al., 2020; Yip et al., 2022b), it is necessary to involve all stakeholders and utilize a variety of approaches (Worm et al., 2017; Lau et al., 2020), including policy-focused (Fürst and Feng, 2022; Grabiel et al., 2022; Lauer and Nowlin, 2022), technological (Morrison et al., 2022; Stolte et al., 2022; Alnahdi et al., 2023), industry-focused (Diana et al., 2022), and theoretical (Diana et al., 2022; Morrison et al., 2022; Murphy et al., 2022) responses (Figure 1).

Strong theoretical underpinnings support effective solutions to plastic pollution. A seascape ecology (SE) theoretical framework is recommended for examining spatially-explicit plastic pollution questions (Murphy et al., 2022). SE is transdisciplinary, multi-scale, and incorporates "governance systems, human actors, and ecological components … that contribute to patterns of plastic production, use, and pollution…" (quoted in Murphy et al., 2022). Diana et al. (2022) applied the four pathways to global sustainability, created by Folke et al. (2021), to plastic pollution interventions.

Governments worldwide have adopted policies to reduce plastic pollution (Xanthos and Walker, 2017; Schnurr et al., 2018; Karasik et al., 2020; Diana et al., 2022b). The United Nations Environment Assembly is drafting a legally-binding global treaty to reduce plastic pollution by 2024 (Simon et al., 2021). Researchers suggest using the Montreal Protocol as a model for the treaty, which includes fact-finding (*i.e.*, plastic production reporting, licensing, setting baselines) and policymaking stages (*i.e.*, phased decreases, production caps, independent assessments, exemptions for essential plastics) (Grabiel et al., 2022).

Consistent with global trends (Xanthos and Walker, 2017; Schnurr et al., 2018; Karasik et al., 2020; Diana et al., 2022b), Chinese governments adopted and implemented plastic pollution policies from January 2000 and June 2021, increasing 925% (Fürst and Feng, 2022). Policies frequently employed regulatory (*e.g.*, bans, limits) and information instruments (*e.g.*, education and outreach,

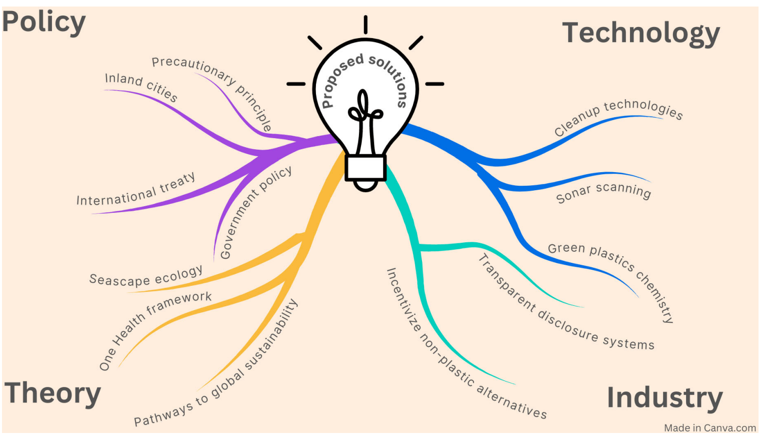

FIGURE 1
Proposed solutions to address plastic pollution.

campaigns) to target plastic waste and bags, but not plastic production (Fürst and Feng, 2022).

All stakeholders have an important role in reducing marine debris, as pollution generated inland can be transported to the ocean *via* rivers or the wind (Meijer et al., 2021; Napper et al., 2021; Youngblood et al., 2022). City governments, managers, and community groups may 1) collect data on dominant plastic litter or waste to understand the magnitude of the problem, 2) develop policies that reduce plastic consumption and waste, and 3) utilize controls (*e.g.*, stormwater covers, riverine booms) to capture and prevent pollution (Lauer and Nowlin, 2022). To be equitable, plastic bag fees should exempt low-income residents and distribute free reusable items (*e.g.*, cotton reusable bags, takeout containers) (Lauer and Nowlin, 2022).

Cleanup/bioremediation technologies and developing circularity concepts (Sheth et al., 2019; Schmaltz et al., 2020; Alnahdi et al., 2023) complement policies to reduce plastic pollution (Morrison et al., 2022; Stolte et al., 2022);. Compared to previous methods, the sonar approach led by Stolte et al. (2022) has greater success in removing lost fishing gear and is less destructive to seafloor ecosystems. Alnahdi et al. (2023) suggest developing a marine-microbial ecosystem to degrade microplastics, nanoplastics, and additives. Such plastic clean-up and bioremediation efforts may be incentivized; however, efforts to reduce plastic upstream need to be prioritized, such as eliminating unnecessary plastics production (UNEP, 2021b; Bergmann et al., 2022) and incentivizing reusable alternatives (Amon et al., 2022; Moss et al., 2022; Diana et al., 2022a). For those plastics that are necessary, further efforts should be made to produce fully recyclable plastics, have half-lives similar to the usage period, and incorporate biologically-compatible additives (Diana et al., 2022).

5 Conclusions

This special issue focused on articles related to plastic pollution issues and proposed potential solutions. Further research is needed to characterize human co-exposure to plastic chemical mixtures over time (Morrison et al., 2022) and develop sustainable plastic chemistry (Diana et al., 2022). Despite unknowns, researchers recommend applying the precautionary principle by regulating plastics (Karasik et al., 2023). Diverse stakeholder inputs are needed to reduce plastic pollution and reverse deleterious environmental and human health effects.

Author contributions

ZD provided the first draft of the manuscript. All authors reviewed and revised the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Allen, A. S., Seymour, A. C., and Rittschof, D. (2017). Chemoreception drives plastic consumption in a hard coral. *Mar. pollut. Bull.* 124, 198–205. doi: 10.1016/j.marpolbul.2017.07.030

Amon, D., Metaxas, A., Stentiford, G., Escovar-Fadul, X., Walker, T. R., Diana, Z., et al. (2022). Blue economy for a sustainable future. *One Earth* 5, 960–963. doi: 10.1016/j.oneear.2022.08.017

Bergmann, M., Almroth, B. C., Brander, S. M., Dey, T., Green, D. S., Gundogdu, S., et al. (2022). A global plastic treaty must cap production. *Science* 376, 469–470. doi: 10.1126/science.abq0082

Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., et al. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science* 369, 1515–1518. doi: 10.1126/science.aba3656

Danopoulos, E., Twiddy, M., West, R., and Rotchell, J. M. (2021). A rapid review and meta-regression analyses of the toxicological impacts of microplastic exposure in human cells. *J. Haz. Materials* 127861. doi: 10.1016/j.jhazmat.2021.127861

Diana, Z., Reilly, K., Karasik, R., Vegh, T., Wang, Y., Wong, Z., et al. (2022a). Voluntary commitments made by the world's largest companies focus on recycling and packaging over other actions to address the plastics crisis. *One Earth* 5, 1286–1306. doi: 10.1016/j.oneear.2022.10.008

Diana, Z., Sawickij, N., Rivera, N. A., Hsu-Kim, H., and Rittschof, D. (2020). Plastic pellets trigger feeding responses in sea anemones. *Aquat. Toxicol.* 222, 105447. doi: 10.1016/j.aquatox.2020.105447

Diana, Z., Vegh, T., Karasik, R., Bering, J., D. Llano Caldas, J., Pickle, A., et al. (2022b). The evolving global plastics policy landscape: an inventory and effectiveness review. *Environ. Sci. Policy* 134, 34–45. doi: 10.1016/j.envsci.2022.03.028

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., et al. (2021). Our future in the anthropocene biosphere. *Ambio* 50, 834–869. doi: 10.1007/s13280-021-01544-8

Groh, K. J., Backhaus, T., Carney-Almroth, B., Geueke, B., Inostroza, P. A., Lennquist, A., et al. (2019). Overview of known plastic packaging-associated chemicals and their hazards. *Sci. Total Environ.* 651, 3253–3268. doi: 10.1016/j.scitotenv.2018.10.015

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., and Purnell, P. (2018). An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. *J. Haz. Materials* 344, 179–199. doi: 10.1016/j.jhazmat.2017.10.014

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347, 768–771. doi: 10.1126/science.1260352

Karasik, R., Vegh, T., Diana, Z., Bering, J., Caldas, J., Pickle, A., et al. (2020). *20 years of government responses to the global plastic pollution problem* (Durham, NC, USA: Nicholas Institute for Environmental Policy Solutions, Duke University). Available at: https://nicholasinstitute.duke.edu/publications/20-years-government-responses-global-plastic-pollution-problem.

Lau, W. W. Y., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., et al. (2020). Evaluating scenarios toward zero plastic pollution. *Science* 369, 1455–1461. doi: 10.1126/science.aba9475

Li, H.-X., Getzinger, G. J., Ferguson, P. L., Orihuela, B., Zhu, M., and Rittschof, D. (2016). Effects of toxic leachate from commercial plastics on larval survival and settlement of the barnacle amphibalanus amphitrite. *Environ. Sci. Technol.* 50, 924–931. doi: 10.1021/acs.est.5b02781

Mahadevan, G., and Valiyaveettil, S. (2021). Comparison of genotoxicity and cytotoxicity of polyvinyl chloride and poly(methyl methacrylate) nanoparticles on normal human lung cell lines. *Chem. Res. Toxicol.* 34, 1468–1480. doi: 10.1021/acs.chemrestox.0c00391

Meijer, L. J. J., van Emmerik, T., van der Ent, R., Schmidt, C., and Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Sci. Adv.* 7, eaaz5803. doi: 10.1126/sciadv.aaz5803

Moss, E., Gerken, K., Youngblood, K., and Jambeck, J. R. (2022). Global landscape analysis of reuse and refill solutions. *Front. Sustain.* 3, 1006702. doi: 10.3389/frsus.2022.1006702

Napper, I. E., Baroth, A., Barrett, A. C., Bhola, S., Chowdhury, G. W., Davies, B. F. R., et al. (2021). The abundance and characteristics of microplastics in surface water in the transboundary Ganges river. *Environ. pollut.* 116348. doi: 10.1016/j.envpol.2020.116348

OECD (2022). *Global plastics outlook: policy scenarios to 2060* (Paris: OECD). doi: 10.1787/aa1edf33-en

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., et al. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environ. Sci. Technol.* 56, 1510–1521. doi: 10.1021/acs.est.1c04158

Rochman, C. M., Brookson, C., Bikker, J., Djuric, N., Earn, A., Bucci, K., et al. (2019). Rethinking microplastics as a diverse contaminant suite. *Environ. Toxicol. Chem.* 38, 703–711. doi: 10.1002/etc.4371

Savoca, M. S., Tyson, C. W., McGill, M., and Slager, C. J. (2017). Odours from marine plastic debris induce food search behaviours in a forage fish. *Proc. Biol. Sci.* 284. doi: 10.1098/rspb.2017.1000

Savoca, M. S., Wohlfeil, M. E., Ebeler, S. E., and Nevitt, G. A. (2016). Marine plastic debris emits a keystone infochemical for olfactory foraging seabirds. *Sci. Adv.* 2, e1600395. doi: 10.1126/sciadv.1600395

Schmaltz, E., Melvin, E. C., Diana, Z., Gunady, E. F., Rittschof, D., Somarelli, J. A., et al. (2020). Plastic pollution solutions: emerging technologies to prevent and collect marine plastic pollution. *Environ. Int.* 144, 106067. doi: 10.1016/j.envint.2020.106067

Schnurr, R. E. J., Alboiu, V., Chaudhary, M., Corbett, R. A., Quanz, M. E., Sankar, K., et al. (2018). Reducing marine pollution from single-use plastics (SUPs): a review. *Mar. pollut. Bull.* 137, 157–171. doi: 10.1016/j.marpolbul.2018.10.001

Sheth, M. U., Kwartler, S. K., Schmaltz, E. R., Hoskinson, S. M., Martz, E. J., Dunphy-Daly, M. M., et al. (2019). Bioengineering a future free of marine plastic waste. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00624

Simon, N., Raubenheimer, K., Urho, N., Unger, S., Azoulay, D., Farrelly, T., et al. (2021). A binding global agreement to address the life cycle of plastics. *Science* 373, 43–47. doi: 10.1126/science.abi9010

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S. E., Fetzer, I., Bennett, E. M., et al. (2015). Planetary boundaries: guiding human development on a changing planet. *Science* 347, 1259855–1259855. doi: 10.1126/science.1259855

Thaysen, C., Stevack, K., Ruffolo, R., Poirier, D., De Frond, H., DeVera, J., et al. (2018). Leachate from expanded polystyrene cups is toxic to aquatic invertebrates (*Ceriodaphnia dubia*). *Front. Mar. Sci.* 5. doi: 10.3389/fmars.2018.00071

Turner, A.. (2018). Mobilisation kinetics of hazardous elements in marine plastics subject to an avian physiologically-based extraction test. *Environ. pollut.* 236, 1020–1026. doi: 10.1016/j.envpol.2018.01.023

UNEP (2021a). *NEGLECTED: environmental justice impacts of marine litter and plastic pollution* (Nairobi:UNEP - UN Environment Programme). Available at: http://www.unep.org/resources/report/neglected-environmental-justice-impacts-marine-litter-and-plastic-pollution.

UNEP (2021b). *From pollution to solution: a global assessment of marine litter and plastic pollution* (Nairobi:UNEP - UN Environment Programme). Available at: http://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution.

Wiesinger, H., Wang, Z., and Hellweg, S. (2021). Deep dive into plastic monomers, additives, and processing aids. *Environ. Sci. Technol.* 55, 9339–9351. doi: 10.1021/acs.est.1c00976

World Health Organization (WHO) (2022). *Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health* (Geneva: World Health Organization).

Worm, B., Lotze, H. K., Jubinville, I., Wilcox, C., and Jambeck, J. (2017). Plastic as a persistent marine pollutant. *Annu. Rev. Environ. Resour.* 42, 1–26. doi: 10.1146/annurev-environ-102016-060700

Xanthos, D., and Walker, T. R. (2017). International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review. *Mar. pollut. Bull.* 118, 17–26. doi: 10.1016/j.marpolbul.2017.02.048

Yip, Y. J., Lee, S. S. C., Neo, M. L., Teo, S. L. M., and Valiyaveettil, S. (2022b). A comparative investigation of toxicity of three polymer nanoparticles on acorn barnacle (*Amphibalanus amphitrite*). *Sci. Total Environ.* 806, 150965. doi: 10.1016/j.scitotenv.2021.150965

Yip, Y. J., Sivananthan, G. D., Lee, S. S. C., Neo, M. L., Teo, S. L.-M., and Valiyaveettil, S. (2022a). Transfer of poly(methyl methacrylate) nanoparticles from parents to offspring and the protection mechanism in two marine invertebrates. *ACS Sustain. Chem. Eng.* 10, 37–49. doi: 10.1021/acssuschemeng.1c01818

Yong, C. Q. Y., Valiyaveettil, S., and Tang, B. L. (2020). Toxicity of microplastics and nanoplastics in mammalian systems. *Int. J. Environ. Res. Public Health* 171509. doi: 10.3390/ijerph17051509

Youngblood, K., Brooks, A., Das, N., Singh, A., Sultana, M., Verma, G., et al. (2022). Rapid characterization of macroplastic input and leakage in the Ganges river basin. *Environ. Sci. Technol.* 56, 4029–4038. doi: 10.1021/acs.est.1c04781

Zettler, E. R., Mincer, T. J., and Amaral-Zettler, L. A. (2013). Life in the "Plastisphere": microbial communities on plastic marine debris. *Environ. Sci. Technol.* 47, 7137–7146. doi: 10.1021/es401288x

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Microplastic prevalence in marine fish from onshore Beibu Gulf, South China Sea

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In recent years, microplastics have been widely detected in marine fish and may pose potential risks to fish and human health. Even though microplastic pollution is a critical issue, it represents as yet non-quantified threat for some context in the marine environment. In this study, 271 individuals comprising 32 species of marine fish collected from Beibu Gulf were examined for microplastic prevalence, with an aim to provide data on the abundance, physical classification, and chemical characterization of microplastics in the great bay along South China Sea. The results showed that the occurrence rate of microplastics was 93.7%, and the average abundance of microplastics was 1.02 $\pm$ 0.18 items per individual (ranging from 0.03 to 4.00 items per individual). Microplastic accumulation was observed with a great variation in different species, body sizes, living habitats, and feeding habits of marine fishes. The dominant polymers identified by μ-FTIR were polyethylene terephthalate and polypropylene. Fibers, smaller sizes (<1 mm), and transparent color were the major characteristics of the detected microplastics, which might be important factors affecting the bioaccumulation. The present study revealed that microplastics in marine fish is a widespread issue in onshore Beibu Gulf.

KEYWORDS

microplastics, marine fish, contamination, abundance, fibers

Introduction

The durability of plastics which make them particularly useful in the modern world can also be a lethal disaster to marine wildlife (Hammer et al., 2012). Microplastics (<5 mm) derived from the fragments or degradation of plastics is a widespread occurrence in aquatic environments and has become a tremendous concern worldwide (Auta et al., 2017). Microplastics with a high density that exceeds that of seawater (>1.02 g/cm^3) probably sink through the water column and accumulate in the sediment, while low-density particles tend to float on the sea surface and in the water column. Given the abundance and the small sizes of microplastics, it is not surprising that microplastics now appear to be a ubiquitous pollutant for various marine organisms in the oceans (Claessens et al., 2011; Rezania et al., 2018).

Microplastics are more likely in the same size range as planktons, and the possibility for uptake by many marine organisms are high (Browne et al., 2008). According to a recent review (Savoca et al., 2021), 386 marine fish species—including 210 commercially important species—have ingested microplastics, and the incidence rate of plastic ingestion has been increasing by 2.4 ± 0.4% per year during the last decade. Microplastics were frequently found in the gastrointestinal tracts and gills of marine fishes and even detected in the skin, liver, and muscles (Savoca et al., 2021; Ugwu et al., 2021). Once microplastics ingested by organisms end up in the digestive tract, contaminants may desorb from the plastic material and accumulate in the tissue or blood of the organism. It is particularly concerning that microplastics and their associated pollutants (*e.g.*, PCBs and PBDEs) can be accumulated in marine fishes and transferred to other animals at higher trophic levels (Antao Barboza et al., 2018). Accordingly, it is predictable that humans are exposed to microplastics at different levels due to high seafood consumption worldwide (Antao Barboza et al., 2018). Humans occupy a high trophic level in the marine food chain and can potentially be exposed to micro- and nanoplastics. Therefore, microplastic contamination in marine fish needs to be closely monitored for their potential health risks on food safety.

In recent years, microplastic research in China has directed increased attention towards microplastic pollution in aquatic environments. Beibu Gulf is located in the northwestern part of the South China Sea. The total area of Beibu Gulf is approximately 130,000 km^2 and rich in oil, gas, and biological resources (Gao et al., 2017). It is directed west to Vietnam, and two Chinese provinces, Guangxi and Hainan, lie to the north and east, respectively. It is also rich in fish resources and represents as a traditional fishing ground of China and the China-Indo Peninsula. There are several evidence from recently published articles about the emerging microplastic contamination in water, sediment, and biota from Beibu Gulf, such as in Maowei Sea (Zhu et al., 2019; Zhu et al., 2021), Qin River (Zhang et al., 2020a), fishery areas, and mangrove wetlands (Li et al., 2019; Xue et al., 2020; Zhang et al., 2020b; Zhang et al., 2021). According to Zhu et al. (2022), the abundances of microplastics in seawater and sediment in Beibu Gulf were 0.67 items/m^3 and 4.33 items/kg of dry weight, which give a hint on the possibility of microplastic transportation to fish and other marine organisms. Even though there are few studies regarding microplastic pollution in the sediments and water around Beibu Gulf, there still remains a gap on data on the occurrence of microplastics in fishes from the gulf. Therefore, it is important to have some statistics on the accumulation level of microplastics in fish from Beibu Gulf. Furthermore, Beibu Gulf is a typical area to study the co-influence of social behaviors and the fishery industry on microplastic pollution, and recognizing the status of the pollution and their ecological impacts in research regions would be helpful in taking mitigation measures and policies to reduce microplastics in the oceans.

Materials and methods

In this study, marine fishes were collected by trawling in 30 sampling sites from onshore Beibu Gulf area (21.04–22° N, 108.21–109.45° E) (**Figure 1**). Trawling was performed within 30 min in each site under the speed of 3 to 4 knots per hour. Fishes were collected and classified, and the body size and weight were measured on board. A list of the measured data with the name of all species is provided in **Supplementary Table S1**. Then, the fish surfaces were cleaned with ultrapure water and dissected carefully with sterilized tools. The gastrointestinal tracts (GITs, including the stomach and intestine) and gills were extracted for microplastic detection. The collected tissues were digested with 10% KOH solution in glass conical flasks and incubated in an oscillation incubator at 60°C with a rotation speed of 80 rpm for at least 24 h to remove organic matters. After digestion, saturated NaCl solution (1.2 g/ml in density) was added into the flask, stirred using a glass rod, and kept for 2 h to separate the microplastics *via* density separation. The overlying water was directly filtered with membrane filter (Millipore NY20, pore size 20 µm) using a vacuum pump. The flotation and filtering were repeated several times to reduce the loss of microplastics as much as possible. The filter paper was placed into a cleaned glass petri dish with a cover for further analysis. To avoid contamination, all the liquids, including ultrapure water and NaCl and KOH solutions, were filtered with glass microfiber filters (Whatman GF/F, pore size = 0.7 µm) prior to use. All apparatuses used for microplastic analysis were rinsed three times with filtered water and were immediately covered when not in use. A procedural blank without sample was performed during microplastic extraction and inspection to analyze the airborne contamination. The blanks were in triplicate, and data were corrected for procedural contamination. Microplastic identification was detected under a stereo light microscope (Olympus SZX10, Tokyo, Japan). Images of the suspected plastic items were taken with a digital camera

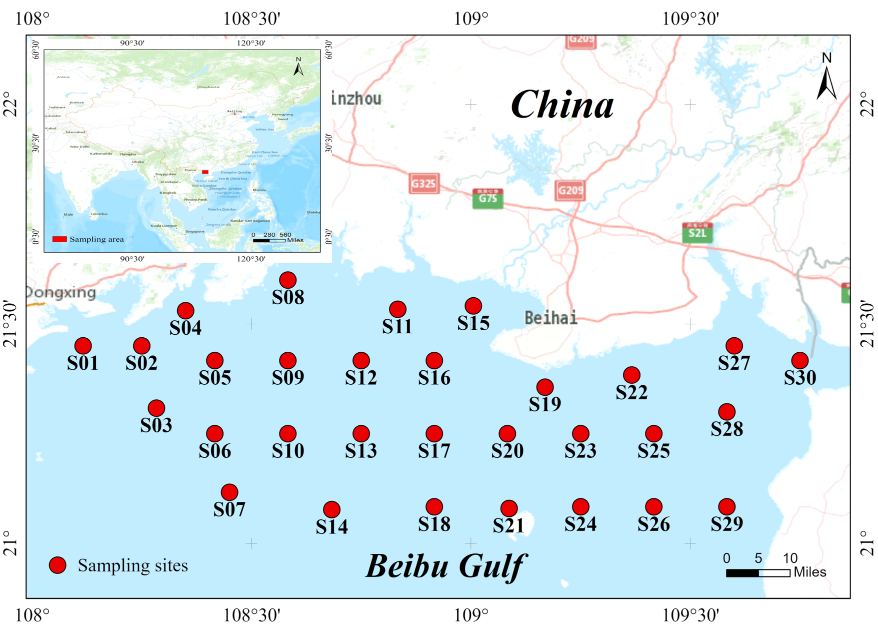

FIGURE 1
Sampling sites in onshore Beibu Gulf, South China Sea.

(Olympus DP80, Tokyo, Japan). A subsample (>40%) of suspected microplastics were selected and detected by FTIR (Nicolet iN 10, Thermo Fisher, USA) coupled with MCT detector to identify the polymer composition. The range of 4,000–400 cm^{-1} under the infrared spectrum was measured, and 16 acquisitions on each particle were identified. OMNIC software (Thermo Fisher, USA) was used as the reference of standard FTIR spectrum databases for the comparison of the obtained spectra. Microplastics were confirmed based on the matching degree with the standard spectrum at >80%. There were some fibers collected from the blank controls which have been confirmed by µ-FTIR as cotton cellulose, which were not included in the calculation of microplastic data. Statistical analyses such as one-way ANOVA, *t*-test, or nonparametric tests were carried out using IBM SPSS Statistics (version 20.0) at a significance level of $p < 0.05$. Furthermore, linear regression analyses were conducted between the number of fish traits (*i.e.*, body size, living and feeding habits) and microplastic abundances of fishes with linear regression models. All fish trait regression models were conducted with pooled and individual species data.

Results

Microplastics were found in 23 out of 32 fish species with an occurrence rate of 93.7% within 254 of the total 271 individuals. Of the accumulated microplastic fish, the microplastic abundance ranged from 0.03 to 4.00 items per individual, with an average of 1.02 ± 0.18 items per individual (**Figure 2A**). The highest abundance of microplastics was observed in *Sillago sihama* (4.00 items per individual), *Centrobergx lineatus* (2.46 items per individual), and *Scatophagus argus* (2.00 items per individual). Therefore, the present study confirmed that fish from onshore Beibu Gulf were widely contaminated with microplastics. Microplastic accumulation was observed in both gills and GITs. There was a slight difference of microplastic occurrence rate in GIT (54.4%) and gills (45.6%). However, there was no statistically significant correlation between microplastic abundance and body length ($p = 0.287$, *t*-test), but a positive relationship ($p = 0.000$, *t*-test) was distinguished between the microplastic abundance and the wet weight of fish samples. Demersal fishes contained lower microplastic abundance (0.95 ± 0.17 items per individual) than the pelagic fishes (1.27 ± 0.46 items per individual), but no significant difference was found ($p = 0.59$, *t*-test).

According to the physical characteristics, fibers (98%) were the dominant microplastic shape, followed by fragments (1%) and films (1%) (**Figure 2B**). Besides the three species, the microplastics collected from 20 other species were all fibers. A small fraction of fragments was found in *Chorinemus* sp. (CH) and *S. sihama*, while fibers, fragments, and films were obtained from *Cathorops steindachneri* (**Figure 2B**). The dominant size of microplastics was in the range of 0.02–1 mm, accounting for 66% of microplastics (**Figure 2C**). According to the colors, a comparative variation was found within different fish species. Transparent (27%), black (25%), and blue (24%) colors were the

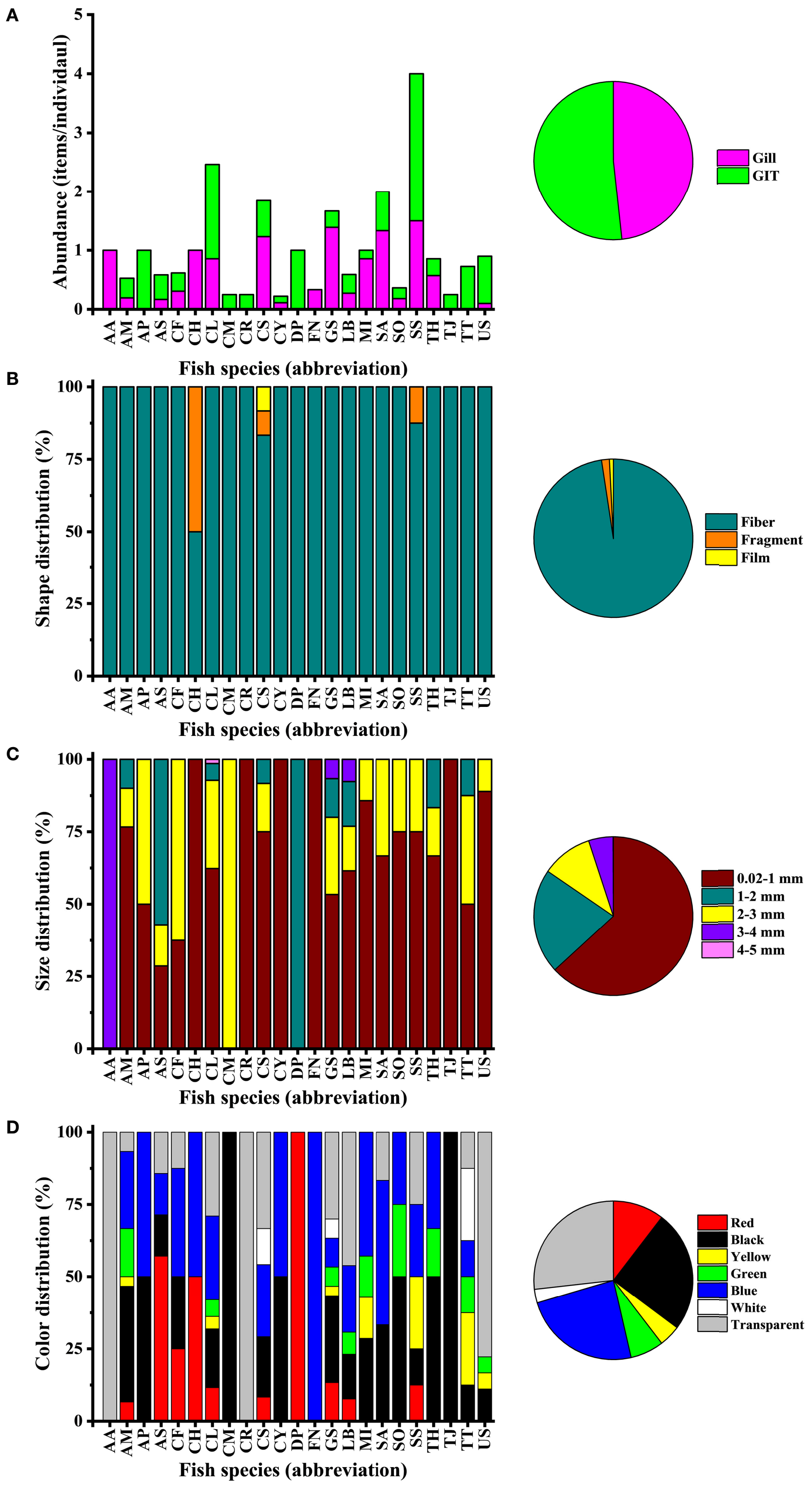

FIGURE 2
The abundances **(A)**, shapes **(B)**, sizes **(C)**, and colors **(D)** of microplastics detected in marine fishes from Beibu Gulf (for the species abbreviations, refer to Supplementary Table S1).

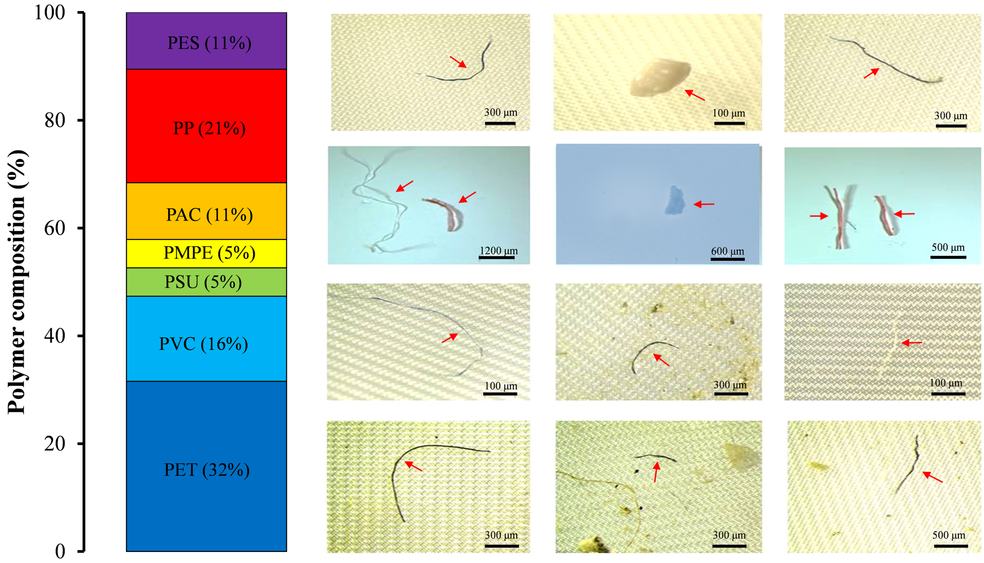

FIGURE 3
Polymer composition and the representative microplastics detected in marine fish samples from Beibu Gulf. PES, polyester; PP, polypropylene; PAC, polyacrylic; PMPE, poly methyl propenyl ether; PSU, polysulfide; PVC, polyvinyl chloride; PET, polyethylene terephthalate.

dominant colors, while red (10%), green (7%), yellow (4%), and white (3%) were less in amount (**Figure 2D**). Polyethylene terephthalate (PET) showed the highest percentage (32%), and then polypropylene (PP) (21%) was followed as the second dominant polymer. Polyvinyl chloride (PVC) (16%), polyester (PES) (11%), polyacrylic (PAC) (11%), polysulfide (PSU) (5%), and poly methyl propenyl ether (PMPE) (5%) were also detected in the samples..

Discussion

Microplastic abundance

It is well known that microplastics are accumulated in some organs of the fish body. Fish may consume microplastics by mistake since the sizes of microplastics are similar to the food particles. Previous field studies have revealed microplastic ingestion by many commercial fish species from the Yellow Sea (Sun et al., 2019), the Bohai Sea (Wang et al., 2021), the North Sea (Kühn et al., 2020), the East China Sea (Wu et al., 2020), and the North America (Baechler et al., 2020). However, the quantities of microplastics observed in fishes are generally small in amount, in the range <2 particles per individual (Savoca et al., 2021). Zhang et al. (2021) KK found that the microplastic abundance in fish from the mangrove wetland of Beibu Gulf was 0.72–5.39 items per individual, and the count was also high in GITs than in gills. Of the 80 fish studied, only three had no microplastics, and the average quantity was 6.6 items per individual in fish bodies from central and western coastal areas of Guangdong Province (Pan et al., 2021). Moreover, the average abundance of 584 fish individuals was 2.14 items per individual from Bohai Sea, China (Wang et al., 2021). Similarly, in this study, the microplastic abundance ranged from 0.027 to 4.000 items per individual in collected marine fishes. A previous study also confirmed that fish samples captured from offshore Beibu Gulf were contaminated with microplastics (Koongolla et al., 2020). According to that, the microplastic abundance in offshore Beibu Gulf ranged from 0.027 to 1.000 items per individual, with an average of 0.228 ± 0.080 items per individual within 12 fish species. We can predict the reason for the higher abundance of microplastics accumulation in onshore fish as to the direct contamination of land-based microplastics. Due to the wave reactions and current patterns of the seawater, microplastics can be present in high amounts in deep water areas. Therefore, onshore and offshore results may reveal the microplastic pollution variation with respect to the impacts of human activities by the distance from the coastline. A study from Dafeng River revealed that the microplastic pollution level in the water and sediment during the dry season was approximately two to three times higher than that during the rainy season (Liu et al., 2021). Moreover, Liu et al. (2021) found the microplastic pollution levels in the water, sediment, and fish of Dafeng River to decrease in the following order: fish > sediment > surface water in terms of items/kg. Therefore, it is obvious that environmental factors directly influence the microplastic prevalence in fish.

Recently, several studies have been conducted on the ingestion of microplastics by commercially important marine species throughout the world, where microplastics were detected frequently (Savoca et al., 2021; Ugwu et al., 2021). The direct consumption of microplastics and the incidental accumulation by a contaminated prey at lower trophic levels are reasons for the presence of microplastics in the intestine and stomach of fish (Jovanovic et al., 2018). According to Lam et al. (2022), microplastics were detected in cultured fish with an average abundance of 35.36 items per individual. The fish intestine contained more microplastics (23.91 items per individual) than the stomach (12.80 items per individual). Another study from Dafeng River showed the contents of microplastics in the digestive tracts and gills of fish, which ranged from 0.3–6.7 items per individual and 0.1–3.0 items per individual, respectively (Liu et al., 2021). In this study, microplastics were observed in both gills and GITs. The highest abundance of microplastics was found inside the GITs and accounted for 54.4% of the total microplastics, while those in the gills accounted for 45.6%. The percentage of fish with microplastics in the GIT is variably reported in the literatures, such as 65% of 178 individuals of fish from the Red Sea (Baalkhuyur et al., 2018), 58% of 1,337 individuals of fish from the Mediterranean Sea (Guven et al., 2017), 38% of 120 individuals of fish from the Mondego River estuary in Portugal (Bessa et al., 2018), and 19.8% of 263 individuals of fish from Portuguese coastal waters (Neves et al., 2015). According to these reports, microplastic accumulation in fish may be depend on the region and the number of fish samples collected.

Characteristics of microplastics

Based on their geometry, microplastics were classified into the following classes in this study: pellets, fragments, film, and fibers. In this study, 98% of collected microplastics were fibers, 1% fragments, and 1% films, respectively. Fibers can be aggregated in the marine environment due to the fragmentation of fishing nets, and hence there is a high probability for this to be ingested mistakenly by fish. According to the literature survey, the main sources of fibers are generated by human activities, including ship traffic, fisheries, sewage discharges, and wastewater from coastal areas (Cesa et al., 2017; Gago et al., 2018). Importantly, the aggregation of microplastics in the environment can directly influence the possibility of accumulation of microplastics inside fish. Several studies showed higher frequencies of fibers compared with other forms of microplastics within a variety of marine environments (Zhao et al., 2014; Koongolla et al., 2018). However, ingestion of plastic fibers can get tangled and form agglomerates that can potentially block the GITs, resulting in the accumulation of plastic fibers inside the fish body (Neves et al., 2015; Lin et al., 2020).

Moreover, the size variation of microplastics plays an important role, which leads to a high impact on microplastic pollution. According to this study, the dominant size range of the collected microplastics inside fish was between 0.02 and 1 mm, but there was not any relationship with microplastic abundance in benthic and pelagic fishes with reference to the size of microplastics (p = 0.5664). Interestingly, large-sized fishes such as *Grammoplites scaber* (30 *cm*) and *C. lineatus* (40 *cm*) accumulated only 2- to 3-mm range and 4- to 5-mm range of microplastics, respectively. It may imply that large-sized fishes which have a large mouth gape tend to consume large-sized microplastics, while small fishes ingested small microplastics. This effect was already noticed in 1994 by Shaw and Day, who recognized the preferential removal of smaller-sized particles by marine organisms (Shaw and Day, 1994). Several colors of microplastics were noticed, such as transparent (27%), black, (25%) and blue (24%) as the dominant colors, while red, yellow, green, and white were lesser in amount. The dominant colors (transparent, black, and blue) are hardly visible under the seawater environment. Therefore, it may create a higher possibility for fish ingestion by mistake.

The fingerprint-like molecular composition of polymers with a repeat unit structure allows for a clear assignment of microplastic samples. According to this study, we found PET and PP as the dominant polymers in the collected microplastics of fish from onshore Beibu Gulf. However, we also obtained few other polymer types, such as PVC, PSU, PAC, PES, and PMPE (Figure 3). The polymer composition diversity of microplastics in fish might be derived from different sources of plastic pollution in the marine environments. In fact, most fibers (*e.g.*, PET and PA fibers) reported in this study can be denser than water and are expected to sink and therefore become available to benthic feeders. Pelagic fish are usually visual predators and are more likely to confound particles and prey items (de Sa et al., 2015). However, polyethylene, PP, and PES are the most prevalent in the aquatic environment (Rezania et al., 2018). These materials have also been identified as the most abundant in previous assessments in biota (de Sa et al., 2018). However, it is essential to conduct long-time monitoring projects on microplastic relevant to the associated contaminants in marine organisms. Thus, one-time fish collection only provides a snapshot of microplastic accumulation in fish. Furthermore, the presence of microplastics found in stomachs of several commercially important fish species may present a potential risk to human health due to the transfer of these small plastic items and/or associated contaminants to edible fish tissues (Gallo et al., 2018). Regions where fish consumption is especially high were reported to be contaminated with a large number of microplastics (Antao Barboza et al., 2018). However, these findings reveal significant data for global microplastic pollution with reference to microplastics in marine fish body.

Conclusion

This study was conducted with the objective to reveal the current state of microplastic contamination in commercial fish species from Beibu Gulf with reference to distribution, morphology, and chemical characteristics. Among the collected fish species, the highest abundance of microplastics was observed in *S. sihama*, *C. lineatus*, and *S. argus.* Overall, the average microplastic abundance was 1.02 ± 0.18 items per individual from 23 fish species. According to habitat, a higher microplastic abundance was found in benthic species than that in pelagic species. There is also a positive relationship between microplastic occurrence and the wet weight of 254 fish samples. The microplastic occurrence rate was divided within two organs such as GIT (54.4%) and gills (45.6%). Fibers were the dominant form accounting for more than 98% from each station, and 0.02- to 1.00-mm size range was prominent. However, a wide variety of colors could be seen in the collected microplastics, while transparent, black, and blue were common. Based on FTIR results, the majority of microplastics were identified as PET (32%) and PP (21%). These exposed risks need to be assessed through further investigation considering the environmental realistic concentrations of microplastics and the potential transfer of pollutants to human.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

JK: formal analysis, visualization, writing—original draft, and writing—review and editing. LL: methodology, formal analysis, and visualization. C-PY: investigation and sample analysis. SL: methodology. Y-FP: data curation. X-RX: review and editing and supervision. H-XL: conceptualization and writing and review. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.964461/full#supplementary-material

References

Antao Barboza, L. G., Dick Vethaak, A., Lavorante, B. R. B. O., Lundebye, A.-K., and Guilhermino, L. (2018). Marine microplastic debris: An emerging issue for food security, food safety and human health. *Mar. Pollut. Bull.* 133, 336–348. doi: 10.1016/j.marpolbul.2018.05.047

Auta, H. S., Emenike, C. U., and Fauziah, S. H. (2017). Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions. *Environ. Int.* 102, 165–176. doi: 10.1016/j.envint.2017.02.013

Baalkhuyur, F. M., Bin Dohaish, E.-J. A., Elhalwagy, M. E. A., Alikunhi, N. M., AlSuwailem, A. M., Rostad, A., et al. (2018). Microplastic in the gastrointestinal tract of fishes along the Saudi Arabian red Sea coast. *Mar. Pollut. Bull.* 131, 407–415. doi: 10.1016/j.marpolbul.2018.04.040

Baechler, B. R., Stienbarger, C. D., Horn, D. A., Joseph, J., Taylor, A. R., Granek, E. F., et al. (2020). Microplastic occurrence and effects in commercially harvested north American finfish and shellfish: Current knowledge and future directions. *Limnol. Oceanog. Lett.* 5, 113–136. doi: 10.1002/lol2.10122

Bessa, F., Barria, P., Neto, J. M., Frias, J. P. G. L., Otero, V., Sobral, P., et al. (2018). Occurrence of microplastics in commercial fish from a natural estuarine environment. *Mar. Pollut. Bull.* 128, 575–584. doi: 10.1016/j.marpolbul.2018.01.044

Browne, M., Dissanayake, A., Galloway, T., Lowe, D., and Thompson, R. (2008). Ingested microscopic plastic translocates to the circulatory system of the mussel, Mytilus edulis (L.). *Environ. Sci. Technol.* 42 (13), 5026–5031. doi: 10.1021/es800249a

Cesa, F. S., Turra, A., and Baruque-Ramos, J. (2017). Synthetic fibers as microplastics in the marine environment: A review from textile perspective with a focus on domestic washings. *Sci. Total Environ.* 603, 836–836. doi: 10.1016/j.scitotenv.2017.04.172

Claessens, M., Meester, S., Landuyt, L., Clerck, K., and Janssen, C. (2011). Occurrence and distribution of microplastics in marine sediments along the Belgian coast. *Mar. Pollut. Bull.* 62 (10), 2199–2204. doi: 10.1016/j.marpolbul.2011.06.030

de Sa, L. C., Luis, L. G., and Guilhermino, L. (2015). Effects of microplastics on juveniles of the common goby (Pomatoschistus microps): Confusion with prey, reduction of the predatory performance and efficiency, and possible influence of developmental conditions. *Environ. Pollut.* 196, 359–362. doi: 10.1016/j.envpol.2014.10.026

de Sa, L. C., Oliveira, M., Ribeiro, F., Rocha, T. L., and Futter, M. N. (2018). Studies of the effects of microplastics on aquatic organisms: What do we know and where should we focus our efforts in the future? *Sci. Total Environ.* 645, 1029–1039. doi: 10.1016/j.scitotenv.2018.07.207

Gago, J., Carretero, O., Filgueiras, A. V., and Vinas, L. (2018). Synthetic microfibers in the marine environment: A review on their occurrence in seawater and sediments. *Mar. Pollut. Bull.* 127, 365–376. doi: 10.1016/j.marpolbul.2017.11.070

Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J., Ingram, I., et al. (2018). Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures. *Environ. Sci. Europe* 30, 13. doi: 10.1186/s12302-018-0139-z

Gao, J., Wu, G., and Ya, H. (2017). Review of the circulation in the beibu gulf, south China Sea. *Continental Shelf Res.* 138, 106–119. doi: 10.1016/j.csr.2017.02.009

Guven, O., Gokdag, K., Jovanovic, B., and Kideys, A. E. (2017). Microplastic litter composition of the Turkish territorial waters of the Mediterranean Sea, and its occurrence in the gastrointestinal tract of fish. *Environ. Pollut.* 223, 286–294. doi: 10.1016/j.envpol.2017.01.025

Hammer, J., Kraak, M., and Parsons, J. (2012). Plastics in the marine environment: The dark side of a modern gift. *Rev. Environ. Contamination Toxicol.* 220, 1–44. doi: 10.1007/978-1-4614-3414-6_1

Jovanovic, B., Gokdag, K., Guven, O., Emre, Y., Whitley, E. M., and Kideys, A. E. (2018). Virgin microplastics are not causing imminent harm to fish after dietary exposure. *Mar. pollut. Bull.* 130, 123–131. doi: 10.1016/j.marpolbul.2018.03.016

Koongolla, J. B., Andrady, A. L., Kumara, P. B. T. P., and Gangabadage, C. S. (2018). Evidence of microplastics pollution in coastal beaches and waters in southern Sri Lanka. *Mar. Pollut. Bull.* 137, 277–284. doi: 10.1016/j.marpolbul.2018.10.031

Koongolla, J. B., Lin, L., Pan, Y.-F., Yang, C.-P., Sun, D.-R., Liu, S., et al. (2020). Occurrence of microplastics in gastrointestinal tracts and gills of fish from beibu gulf, south China Sea. *Environ. Pollut.* 258, 113734. doi: 10.1016/j.envpol.2019.113734

Kühn, S., van Franeker, J. A., O'Donoghue, A. M., Swiers, A., Starkenburg, M., van Werven, B., et al. (2020). Details of plastic ingestion and fibre contamination in north Sea fishes. *Environ. pollut.* 257, 113569. doi: 10.1016/j.envpol.2019.113569

Lam, T., Fok, L., Ma, A., Li, H., Xu, X., Cheung, L., et al. (2022). Microplastic contamination in marine-cultured fish from the pearl river estuary, south China. *Sci. Total Environ.* 827, 154281. doi: 10.1016/j.scitotenv.2022.154281

Lin, L., Ma, L. S., Li, H. X., Pan, Y. F., Liu, S., Zhang, L., et al. (2020). Low level of microplastic contamination in wild fish from an urban estuary. *Mar. pollut. Bull.* 160, 111650. doi: 10.1016/j.marpolbul.2020.111650

Liu, S., Chen, H., Wang, J., Su, L., Wang, X., Zhu, J., et al. (2021). The distribution of microplastics in water, sediment, and fish of the dafeng river, a remote river in China. *Ecotoxicol. Environ. Saf.* 228, 113009. doi: 10.1016/j.ecoenv.2021.113009

Li, R., Zhang, L., Xue, B., and Wang, Y. (2019). Abundance and characteristics of microplastics in the mangrove sediment of the semi-enclosed maowei Sea of the south China sea: New implications for location, rhizosphere, and sediment compositions. *Environ. Pollut.* 244, 685–692. doi: 10.1016/j.envpol.2018.10.089

Neves, D., Sobral, P., Ferreira, J. L., and Pereira, T. (2015). Ingestion of microplastics by commercial fish off the Portuguese coast. *Mar. pollut. Bull.* 101, 119–126. doi: 10.1016/j.marpolbul.2015.11.008

Pan, Z., Zhang, C., Wang, S., Sun, D., Zhou, A., Xie, S., et al. (2021). Occurrence of microplastics in the gastrointestinal tract and gills of fish from guangdong, south China. *J. Mar. Sci. Eng.* 9, 981. doi: 10.3390/jmse9090981

Rezania, S., Park, J., Din, M. F. M., Taib, S. M., Talaiekhozani, A., Yadav, K. K., et al. (2018). Microplastics pollution in different aquatic environments and biota: A review of recent studies. *Mar. Pollut. Bull.* 133, 191–208. doi: 10.1016/j.marpolbul.2018.05.022

Savoca, M. S., McInturf, A. G., and Hazen, E. L. (2021). Plastic ingestion by marine fish is widespread and increasing. *Global Change Biol.* 27, 2188–2199. doi: 10.1111/gcb.15533

Shaw, D., and Day, R. (1994). Colour- and form-dependent loss of plastic micro-debris from the north pacific ocean. *Mar. pollut. Bull.* 28, 39–43. doi: 10.1016/0025-326X(94)90184-8

Sun, X., Li, Q., Shi, Y., Zhao, Y., Zheng, S., Liang, J., et al. (2019). Characteristics and retention of microplastics in the digestive tracts of fish from the yellow Sea. *Environ. pollut.* 249, 878–885. doi: 10.1016/j.envpol.2019.01.110

Ugwu, K., Herrera, A., and Gomez, M. (2021). Microplastics in marine biota: A review. *Mar. pollut. Bull.* 169, 112540. doi: 10.1016/j.marpolbul.2021.112540

Wang, Q., Zhu, X., Hou, C., Wu, Y., Teng, J., Zhang, C., et al. (2021). Microplastic uptake in commercial fishes from the bohai Sea, China. *Chemosphere* 263, 127962. doi: 10.1016/j.chemosphere.2020.127962

Wu, J., Lai, M., Zhang, Y., Li, J., Zhou, H., Jiang, R., et al. (2020). Microplastics in the digestive tracts of commercial fish from the marine ranching in east China sea, China. *Case Stud. Chem. Environ. Eng.* 2, 100066. doi: 10.1016/j.cscee.2020.100066

Xue, B., Zhang, L., Li, R., Wang, Y., Guo, J., Yu, K., et al. (2020). Underestimated microplastic pollution derived from fishery activities and "Hidden" in deep sediment. *Environ. Sci. Technol* 54, 2210–2217. doi: 10.1021/acs.est.9b04850

Zhang, L., Liu, J., Xie, Y., Zhong, S., Yang, B., Lu, D., et al. (2020a). Distribution of microplastics in surface water and sediments of qin river in beibu gulf, China. *Sci. Total Environ.* 708, 135176. doi: 10.1016/j.scitotenv.2019.135176

Zhang, S., Sun, Y., Liu, B., and Li, R. (2021). Full size microplastics in crab and fish collected from the mangrove wetland of beibu gulf: Evidences from raman tweezers (1-20 μm) and spectroscopy (20-5000 μm). *Sci. Total Environ.* 759, 143504. doi: 10.1016/j.scitotenv.2020.143504

Zhang, L., Zhang, S., Guo, J., Yu, K., Wang, Y., and Li, R. (2020b). Dynamic distribution of microplastics in mangrove sediments in beibu gulf, south China: Implications of tidal current velocity and tidal range. *J. Hazardous Materials* 399, 122849. doi: 10.1016/j.jhazmat.2020.122849

Zhao, S., Zhu, L., Wang, T., and Li, D. (2014). Suspended microplastics in the surface water of the Yangtze estuary system, China: First observations on occurrence, distribution. *Mar. Pollut. Bull.* 86, 562–568. doi: 10.1016/j.marpolbul.2014.06.032

Zhu, Z., Wei, H., Huang, W., Wu, X., Guan, Y., and Zhang, Q. (2022). Occurrence of microplastic pollution in the beibu gulf, the northern south China Sea. *Front. Mar. Sci.* 8, 821008. doi: 10.3389/fmars.2021.821008

Zhu, J., Zhang, Q., Huang, Y., Jiang, Y., Li, J., Michal, J. J., et al. (2021). Long-term trends of microplastics in seawater and farmed oysters in the maowei Sea, China. *Environ. pollut.* 273, 116450. doi: 10.1016/j.envpol.2021.116450

Zhu, J., Zhang, Q., Li, Y., Tan, S., Kang, Z., Yu, X., et al. (2019). Microplastic pollution in the maowei Sea, a typical mariculture bay of China. *Sci. Total Environ.* 658, 62–68. doi: 10.1016/j.scitotenv.2018.12.192

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Achieving sustainable production and consumption of virgin plastic polymers

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The United Nations Environment Assembly (UNEA) recently adopted a resolution with a mandate to negotiate a new international legally binding instrument (a treaty) on plastic pollution. The mandate includes the need to 'prevent' as well as 'reduce' and 'eliminate' plastic pollution through a 'comprehensive approach that addresses the full life cycle of plastic'. Unsustainable production and consumption of virgin (primary) plastic polymers represents the single greatest threat to preventing plastic pollution and risks undermining the incoming treaty. However, current discussions on a global plastics treaty overlook upstream measures that address virgin plastic production and consumption, focusing instead on midstream and downstream measures on product design and waste management. This article presents the justification for and benefits of a stepwise approach for controlling virgin plastic production and consumption internationally, inspired by the Montreal Protocol on Substances that Deplete the Ozone Layer;

KEYWORDS

plastics, treaty, virgin, production, montreal protocol, prevention, pollution

1 Introduction

Virgin - also referred to as primary -plastic production and consumption are increasingly recognised as having reached unsustainable levels (Lau et al., 2020; Cabernard et al., 2022; Ford et al., 2022; Bergmann et al., 2022). Countries are inundated by an acute overabundance of inexpensive virgin plastics, undermining secondary markets for recycled material and investments in collection and recycling infrastructure (Bauer et al., 2020; Simon et al., 2021). As pressure mounts on the oil and gas industry in the context of a serious climate change response, fossil fuel companies are relying on plastics as the major growth industry (International Energy Agency, 2018; Yale Environment 360, 2019).

The petrochemicals used to produce virgin plastic polymers and other products account for 8% and 14% of total primary demand for gas and oil, respectively, and will soon become the world's biggest driver of oil demand, ahead of trucks, aviation and shipping (International Energy Agency, 2018). The result is a system where inexpensive virgin plastic is used freely and inefficiently, with unfavourable economics for most recycling, leading to a stark discrepancy between how much plastic is produced and how much is recycled. At the end of 2017, of all plastic waste ever produced, only 10% has been recycled; 14% was incinerated and a further 76% ended up in landfills or the natural environment (Geyer, 2020).

Policymakers increasingly draw the connection between eliminating plastic pollution and promoting a circular economy for plastics (European Commission, 2018). The two are inextricably linked. The recent adoption of UNEA Resolution 5/14 entitled *'End Plastic Pollution: Towards an international legally binding instrument'* will convene an Intergovernmental Negotiating Committee (INC) to negotiate a new legally binding instrument to end plastic pollution in all environments (herein termed 'the treaty'). The resolution expressly recognises the need for 'circular economy approaches', taking a 'comprehensive approach that addresses the full life cycle of plastic', in persuit of 'sustainable production and consumption of plastics' (United Nations Environment Assembly [UNEA], 2022). Yet current trends in virgin plastic production and consumption are forecast to overwhelm all efforts to improve waste management, widening the discrepancy even further (Organization for Economic Cooperation and Development [OECD], 2022b). Based on a 2016 baseline, annual virgin plastic production is set to double by 2040 and increase to 1.1 billion tonnes in 2050 (Lau et al., 2020; Geyer, 2020). Already, production of virgin plastic polymers and their conversion from fossil fuels are responsible for 90% of the plastic life cycle's carbon footprint (Organization for Economic Cooperation and Development [OECD], 2022a).

Because virgin plastic polymers are raw materials, products, and pollutants with a few hundred companies dominating production (Charles et al., 2021), a situation similar to ozone-depleting substances (ODS), there are clear learnings for the global community seeking to end plastic pollution in the approach taken by the Montreal Protocol on Substances that Deplete the Ozone Layer (Raubenheimer and McIlgorm, 2017; Andersen et al., 2021). The Protocol is widely considered to be the most successful multilateral environmental agreement (MEA) of all time (Gonzalez et al., 2015; Liu et al. 2016).

This paper reviews how measures under the Montreal Protocol could be adapted to virgin plastic polymers and, in so doing, provides an upstream global regulatory framework that addresses plastic pollution.

2 Policy considerations

2.1 Defining the lifecycle – where should intervention begin?

The need for a 'full life cycle approach' is explicitly mentioned in both preambular and operative sections in UNEA Resolution 5/14. However, no commonly agreed definition of the plastics life cycle exists. While it is obvious that the life cycle ends with plastic waste or its presence in the environment as pollution, it is less clear where it should begin. This presents policymakers with the challenge of defining it for the purpose of the treaty.

Adopted in 2013, the Minamata Convention on Mercury 'addresses mercury throughout its life cycle from its mining to its management as waste' (United Nations Environment Programme [UNEP], 2013). This approach identifies the full life cycle as beginning at the resource extraction phase. However, no other global policy instrument regulates any aspect of the mercury life cycle, and while related, the situation with plastics is much more nuanced. For instance, 99% of plastics are derived from fossil fuels (Nielsen et al., 2020), meaning the juristiction and competencies of the UN Framework Convention on Climate Change (UNFCCC) must also be considered alongside the possibility of a future fossil fuel non-proliferation treaty (Newell and Simms, 2020). As such, the life cycle of plastic needs to consider the life cycle of oil and gas to identify the minimum point at which intervention must begin.[1]

The lifecycle of oil and gas is typically divided into three stages based on functions and operations: upstream, midstream and downstream. Upstream involves the extraction and gathering of fossil resources; midstream involves the transportation of the fossil resources, including through pipelines, and downstream includes processing into petrochemicals (Al-Janabi, 2020). In this context, plastic does not yet exist.

As a material, plastic comes into existence upon polymerisation - a process of reacting monomers (e.g. ethylene) together to form polymer chains (see Figure 1). For this reason, while consideration should also be given to how best to address issues associated with the extraction of raw materials and sourcing of feedstocks for plastic production, including linkages to other conventions, polymerisation is squarely within the scope of the treaty. This is the beginning of plastic as a material – with the lifecycle thereafter divided into four stages:

i. upstream, *i.e.* production of virgin plastic polymers;
ii. midstream, *i.e.* product design and use;
iii. downstream, *i.e.* plastic waste management and treatment (De Silva et al., 2021);
iv. leakage, *i.e.* plastic in the environment.

Such an approach also ensures scope at least covers plastics when they come into existence as materials, and coincides with

1 This article focusses on fossil-based plastics that comprise ~99% of virgin production. However, the ~1% synthesised from bio-based feedstock (so-called 'bioplastics') also require inclusion within the scope of upstream controls.

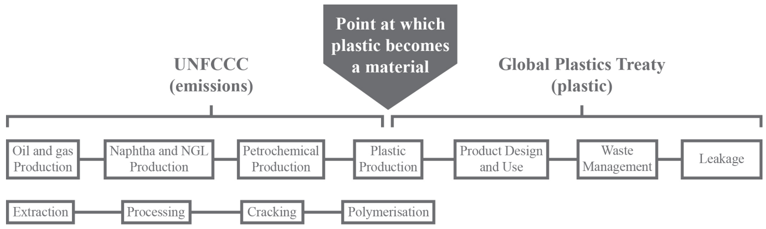

FIGURE 1
A diagram displaying the life cycle of fossil fuels (oil, gas, and coal) in relation to the life cycle of plastics. Polymerisation is the point at which plastics become materials and the minimum stage at which intervention under the incoming treaty needs to begin. However, this should not preclude negotiators from considering measures associated with the extraction of raw materials and sourcing of feedstocks for plastic production and its interlinkages to other conventions.

when plastic first enters the environment as a pollutant in the form of spilled pellets, flakes and powders (Karlsson et al., 2018). Using this definition also follows the approach taken in the Montreal Protocol, whose control measures begin at the point at which ODS are produced (De Sombre, 2000).

It also clearly delineates the scope of measures to be taken in relation to the UNFCCC, which addresses greenhouse gas emissions associated with the oil and gas industry and is mandated to address the negative externalities related to climate change (see Figure 1), though this should not preclude negotiators considering measures further upstream.

2.2 Policy to prevent pollution

UNEA Resolution 5/14 mentions the need to 'prevent' as well as 'reduce' and 'eliminate' plastic pollution (United Nations Environment Assembly [UNEA], 2022), which will not be achieved with mid- and downstream measures alone (Simon et al., 2021). Around 90% of all plastic waste ever produced was used just once (Geyer, 2020), demonstrating the necessity of upstream controls on virgin production to support mid- and downstream measures.

The Montreal Protocol controls harmful chemicals through limits at the production level and on the amount of 'consumption' in products and equipment, rather than downstream post-consumption, which has been the most significant driver of the successful ODS phase-outs. This success inspired authors such as Raubenheimer and McIlgorm (2017) to propose the use of the Protocol as a model to regulate land-based sources of marine plastic debris, and Andersen et al. (2021) to propose narrowing the exemptions for feedstocks used to produce plastics, which they estimate has the potential to reduce up to around 6% of total plastics production. It therefore follows that upstream measures regulating the production and consumption of virgin plastic polymers are also needed to effectively prevent plastic pollution, with the Montreal Protocol representing an appropriate lens through which to design and conceptualise them (Simon et al, 2021; Bergmann et al., 2022).

Furthermore, the Montreal Protocol was designed from the beginning as a flexible and adaptable "start-and-strengthen" instrument (Gonzalez et al., 2015). At its inception, there were still many uncertainties and unknowns relating to both ODS pollution impact and alternatives, requiring policymakers to base precautionary policies on the information and alternatives that were available (De Sombre, 2000). While there are far fewer uncertainties in the context of plastic pollution, many remain, and enduring success is likely to be achieved through the gradual strengthening of controls over time as new information and alternatives become available (Kaniaru et al., 2007; Andersen et al., 2021; Simon et al., 2021). Such an approach would also provide an enabling environment for industry innovation that will take place as demand for alternatives rise.

Parties should therefore strongly consider tackling plastic pollution through controls on virgin plastic production and consumption, *via* a start-and-strengthen approach. Throughout the INC and beyond, this could be operationalised in two distinct phases - fact-finding and policymaking.

3 Recommended measures

3.1 Phase I – fact-finding

3.1.1 Controlled substances

Article 2 of the Montreal Protocol identifies the control measures to be imposed on the production and consumption of controlled substances, which are listed in Annexes A, B, C, E and F. In the context of plastics, Parties must first identify the substances (polymers) to be controlled. Plastic polymers can be broadly placed into two categories: thermosets, which cannot be remelted and remolded (~20%); and thermoplastics, which can be melted and remolded (~80%) (Shieh et al., 2020). Industry further classifies thermoplastics into three main categories: *(i)* standard, used in common applications (~90%

of total market share); *(ii)* engineering, which possess improved mechanical or thermal properties (~10% of total market share); and *(iii)* high-performance, used for exceptional end-use applications and niche products (<1% of total market share) (Manas et al., 2008). Parties should clearly set out the polymers to be controlled under the new agreement in an annex, which thereafter constitutes the "controlled substances" subject to all other measures. Updates to the annex to account for new polymers should be made possible *via* Decisions by the Parties without need for further ratification.

3.1.2 Reporting

Article 7 of the Montreal Protocol requires all Parties to provide statistical data about ODS to the Ozone Secretariat every year. The Ozone Secretariat uses the data to calculate annual ODS production and consumption for each Party on an ozone-depleting potential (ODP) basis. In the context of plastics, reporting obligations should also allow for the determination of annual production and consumption of virgin plastic polymers. Mirroring the Montreal Protocol approach, 'production' should refer to the amount of virgin plastic a country produces, with 'consumption' referring to the amount of virgin plastic a country consumes, calculated as production plus imports minus exports of virgin plastics (Brack, 2003). 'Use' would refer to the sector the polymers are used in, such as packaging, agriculture and fisheries, building and construction, automotive, electrical and electronic, household, textile, leisure and sports plus others, including medical and laboratory.

Four key data points should form the basis of reporting obligations for virgin plastic by polymer type: (i) production; (ii) imports; (iii) exports; (iv) use. Fortunately, reporting is greatly facilitated by the relatively few virgin polymer producers, approximately 300 worldwide in 2019, about 100 of which account for 90% of all single-use plastics (Charles et al., 2021). The Parties should work to ensure a harmonised approach toward reporting, premised on mandatory obligations and clear definitions and formats with technical and financial assistance made available for developing countries and economies in transition.

In addition to forming the basis for fact-finding, reporting has independent value. Virgin plastic production is a key indicator for understanding progress toward eliminating plastic pollution and promoting a circular economy for plastics that is protective of human health (Lau et al., 2020). In other words, scientists and policymakers are hamstrung in drawing conclusions on the evolution of plastic pollution in the environment and effectiveness of measures on product design, use and waste management and treatment without knowing the quantities and types of virgin plastic entering the global economy each year.

3.1.3 Licensing systems

As supplies of chlorofluorocarbons (CFCs) and other ODS were significantly reduced under the Montreal Protocol phase-out schedules, the continued demand in some countries lead to a significant illegal trade in the controlled chemicals (Liu et al. 2016). By the mid-1990s, an estimated 20,000 tonnes of ODS were being traded illegally each year, equivalent to 20% of legitimate trade, and sophisticated smuggling networks had appeared (Environmental Investigation Agency [EIA], 2013). In response to this threat, the Parties agreed to establish cross-border licensing systems to monitor the flow of ODS and to prevent ODS from ending up on the black market. Licensing systems are regulatory schemes whereby a license is granted by authorities for a company to produce, export or import controlled substances, supported by a ban on unlicensed production, exports and imports. Many MEAs require licensing systems, including the Montreal Protocol as well as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. The objectives for a licensing system for virgin plastics could be to: (i) assist the collection of information to facilitate compliance with reporting; (ii) facilitate notification and cross-checking of reported information; (iii) assist in preventing illegal trade (Montreal Protocol, 1997).

3.1.4 Baselines

The control measures under Article 2 of the Montreal Protocol establish a baseline for production and consumption from which the phase-out schedule is implemented. Such baselines will also be needed for virgin plastic production and consumption, by polymer, from which progress could be monitored. These should be based on average production and consumption by weight, over a multi-year period to compensate for annual fluctuations. The selection of the multi-year period that constitutes the baseline has important implications for virgin plastic production. A prospective baseline, for example 2025-27, would encourage expansion of virgin plastic production and consumption up to and through the baseline years, in direct contrast to the objectives of the treaty. This occurred prior to the adoption of the Montreal Protocol in 1987, which resulted in a net increase of aggregate world CFC production (Auffhammer et al., 2005). Similarly, multiple countries increased hydrochlorofluorocarbon (HCFC) consumption in the baseline calculation years prior to the start of the HCFC phase-out, resulting in artificially inflated baselines (Environmental Investigation Agency [EIA], 2016). On the other hand, a historical baseline such as 2019-21 would discourage expansion of virgin plastic production, serving as a soft freeze until additional controls can be adopted.

3.2 Phase II – policymaking

In accordance with UNEA resolution 5/14, the objective of policymaking should be to establish a set of controls to promote a circular economy, protective of human health, taking a comprehensive life cycle approach to achieve sustainable production and consumption of plastics (United Nations Environment Assembly [UNEA], 2022). Such decisions could be informed through thorough assessment by scientific and technical bodies, balancing environmental objectives and feasibility with societal and economic needs (Busch et al., 2021).

3.2.1 Freezes, phase-downs and phase-outs

Following the Montreal Protocol model, Parties should adopt restrictions on annual production and consumption of controlled substances (*i.e.* virgin plastic polymers). This would likely entail a cap on production and consumption ("freeze") at a certain level, such as 100% of an established baseline, followed by a series of reduction steps ("phase-down") to lower aggregate levels of production and consumption over time. Consideration should be given to schedules for different categories or types of virgin plastic polymers, as did the Montreal Protocol by first targeting five particularly potent and widely used CFCs and halons. For example, less necessary plastics that harbour higher toxicity and are used widely in applications that tend to end up as pollution could be targeted first (for example, polyvinyl chloride), with those used in engineering and high-performance applications accounted for in the tail of allowable production and consumption.

Parties should also target for immediate freeze and phase-out of particularly problematic virgin plastic polymers that are difficult to recycle, have high concentrations of toxic chemicals and for which alternatives are readily available, such as polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PUR) and polycarbonate (PC), which collectively comprise 30% of total market share (Rochman et al., 2013). A similar phase-out schedule should also be considered for chemical families used as additives, catalysts, or polymerisation aids in plastic production that are known to be harmful to human health. This could support the Stockholm Convention on Persistent Organic Pollutants while also preventing repetitive cycles of hazardous chemical use (Sharkey et al., 2020; OECD 2018).

3.2.2 Exemptions

The Montreal Protocol has several categories of exemptions, including global exemptions for certain laboratory or analytical uses as well as critical-use and essential-use exemptions, which authorise a specific country to use a specific amount of a controlled substance for a certain time. Such an approach could be considered in the case of plastics to allow for continued use, for example the medical or automotive sectors, allowing time-limited use of controlled substances considered essential for society until alternatives are readily available and commercialised (Andersen et al., 2021). Such exemptions should also consider critical development issues with direct relevance to the 2030 Agenda for Sustainable Development, such as lack of access to safe drinking water (Sustainable Development Goal 6). While plastic pollution is often discussed in the context of SDG14 – life below water – it also traverses areas of relevance to SDG 3, 6, 11, 12, 13 and 15, amongst others. This is exemplified by the deletion of the word 'marine' in front of 'plastic pollution' in the final Resolution 5/14 text and inclusion of a reference to sustainable production and consumption of plastics (SDG12). As such, the new plastics treaty needs to be developed, implemented, and embedded within the broader sustainable development landscape.

3.2.3 Adjustments

Most multilateral environmental agreements allow for controls to be adjusted and strengthened over time. Under the Montreal Protocol, an "adjustment" of the phase-down schedule of any given controlled substance is possible without the need for a formal amendment, which requires ratification. It is therefore recommended that a mechanism responsive to the objectives of the agreement is established for plastics that enables controls to be gradually strengthened as new scientific, environmental, technical and economic information becomes available (Busch et al., 2021; Simon et al., 2021). This approach has worked exceptionally well in the case of the Montreal Protocol, which under Article 6 requires an assessment and review of control measures every four years (Andersen et al., 2021).

3.2.4 Non-party trade provisions

Provisions on trade by Parties with non-Parties should prohibit or restrict countries party to the agreement from trading in controlled substances with countries not party to the agreement. Article 4 of the Montreal Protocol requires that Parties ban the import and export of controlled substances from and to non-Parties. Such an approach has worked to maximise participation and facilitate compliance. In 2009, the Montreal Protocol was the first UN treaty to receive universal ratification, a key contributing factor being the existence of such controls (Gonzalez et al., 2015).

3.2.5 Assessment panels

Parties to the Protocol are required to base their decisions on current scientific, environmental, technical, and economic information. The Scientific Assessment Panel (SAP), Environmental Effects Assessment Panel (EEAP) and Technology and Economics Assessment Panel (TEAP) all assess information to inform and strengthen ODS policy. Since these are housed within the governing body, their work remains highly applicable and relevant to the agreement's objectives. Having such a high degree of responsiveness allows the Protocol to adapt quickly to new information in a rapid and responsive manner. A similar approach could be adopted in the context of plastics, whereby a dedicated scientific mechanism would be tied directly with the new instrument. Operative paragraph 3(f) of Resolution

5/14 explicitly mentions the need for considering such an approach during negotiations. If adopted, this would likely facilitate a start-and-strengthen approach as new information becomes available by ensuring relevance and responsiveness to the instrument's objectives. Such an approach is a necessary complement to independent science-policy panels, such as the one that will be established as a result of UNEA Resolution 5/8 for chemicals, waste and prevention of pollution.

4 Conclusions

UNEA Resolution 5/14 specifically calls for a 'full lifecycle approach' to achieve 'sustainable production and consumption of plastics.'. As production and consumption of virgin plastic polymers is widely understood to have reached unsustainable levels, there are clear lessons from the approach adopted by the Montreal Protocol.

Upstream (*i.e.* production) controls are a necessary precursor to achieving sustainable production and consumption of virgin plastic polymers, facilitating economic circularity and enabling the reduction and elimination of plastic pollution. While critical, midstream and downstream measures will be inadequate if instituted alone, meaning upstream controls are required as part of a holistic package of policies to address the plastic pollution crisis.

Effective upstream action will assist consumer goods companies and retailers to redesign packaging, transition to alternative product delivery systems such as refillable and reusable packaging and incentivise innovation in alternatives to plastics while avoiding regrettable substitutions. It will also support municipalities and the industry to manage waste in a responsible and environmentally sound manner through streamlining waste streams and relieving pressure on overwhelmed collection and management infrastructure. Such measures would also tackle up to 90% of the plastic value chain's life cycle greenhouse gas emissions, contributing significantly to global efforts to tackle climate change.

Author contributions

TGr conceived the article. TGr and TGa drafted the article. CP and CD contributed to content and structure. TGr, TGa, CD and CP reviewed and edited the article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Al-Janabi, Y. T. (2020). "An overview of corrosion in oil and gas industry: upstream, midstream, and downstream sectors," in *Corrosion inhibitors in the oil and gas industry*, 1–39. (Wiley: New York, NY, USA).

Andersen, S. O., Gao, S., Carvalho, S., Ferris, T., Gonzalez, M., Sherman, N. J., et al. (2021). Narrowing feedstock exemptions under the Montreal protocol has multiple environmental benefits. *Proc. Natl. Acad. Sci.* 118 (49). doi: 10.1073/pnas.2022668118

Auffhammer, M., Morzuch, B. J., and Stranlund, J. K. (2005). Production of chlorofluorocarbons in anticipation of the Montreal protocol. *Environ. Resource Economics* 30 (4), 377–391.

Bauer, F., Holmberg, K., Nilsson, L. J., Palm, E., and Stripple, J. (2020) *Strategising plastic governance: Policy brief* (Lund University). Available at: https://lucris.lub.lu.se/ws/portalfiles/portal/80538112/Policy_brief_Strategising_Plastic_Governance.pdf (Accessed 17th March 2022).

Bergmann, M., Almroth, B. C., Brander, S. M., Dey, T., Green, D. S., Gundogdu, S., et al. (2022). A global plastic treaty must cap production. *Science* 376 (6592), 469–470. doi: 10.1126/science.abq0082

Brack, D. (2003). *Monitoring the Montreal protocol. verification yearbook 2003.* Ed. T. Findlay (London: VERTIC), 209–226.

Busch, P. O., Schulte, M. L., and Simon, N. (2021) *Strengthen the global science and knowledge base to reduce marine plastic pollution* (Nordic Council of Ministers). Available at: https://pub.norden.org/temanord2021-519/temanord2021-519.pdf (Accessed April 15, 2022).

Cabernard, L., Pfister, S., Oberschelp, C., and Hellweg, S. (2022). Growing environmental footprint of plastics driven by coal combustion. *Nat. Sustainability.* 5 (2), 139–148. doi: 10.1038/s41893-021-00807-2

Charles, D., Kimman, L., and Saran, N. (2021) *The plastic waste makers index* (Minderoo Foundation) (Accessed April 1, 2022).

De Silva, L., Doremus, J., and Taylor, R. (2021). *The plastic economy. environmental defense fund economics discussion paper series*. Environmental Defence Fund (EDF); Economics Discussion Series (EDS).

De Sombre, E. R. (2000). The experience of the Montreal protocol: Particularly remarkable, and remarkably particular. *UCLA J. Environ. Law Policy* 19 (49), 49–81.

Environmental Investigation Agency [EIA] (2013). "Chapter 10 – ozone depleting substances," in *Transnational organized crime in East Asia and the pacific - a threat assessment*, 113–120. (Vienna: United Nations Office on Drugs and Crime (UNODC)) Available at: https://www.unodc.org/documents/toc/Reports/TOCTA-EA-Pacific/TOCTA_EAP_c10.pdf.

Environmental Investigation Agency [EIA] (2016) *Averting climate catastrophe*. Available at: https://eia-international.org/wp-content/uploads/EIA-Averting-Climate-Catastophe-FINAL.pdf.

European Commission (2018) *Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of regions: A strategy for plastics in a circular economy* (Accessed March 18, 2022).

Ford, H. V., Jones, N. H., Davies, A. J., Godley, B. J., Jambeck, J. R., Napper, I. E., et al. (2022). The fundamental links between climate change and marine plastic pollution. *Sci. Total Environ.* 806, 150392. doi: 10.1016/j.scitotenv.2021.150392

Geyer, R. (2020). "Chapter 2 - production, use, and fate of synthetic polymers," in *Plastic waste and recycling: Environmental impact, societal issues, prevention, and solutions*. Ed. T. Letcher (Cambridge MA, USA: Academic Press), 13–32.

Gonzalez, M., Taddonio, K. N., and Sherman, N. J. (2015). The Montreal protocol: how today's successes offer a pathway to the future. *J. Environ. Stud. Sci.* 5 (2), 122–129. doi: 10.1007/s13412-014-0208-6

International Energy Agency (2018) *The future of petrochemicals: Towards more sustainable plastics and fertilizers*. Available at: https://www.iea.org/reports/the-future-of-petrochemicals (Accessed February 15, 2022).

Kaniaru, D., Shende, R., Stone, S., and Zaelke, D. (2007). Strengthening the Montreal protocol: Insurance against abrupt climate change. *Sustain. Dev. Law Policy* 3 (9), 74–76.

Karlsson, T. M., Arneborg, L., Broström, G., Almroth, B. C., Gipperth, L., and Hassellöv, M. (2018). The unaccountability case of plastic pellet pollution. *Mar. pollut. Bull.* 129 (1), 52–60.

Lau, W. W., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., et al. (2020). Evaluating scenarios toward zero plastic pollution. *Science* 369 (6510), 1455–1461. doi: 10.1126/science.aba9475

Liu, N., Somboon, V., and Middleton, C. (2016). *Illegal trade in ozone depleting substances. handbook of transnational environmental crime* (Edward Elgar Publishing: Cheltenham, UK; Northampton, MA, USA), 212–234.

Manas, D., Manas, M., Stanek, M., and Danek, M. (2008). Improvement of plastic properties. *Arch. Materials Sci. Eng.* 32 (2), 69–76.

Montreal Protocol (1997) *Decision IX/8: Licensing system. ninth meeting of the parties*. Available at: https://ozone.unep.org/treaties/montreal-protocol/meetings/ninth-meeting-parties/decisions/decision-ix8-licensing-system.

Newell, P., and Simms, A. (2020). Towards a fossil fuel non-proliferation treaty. *Climate Policy.* 20 (8), 1043–1054. doi: 10.1080/14693062.2019.1636759

Nielsen, T. D., Hasselbalch, J., Holmberg, K., and Stripple, J. (2020). Politics and the plastic crisis: A review throughout the plastic life cycle. *Wiley Interdiscip. Reviews: Energy Environ.* 9 (1), e360. doi: 10.1002/wene.360

Organization for Economic Cooperation and Development [OECD] (2018) *Considerations and criteria for sustainable plastics from a chemicals perspective background paper 1* (Copenhagen). Available at: https://www.oecd.org/chemicalsafety/risk-management/considerations-and-criteria-for-sustainable-plastics-from-a-chemicals-perspective.pdf (Accessed March 12, 2022).

Organization for Economic Cooperation and Development [OECD] (2022a). *Global plastics outlook: Economic drivers, environmental impacts and policy options* (Paris: OECD Publishing).

Organization for Economic Cooperation and Development [OECD] (2022b). *Global plastics outlook: Policy scenarios to 2060* (Paris: OECD Publishing).

Raubenheimer, K., and McIlgorm, A. (2017). Is the Montreal protocol a model that can help solve the global marine plastic debris problem? *Mar. Policy* 81, 322–329.

Rochman, C. M., Browne, M. A., Halpern, B. S., Hentschel, B. T., Hoh, E., Karapanagioti, H. K., et al. (2013). Classify plastic waste as hazardous. *Nature* 494 (7436), 169–171. doi: 10.1038/494169a

Sharkey, M., Harrad, S., Abdallah, M. A. E., Drage, D. S., and Berresheim, H. (2020). Phasing-out of legacy brominated flame retardants: The UNEP Stockholm convention and other legislative action worldwide. *Environ. Int.* 144 (2020), 106041.

Shieh, P., Zhang, W., Husted, K. E., Kristufek, S. L., Xiong, B., Lundberg, D. J., et al. (2020). Cleavable comonomers enable degradable, recyclable thermoset plastics. *Nature* 583 (7817), 542–547. doi: 10.1038/s41586-020-2495-2

Simon, N., Raubenheimer, K., Urho, N., Unger, S., Azoulay, D., Farrelly, T., et al. (2021). A binding global agreement to address the life cycle of plastics. *Science* 373 (6550), 43–47. doi: 10.1126/science.abi9010

United Nations Environment Assembly [UNEA] (2022) *Resolution 5/14, end plastic pollution: towards an international legally binding instrument* (Accessed April 7, 2022).

United Nations Environment Programme [UNEP] (2013). *Minamata convention on mercury: Texts and annexes* (Geneva, Switzerland: UNEP Chemicals Branch). Available at: https://www.mercuryconvention.org/en/resources/minamata-convention-mercury-text-and-annexes.

Yale Environment 360 (2019) *The plastics pipeline: A surge of new production is on the way*. Available at: https://e360.yale.edu/features/the-plastics-pipeline-a-surge-of-new-production-is-on-the-way (Accessed June 1, 2022).

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A framework for inland cities to prevent marine debris: A case study from Durham, North Carolina

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Land-based sources of litter are increasingly recognized as significant contributors to marine debris, and rivers can carry debris to the coast from far-inland sources. In this paper, we demonstrate the important role inland cities can play in the marine debris crisis by reducing their own marine debris contributions. Given this role, we provide a framework for inland cities to prevent plastic pollution along with the lessons learned from introducing these strategies in Durham, North Carolina, a mid-sized, inland city that drains to the ocean through the Cape Fear and Neuse River watersheds. This framework guides city officials, resource managers, and community partners on how to characterize the plastic pollution problem in their city by collecting baseline data on plastic waste and litter. This framework also provides practical and equitable solutions for inland cities to address plastic pollution. We recommend that inland cities prioritize policy solutions that reduce waste at the source – to the extent that their state constitutions allow – and to also use authorities for stormwater controls to capture and remove debris as long as litter persists. Replicating this framework in other inland cities opens vast opportunities to manage and reduce marine debris from an often-overlooked source.

KEYWORDS

plastic, waste, pollution, policy, stormwater, marine debris, marine conservation

Introduction

Marine debris, most of which is plastic (Derraik, 2002), is one of the most pressing and challenging environmental threats of our time. Compared to other materials, single-use plastics (e.g., bags, bottles, straws, takeout containers, etc.) are slow to biodegrade in the environment, taking tens to thousands of years depending on the type of plastic and the environmental conditions (Chamas et al., 2020). Much of the plastic that enters the environment accumulates in the oceans, where it chokes and entangles wildlife

(Schuyler et al., 2014; Gall and Thompson, 2015), is a vector for chemical pollutants (Engler, 2012), and breaks up into microplastics and nanoplastics that contaminate the food chain when consumed by fish and other marine organisms (Wang et al., 2020a). The urgency to find solutions for marine plastic pollution is exacerbated by the projected rise in plastic waste generation: in a business-as-usual scenario, the global estimate of mismanaged plastic waste is expected to triple by 2060 (Lebreton and Andrady, 2019).

The United States' role in the marine debris crisis is significant. In 2016, the United States produced 42 million metric tons (MMT) of plastic waste, more than any other country in the world (Law et al., 2020). This ranking is not driven merely by the United States' relatively large population; the United States' per capita plastic waste generation, at 130 kilograms/year, is the highest rate among top plastic waste-generating countries (Law et al., 2020). The wide availability of waste management infrastructure in the United States has not been enough to keep plastic waste from entering the environment. The United States still mismanages 1.13 to 2.24 MMT of plastic waste each year (Law et al., 2020). It is the second largest plastic waste exporter (Brooks et al., 2018) and the third largest contributor of plastic to the coastal environment (Law et al., 2020).

For the United States to seriously curb its contribution to marine pollution, a comprehensive national strategy is needed. Federal statutes enacted to date fall short. The Marine Plastic Pollution Research and Control Act of 1987 prohibits vessels from discharging plastics into jurisdictional waters of the United States but does nothing to address on-land sources of debris. In 2020, Congress took another small step by passing the Save our Seas 2.0 Act, but this statute is inadequate to the task. Instead of reducing plastics at the source, the Act requires research on plastic reuse in consumer products, microfiber pollution, circular polymers, and derelict fishing gear sources and recycling; authorizes funding for domestic clean-up and waste management infrastructure; and encourages international engagement. The Break Free from Plastic Pollution Act of 2021 is the strongest and most aggressive bill introduced to Congress to date to address plastic pollution. Among many directives, the bill places responsibility on producers to manage products after consumer use, phases out single-use products, standardizes labelling for recyclable and compostable products, and limits plastic waste exports to other countries. Whether Congress will pass the Break Free from Plastic Pollution Act into law, however, remains uncertain.

Absent a national plastic reduction strategy, the implementation of reduction policies in the United States has been, and must continue to be, driven by state and local governments. In this paper, we examine how scientific understanding of the geographic sources of marine debris has evolved and argue that local policies must evolve in response. Marine debris is commonly thought to be a coastal problem, and local policies to reduce single-use plastics (i.e., straws, takeout containers, and bags) have been concentrated in coastal areas (The Surfrider Foundation, 2021). However, inland cities have a pivotal role to play in combatting the marine debris crisis by reducing their own contributions of debris to inland waters. Recognizing this critical function, we provide a framework for inland cities to prevent plastic pollution – through effective "upstream" and "downstream" solutions – along with the lessons learned from introducing these strategies in Durham, North Carolina.

Geographic sources of marine debris: (In)land and sea

Riverine plastics

Scientists' understanding of the sources of marine debris has changed since plastic contamination in the ocean was first discovered in the 1970s (Carpenter et al., 1972; Carpenter and Smith, 1972). In early studies, marine plastics were attributed to ocean-based sources, such as shipping vessels (Scott, 1972; Colton et al., 1974; Horsman, 1982), or to discrete wastewater discharges from plastics manufacturing plants (Colton et al., 1974; Kartar et al., 1976). Starting in the late 1980s, the scientific consensus shifted to recognize that most marine debris originates from diffuse, on-land sources, primarily urban runoff and stormwater discharges (Bean, 1987; Gregory, 1991; Faris and Hart, 1994; Nollkaemper, 1994; UNESCO, 1994). Accordingly, focus shifted from ocean-based sources to quantifying and addressing waste mismanagement in coastal communities (Ribic et al., 2010; Jambeck et al., 2015). Jambeck et al. (2015) estimated 8.7 MMT of plastic debris enter the oceans every year from communities within 50 kilometers of the coast.

In the last decade, studies have documented that marine debris can originate farther inland than previous estimates acknowledged, uncovering the role that inland communities play in contributing to, and thus preventing, marine debris. Rivers carry debris to the ocean from inland areas (Lechner et al., 2014; Morritt et al., 2014; Rech et al., 2014; van Emmerik et al., 2019; Duncan et al., 2020), and rivers draining relatively more urbanized watersheds contain higher concentrations of micro- and macro-plastics (Browne et al., 2011; Yonkos et al., 2014; Baldwin et al., 2016; Birch et al., 2020). This is not only because urban areas generate more plastic pollution, but also because plastics are more mobile in urbanized watersheds due to the effectiveness of impervious surfaces and stormwater conveyances at transporting littered plastics (Baldwin et al., 2016).

Scientists are just beginning to understand the magnitude of marine debris contributions from inland areas, but they are finding the contributions are significant. Lebreton et al. (2017) estimated that 1.15 to 2.41 MMT of plastic waste enter the ocean every year from inland areas (>50 km upstream) *via* river transport. Another study on riverine plastic exports generated similar results, estimating that 0.47 to 2.75 MMT of plastic are deposited in the ocean from rivers every year (Schmidt et al., 2017).

Mismanaged plastic exports

River discharges are not the only way that inland cities contribute to marine debris. Plastic waste exports can also become marine debris when mismanaged by the importing country. Beginning in the 1990s, municipal recycling programs profited from exporting plastic waste, as it became costly to process and recycle the low-quality, mixed waste in the United States. From 1988 to 2016, the United States exported 26.7 MMT of plastic waste (Brooks et al., 2018). In 2016 alone, 1.99 MMT of plastic collected by United States' recycling programs were exported (Law et al., 2020). Most of this exported plastic went to countries that mismanage at least 20% of their waste, primarily China. However, since China's National Sword policy went into effect in 2018, banning most plastic waste imports, the recycling market has been severely disrupted. Some municipal recycling programs in the United States shuttered; others redirected their waste exports to countries in Southeast Asia that also have high rates of waste mismanagement, including Thailand, Malaysia, and Vietnam (Jambeck et al., 2015; Law et al., 2020; Wang et al., 2020b). Thus, it is reasonable to assume that a portion of the United States' plastic exports end up as marine debris.

A framework for inland cities to reduce marine debris

A comprehensive solution to the marine debris crisis requires inland cities to reduce their contributions of plastic debris to the environment. However, developing recommendations for local governments presents unique challenges compared to developing a national strategy. Local governments operate under different legal regimes since their powers are granted by the state, and limits on local government authority narrow the policy toolkit. Local governments also have varying access to waste management infrastructure. For example, only 59.5% of the United States' population has access to curbside recycling services (Sustainable Packaging Coalition, 2020-2021). Access to municipal composting to process compostable plastics is rare. Only 7% of the 1,000 largest United States' cities have a municipal curbside composting program that accepts both food waste and compostable packaging (GreenBlue, 2020).

Despite these challenges, we have identified a set of unifying principles for local action and policy. This framework encourages inland cities to 1) collect data prior to policy development, 2) develop policies that reduce waste at the source, and 3) use stormwater controls to capture mismanaged waste (Figure 1). Since 2016, the authors of this perspective have been working with the City of Durham, North Carolina to implement this framework. Durham is a mid-sized (population: 283,506), inland city located 125 miles from the

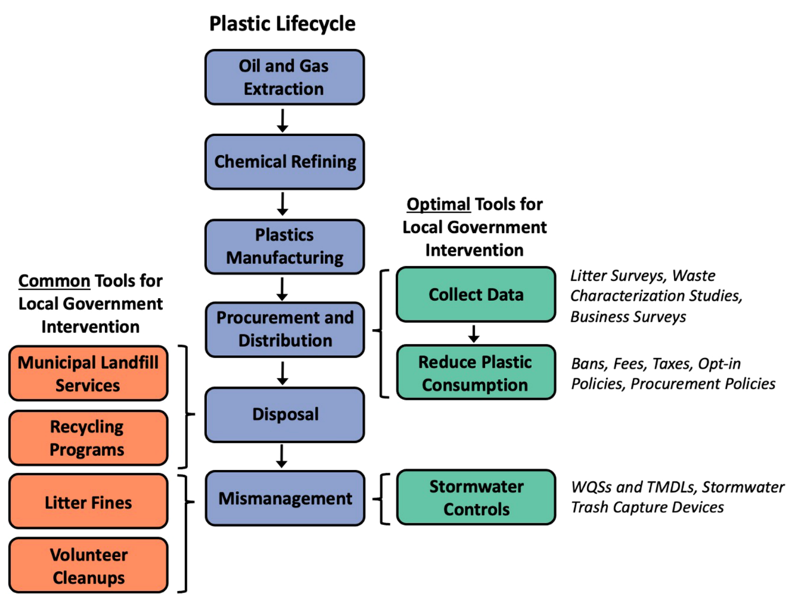

FIGURE 1
The plastics lifecycle shown with the common and optimal policy tools to reduce plastic pollution at the local level.

coast. Durham drains to the Atlantic Ocean through the Neuse River Basin (HUC 030202) and the Cape Fear River Basin (HUC 030300). While our policy work remains in progress as of this writing, our framework and lessons learned are valuable to city officials, resource managers, and community partners in other inland cities.

Collect data to inform policies

One benefit of addressing marine debris at the local level is that policies can be tailored to the needs of an individual community. However, for a policy to be responsive to those needs, data-collection must be done upfront to identify frequently mismanaged plastics and stakeholder concerns. In Durham, we conducted litter surveys, reviewed waste characterization studies, and surveyed local businesses prior to shaping a proposal to require businesses to charge a fee for single-use bags, no matter their material, at the point-of-sale. This proposal was informed by the prevalence of plastic bags and films in Durham's waste and litter streams and widespread support from local businesses for a bag-fee policy.

Litter surveys and waste characterization studies reveal the types and quantities of plastic items that dominate the waste stream and frequently escape to the environment. This information can inform which plastic items a policy should target and provide baseline data for measuring the policy's effectiveness following implementation. In Durham, for example, we documented the number and types of litter in 13 stretches of urban stream, two parks, and along roads of one neighborhood. We categorized over 7,000 pieces of litter and found that plastic film was the most common litter type (39% of litter by number). Municipalities can also conduct a waste characterization study, which identifies the types and amounts of trash the community generates to inform reduction policies and goals. According to Durham's 2015 Waste Characterization Study, ~7% of landfilled waste by weight is non-rigid plastic film, the largest category among plastic waste types.

While litter surveys and waste characterization studies identify the plastic item(s) a policy should target, surveying businesses informs what interventions would be practical for businesses to implement. Prior to developing our proposal, we surveyed local businesses (supermarkets, restaurants, convenience stores, retailers, etc.) on their attitudes about plastic reduction strategies and found that 85% of the 60 responding business supported or were neutral towards a plastic bag fee (Don't Waste Durham, 2021). We also found that businesses were concerned with the cost of alternatives, confirming the need for a policy that would not require businesses to purchase expensive alternatives. Distributing surveys in person provided the opportunity to engage with business owners and managers, who sometimes shared perspectives that went beyond the survey questions. These conversations highlighted the need for city-driven education and outreach to accompany any policy, and for the city to provide free reusable alternatives to low-wealth community members.

Reduce waste at the source

For inland cities, the problems with plastic consumption and pollution extend beyond the downstream effects of marine debris. Limited landfill space, the siting of landfills in low-wealth communities of color (Norton et al., 2007), the costs to clean up litter (Stickel et al., 2013), microplastics in drinking water (Pivokonsky et al., 2018), and contamination of the municipal recycling stream may all be reasons why an inland city government would act. Indeed, all local governments in the United States implement some laws and programs to reduce mismanaged plastics. For example, all 50 states have some form of litter law to discourage litter through fines and penalties (NCSL, 2022). Many local governments provide curbside garbage collection and remove litter along roadways through street sweeping and storm drain cleaning. Local governments also partner with non-profits, such as Keep America Beautiful affiliates and Riverkeepers, to support volunteer cleanups. However, these common interventions manage plastics only at the end-of-life. To maximize the co-benefits of a marine debris policy, we recommend that inland cities shift their policies and programs to intervene as early in the plastic lifecycle as possible by prioritizing reduction at the source (Figure 1). Source reductions should prioritize items that dominate the litter and waste streams.

Reducing plastic use and waste generation has shown to reduce mismanaged plastic waste in models (Jambeck et al., 2015; Lebreton and Andrady, 2019) and in practice. Bans, fees, and taxes have been successful in reducing single-use plastic consumption and mismanagement. Following taxes on single-use bags in Chicago, Illinois (Homonoff et al., 2018) and Montgomery County, Maryland (Homonoff, 2018), fewer customers used single-use bags, more customers used reusable bags or no bag at all, and customers who still used disposable bags used fewer. Diana et al. (2022) found that bans and fees reduced plastic bag consumption by an average of 66% across 27 jurisdictions all over the world. These reductions have translated into less bag waste and fewer bags littered in the environment (Schnurr et al., 2018).

Plastic bag reduction policies are one of the most common local policy tools (Wagner, 2017), likely due to the prevalence of bags and the many problems specific to mismanaged bags. Littered plastic bags are eye-catching and mobile, and easily snag on trees and storm drains. Plastic bags also jam equipment at sorting facilities for recyclables and can be costly to clear from machinery. In Durham, our immediate proposal targets single-use bags only. However, a comprehensive reduction strategy would target all plastics that commonly end up as marine debris, such as utensils, straws, beverage bottles, and take-out containers

(Ocean Conservancy, 2021). The reduction policy toolkit available to local governments is provided in Table 1. Importantly, some municipalities will be limited in what they can do by their state constitutions. In other states, local governments are preempted from regulating plastics (Bell and Todoran, 2022). In such cases, local governments can encourage businesses to voluntarily reduce plastics by recognizing their efforts through a certification or other market-based incentive program. They may also prohibit using municipal funds to buy single-use plastics.

Plastic reduction strategies should be designed to minimize burdens on disadvantaged community members. Low-income households are disproportionately affected by fees and taxes because they spend a larger proportion of their income on food and basic expenses (Johnson, 1999). One way to make fee-policies more equitable is to exempt low-income residents, defined by those who participate in supplemental assistance programs, such as SNAP, WIC, or Medicaid. Another strategy is to distribute and recirculate free reusable items. Local Durham nonprofit and our client, Don't Waste Durham, runs two programs, Boomerang Bags and GreenToGo, that provide and recirculate reusable bags and takeout containers through select retailers. In Durham, we proposed using the revenue from a bag fee policy to support and expand this type of reuse infrastructure to provide low-wealth residents with easily accessible, free alternatives to single-use plastics.

Use stormwater controls to capture leaks

Even with a comprehensive reduction strategy, plastics will escape to the environment. While common strategies implemented by local governments target plastics at the end of life, these strategies largely ignore stormwater- and river-transported plastics, major inland sources of marine debris. However, all local governments have the authority to manage these sources under the federal Clean Water Act. Under this authority, which requires urban areas to obtain pollution control permits for discharges from their Municipal Separate Storm Sewer Systems (MS4), local governments can require trash capture devices such as curb inlet covers, catch basin screens, and in-stream booms to reduce the amount of trash discharged *via* stormwater. In addition, governments can require businesses whose waste is collected by the MS4 to improve their on-site solid waste management practices (Sechley and Nowlin, 2017).

Trash capture devices, especially those installed at the stormwater inlet, can contribute to flooding during heavy storms if not properly maintained. As such, cities must invest in the necessary infrastructure (staff capacity, vacuum trucks, etc.) to ensure devices are regularly cleared. Since our initial 2018 proposal to the City of Durham to amend Durham's Stormwater Management Program Plan to address litter, the City of Durham has begun a pilot study to determine the effectiveness of catch basin collection devices. The city has partnered with a local non-profit, the Ellerbe Creek Watershed Association, to monitor and clean the devices. This type of partnership can lessen the time burden to municipal stormwater offices and may be vitally important to ensure that trash capture devices are well-maintained. In such an arrangement, non-profits will incur additional expenses and should be compensated. In sum, the costs and efforts associated with waste removal underscore the importance of reduction at the source.

TABLE 1 Policy options available to local governments aimed at reducing plastics at the source.

Policy tool	Commonly targeted plastics	Description	Considerations
Bans	Bags, Straws, Stirrers, Polystyrene Foodware	Prohibits retailers from providing single-use item(s).	As has been shown for single-use bags (Taylor and Villas-Boas, 2016; Taylor, 2019; Macintosh et al., 2020), increased consumption of other single-use items can occur unless there is a ban or fee on the alternatives.
Fees and Taxes	Bags, Bottled Beverages, Takeout Containers	Requires retailers to charge a small fee ($0.05-$0.25) for the item(s). Fees may be retained by the retailer, by the government, or shared.	The design of the charge is important for determining its classification as a fee or a tax. For some municipalities, imposing a tax is unlawful without explicit state government approval. If the charge is remitted to the city, it can be classified as a fee if designated to a fund for related purposes, such as waste management, litter clean-ups, or providing reusable items to residents.
Opt-in or "Available Only Upon Request" Policies	Takeout Utensils, Straws, Stirrers, Condiment Packets	Retailer provides item(s) only if a customer specifically requests the item(s).	Opt-in policies reduce unnecessary plastic waste while saving businesses money. They require additional employee training and consumer education to implement.
Procurement Policies	Potentially All Single-use Plastics, including Bags, Foodware, Bottled Beverages, etc.	Prohibits the use of government funds to purchase single-use item(s).	Significant consideration should be given to replacement items to ensure that one environmental harm is not being replaced with another. If replacing plastic with compostable or disposable alternatives, the city must have the appropriate composting or recycling infrastructure to properly manage the waste.

Conclusions

Inland cities contribute significantly to marine debris through river discharges and mismanaged plastic exports. Until an effective national plastic reduction strategy is implemented, local level action is an essential component of a response to the marine debris crisis. The framework presented in this article encourages inland city officials, resource managers, and community partners to 1) collect data prior to policy development, 2) develop policies that reduce waste at the source, and 3) use stormwater controls to capture mismanaged waste. Stakeholder involvement and equity must be a central focus of any plastic reduction strategy to lessen the burden on and respond to the needs of those most affected, especially local businesses and low-wealth residents. Implementing this framework in inland cities across the United States will reduce the problems with marine debris downstream and the problems with plastic waste at home, such as contaminated drinking water, contaminated recycling, landfill space, and litter.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

NL wrote the first draft of the manuscript. MN revised the manuscript several times. Both authors contributed to the conception of the framework and the supporting research. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The Duke Environmental Law and Policy Clinic is an academic, experiential-learning program offered by Duke Law School and open to law students as well as professional degree students from Duke's Nicholas School of the Environment. The Clinic is funded by the Law School. The Clinic teaches the practice of environmental law and policy through formal representation of non-profit clients that seek assistance addressing environmental problems in their respective communities. Under supervision of Clinic faculty, students interact directly with these clients, conduct legal, scientific and policy research on their behalf, provide guidance, and represent their interests in legal, regulatory, and policy settings as appropriate. All services are provided on a pro bono basis. Our article arises from work we and our students have conducted on behalf of Clinic client Don't Waste Durham. Our perspective and distillation of best practices is based on this experience.

Publisher's note

References

Baldwin, A. K., Corsi, S. R., and Mason, S. A. (2016). Plastic debris in 29 great lakes tributaries: Relations to watershed attributes and hydrology. *Environ. Sci. Technol.* 50 (19), 10377–10385. doi: 10.1021/acs.est.6b02917

Bean, M. J. (1987). Legal strategies for reducing persistent plastics in the marine environment. *Mar. Pollut. Bull.* 18 (6), 357–360. doi: 10.1016/S0025-326X(87)80026-7

Bell, L., and Todoran, G. S. (2022). Plastic bag legislation in the united states: influential factors on its creation. *J. Environ. Stud. Sci.* 12 (2), 260–271. doi: 10.1007/s13412-021-00736-8

Birch, Q. T., Potter, P. M., Pinto, P. X., Dionysiou, D. D., and Al-Abed, S. R. (2020). Sources, transport, measurement and impact of nano and microplastics in urban watersheds. *Rev. Environ. Sci. Biotechnol.* 19 (2), 275–336. doi: 10.1007/s11157-020-09529-x

Brooks, A. L., Wang, S., and Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. *Sci. Adv.* 4 (6), eaat0131. doi: 10.1126/sciadv.aat0131

Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., et al. (2011). Accumulation of microplastic on shorelines woldwide: Sources and sinks. *Environ. Sci. Technol.* 45 (21), 9175–9179. doi: 10.1021/es201811s

Carpenter, E. J., Anderson, S. J., Harvey, G. R., Miklas, H. P., and Peck, B. B. (1972). Polystyrene spherules in coastal waters. *Science* 178 (4062), 749–750. doi: 10.1126/science.178.4062.749

Carpenter, E. J., and Smith, K. L. (1972). Plastics on the Sargasso Sea surface. *Science* 175 (4027), 1240–1241. doi: 10.1126/science.175.4027.1240

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., et al. (2020). Degradation rates of plastics in the environment. *ACS Sustain. Chem. Eng.* 8 (9), 3494–3511. doi: 10.1021/acssuschemeng.9b06635

Colton, J. B., Knapp, F. D., and Burns, B. R. (1974). Plastic particles in surface waters of the northwestern Atlantic. *Science* 185 (4150), 491–497. doi: 10.1126/science.185.4150.491

Derraik, J. G. B. (2002). The pollution of the marine environment by plastic debris: a review. *Mar. Pollut. Bull.* 44 (9), 842–852. doi: 10.1016/S0025-326X(02)00220-5

Diana, Z., Vegh, T., Karasik, R., Bering, J., D. Llano Caldas, J., Pickle, A., et al. (2022). The evolving global plastics policy landscape: An inventory and effectiveness review. *Environ. Sci. Policy* 134, 34–45. doi: 10.1016/j.envsci.2022.03.028

Don't Waste Durham (2021) *The cost of single-use plastic bags in Durham, north Carolina*. Available at: http://www.dontwastedurham.org/plastic-waste-prevention-policy (Accessed August 26, 2022).

Duncan, E. M., Davies, A., Brooks, A., Chowdhury, G. W., Godley, B. J., Jambeck, J., et al. (2020). Message in a bottle: Open source technology to track the movement of plastic pollution. *PloS One* 15 (12):1–19. doi: 10.1371/journal.pone.0242459

Engler, R. E. (2012). The complex interaction between marine debris and toxic chemicals in the ocean. *Env. Sci. Technol.* 46 (22), 12302–12315. doi: 10.1021/es3027105

Faris, J., and Hart, K. (1994). *"Seas of debris: a summary of the third international conference on marine debris"*. Alaska Fisheries Science Center, Seattle, WA, United States.

Gall, S. C., and Thompson, R. C. (2015). The impact of debris on marine life. *Mar. pollut. Bull.* 92 (1), 170–179. doi: 10.1016/j.marpolbul.2014.12.041

GreenBlue (2020) *Mapping composting infrastructure and supporting legislation*. Available at: https://greenblue.org/work/compostingmaps/ (Accessed June 29, 2022).

Gregory, M. R. (1991). The hazards of persistent marine pollution: drift plastics and conservation islands. *J. R. Soc N. Z.* 21 (2), 83–100. doi: 10.1080/03036758.1991.10431398

Homonoff, T. A. (2018). Can small incentives have large effects? the impact of taxes versus bonuses on disposable bag use. *Am. Econ. J. Econ. Policy* 10 (4), 177–210. doi: 10.1257/pol.20150261

Homonoff, T., Kao, L., Palmer, D., and Seybolt, C. (2018). *Skipping the bag. assessing the impact of chicago's tax on disposable bags* (University of Chicago-Energy and Environment Lab).

Horsman, P. V. (1982). The amount of garbage pollution from merchant ships. *Mar. pollut. Bull.* 13 (5), 167–169. doi: 10.1016/0025-326X(82)90088-1

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347 (6223), 768–771. doi: 10.1126/science.1260352

Johnson, S. M. (1999). Economics v. equity: do market-based environmental reforms exacerbate environmental injustice. *Wash. Lee. L. Rev.* 56, 111.

Kartar, S., Abou-Seedo, F., and Sainsbury, M. (1976). Polystyrene spherules in the Severn estuary — a progress report. *Mar. Pollut. Bull.* 7, 52. doi: 10.1016/0025-326X(76)90092-8

Law, K. L., Starr, N., Siegler, T. R., Jambeck, J. R., Mallos, N. J., and Leonard, G. H. (2020). The united states' contribution of plastic waste to land and ocean. *Sci. Adv.* 6 (44), 1–7. doi: 10.1126/sciadv.abd0288

Lebreton, L., and Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave. Commun.* 5 (1), 6. doi: 10.1057/s41599-018-0212-7

Lebreton, L., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nat. Commun.* 8 (1), 1–10. doi: 10.1038/ncomms15611

Lechner, A., Keckeis, H., Lumesberger-Loisl, F., Zens, B., Krusch, R., Tritthart, M., et al. (2014). The Danube so colourful: a potpourri of plastic litter outnumbers fish larvae in europe's second largest river. *Environ. Pollut.* 188 (100), 177–181. doi: 10.1016/j.envpol.2014.02.006

Macintosh, A., Simpson, A., Neeman, T., and Dickson, K. (2020). Plastic bag bans: Lessons from the Australian capital territory. *Resour. Conserv. Recy.* 154, 104638. doi: 10.1016/j.resconrec.2019.104638

Morritt, D., Stefanoudis, P. V., Pearce, D., Crimmen, O. A., and Clark, P. F. (2014). Plastic in the Thames: A river runs through it. *Mar. Pollut. Bull.* 78 (1), 196–200. doi: 10.1016/j.marpolbul.2013.10.035

NCSL (2022) *States with littering penalties*. Available at: https://www.ncsl.org/research/environment-and-natural-resources/states-with-littering-penalties.aspx (Accessed June 29, 2022).

Nollkaemper, A. (1994). Land-based discharges of marine debris: From local to global regulation. *Mar. Pollut. Bull.* 28 (11), 649–652. doi: 10.1016/0025-326X(94)90299-2

Norton, J. M., Wing, S., Lipscomb, H. J., Kaufman, J. S., Marshall, S. W., and Cravey, A. J. (2007). Race, wealth, and solid waste facilities in north Carolina. *Environ. Health Perspect.* 115 (9), 1344–1350. doi: 10.1289/ehp.10161

Ocean Conservancy (2021). *International coastal cleanup*.

Pivokonsky, M., Cermakova, L., Novotna, K., Peer, P., Cajthaml, T., and Janda, V. (2018). Occurrence of microplastics in raw and treated drinking water. *Sci. Total. Environ.* 643, 1644–1651. doi: 10.1016/j.scitotenv.2018.08.102

Rech, S., Macaya-Caquilpán, V., Pantoja, J. F., Rivadeneira, M. M., Jofre Madariaga, D., and Thiel, M. (2014). Rivers as a source of marine litter–a study from the SE pacific. *Mar. Pollut. Bull.* 82 (1-2), 66–75. doi: 10.1016/j.marpolbul.2014.03.019

Ribic, C. A., Sheavly, S. B., Rugg, D. J., and Erdmann, E. S. (2010). Trends and drivers of marine debris on the Atlantic coast of the united states 1997–2007. *Mar. pollut. Bull.* 60 (8), 1231–1242. doi: 10.1016/j.marpolbul.2010.03.021

Schmidt, C., Krauth, T., and Wagner, S. (2017). Export of plastic debris by rivers into the Sea. *Environ. Sci. Technol.* 51 (21), 12246–12253. doi: 10.1021/acs.est.7b02368

Schnurr, R. E. J., Alboiu, V., Chaudhary, M., Corbett, R. A., Quanz, M. E., Sankar, K., et al. (2018). Reducing marine pollution from single-use plastics (SUPs): A review. *Mar. Pollut. Bull.* 137, 157–171. doi: 10.1016/j.marpolbul.2018.10.001

Schuyler, Q. A., Wilcox, C., Townsend, K., Hardesty, B. D., and Marshall, N. J. (2014). Mistaken identity? visual similarities of marine debris to natural prey items of sea turtles. *BMC Ecol.* 14 (1), 14. doi: 10.1186/1472-6785-14-14

Scott, P. G. (1972). Plastics packaging and coastal pollution. *Int. J. Environ. Stud.* 3 (1-4), 35–36. doi: 10.1080/00207237208709489

Sechley, T., and Nowlin, M. (2017). An innovative, collaborative approach to addressing the sources of marine debris in north Carolina. *Duke. Envtl. L. Pol'y. F.* 28, 243.

Stickel, B., Jahn, A., and Kier, B. (2013). *Waste in our water: The annual cost to California communities of reducing litter that pollutes our waterways* (San Rafael, CA: Kier Associates).

Sustainable Packaging Coalition (2020-2021). *Centralized study on availability of recycling*.

Taylor, R. L. C. (2019). Bag leakage: The effect of disposable carryout bag regulations on unregulated bags. *J. Environ. Econ. Manage.* 93, 254–271. doi: 10.1016/j.jeem.2019.01.001

Taylor, R. L., and Villas-Boas, S. B. (2016). Bans vs. fees: Disposable carryout bag policies and bag usage. *Appl. Econ. Perspect. Policy* 38 (2), 351–372. doi: 10.1093/aepp/ppv025

The Surfrider Foundation (2021). *"The surfrider foundation's U.S. plastics policy map*.

UNESCO (1994). *"Marine debris: Solid waste management action plan for the wider caribbean"*. UNESCO, France.

van Emmerik, T., Tramoy, R., van Calcar, C., Alligant, S., Treilles, R., Tassin, B., et al. (2019). Seine plastic debris transport tenfolded during increased river discharge. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00642

Wagner, T. P. (2017). Reducing single-use plastic shopping bags in the USA. *Waste. Manage.* 70, 3–12. doi: 10.1016/j.wasman.2017.09.003

Wang, Y.-L., Lee, Y.-H., Chiu, I.-J., Lin, Y.-F., and Chiu, H.-W. (2020a). Potent impact of plastic nanomaterials and micromaterials on the food chain and human health. *Int. J. Mol. Sci.* 21 (5), 1–14. doi: 10.3390/ijms21051727

Wang, C., Zhao, L., Lim, M. K., Chen, W.-Q., and Sutherland, J. W. (2020b). Structure of the global plastic waste trade network and the impact of china's import ban. *Resour. Conserv. Recycl.* 153, 104591. doi: 10.1016/j.resconrec.2019.104591

Yonkos, L. T., Friedel, E. A., Perez-Reyes, A. C., Ghosal, S., and Arthur, C. D. (2014). Microplastics in four estuarine rivers in the Chesapeake bay, U.S.A. *Environ. Sci. Technol.* 48 (24), 14195–14202. doi: 10.1021/es5036317

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The quest for ghost gear in the German Baltic Sea: A team effort between WWF, divers, fisherfolk, and public authorities

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In this pilot project, World Wild Fund for Nature (WWF) Germany works together with regional divers, fisherfolk and public authorities to reduce the impact of lost fishing gear in the Baltic Sea. If not removed, ghost gear poses a threat to the marine environment and wildlife including seabirds, seals, harbour porpoises and fish. Over decades to centuries, lost fishing nets and ropes shed microplastic fibres into the marine environment. Removing this hazard reduces both the risk of entanglement as well as the contamination of the marine foodweb through ingestion of microplastics and associated chemicals. Identifying lost fishing gear in the marine environment poses one of the largest challenges impeding mitigation through gear retrieval operations. Lost gear can be drifting on the surface, in the water column, or can be sunken to the seafloor as a result of material composition, fouling, and entanglement. In the Baltic Sea, ghost gear is located on the seafloor and not visible during visual surface surveys from vessels. Identifying an efficient search methodology was therefore a key aspect of WWF's ghost gear project. After trials with different search and retrieval methodologies, WWF Germany found sonar search technology to be the most efficient technique to locate lost gear on the seafloor. Sound waves avoid the limitations faced by divers or visual cameras in low-visibility environments, and a substantially larger area can be covered. In contrast to diving teams focussing on wreck retrievals, the many nets lost on the seafloor remain unnoticed by divers under most circumstances. A combination of sonar search providing exact GPS positions of suspect ghost gear, diver verification through the WWF Ghostdiver App, point-on retrievals with fishing vessels, and manual sorting for waste management provides an efficient methodology for long-term political implementation of regular lost gear retrieval campaigns.

KEYWORDS

lost fishing gear recovery, sonar search technology, marine plastic litter, hazardous waste, microplastics, abandoned, lost or discarded fishing gear (ALDFG)

Introduction

Lost fishing gear is omnipresent in the seas worldwide. Yet the fractions of fishing-related litter such as nets, ropes, lines and pots differ among the amount of plastic litter observed in the marine environment. In the Northeast Atlantic region, Pham et al. (2014) find between 25 and 30% of plastic litter items on the seafloor and near the surface originating from fisheries. In a recent review, Galgani et al. (2015) report up to 89% of seafloor litter in the Atlantic Ocean to originate from the fishing sector. On the surface of the Great Pacific Gyre, Lebreton et al. (2018) identified 46% of plastic items being composed of nets, ropes and lines. Increasing fractions of beach litter items are composed of fisheries plastic waste when progressing north into the Arctic regions of Europe, with as much as 80% of beach plastic litter originating from fisheries on beaches around Spitsbergen, including heavy fishing nets, ropes, and buoys/fenders (Bergmann et al., 2017).

Even in small numbers, abandoned, lost or discarded fishing gear (ALDFG, UNEP/FAO definition: Macfadyen et al., 2009), commonly called "ghost gear", can cause substantial harm through entanglement and ingestion (Kühn and van Franeker, 2020, and references therein, Werner et al., 2016). Between 2,000 and 12,000 tonnes of fishing gear waste are estimated to enter the European seas each year (Sherrington et al., 2016). The amount entering the Baltic Sea alone is not known, although Predki et al. (2011) estimated between 150 and 450 tonnes entering the Baltic each year from the more extensive fishing effort in the early 2000s. Globally, fishing gear causes entanglement of both commercial and endangered species, and is frequently reported in the media for large cetaceans, e.g., in the Mediterranean where both entanglement in and ingestion of ropes and netting is observed (Fossi et al., 2018). In their recent review, Kühn and van Franeker (2020) find that at least 354 marine species are impacted by entanglement, with 27.4% of seabird species, 39.8% of marine mammal species (71% when seals are considered alone), and all 7 marine turtle species. Although no scientific study was identified for the Baltic Sea, entanglement in ALDFG might affect harbour porpoises, grey and common seals. Stranded whales are occasionally found to contain bundles of netting or ropes in their stomachs, which might have prevented natural feeding activity (Jacobsen et al., 2010). From our observations, entanglement of species in ALDFG in the Baltic Sea is rare in comparison to the impact of active fishing gear, because lost trawl netting made from nylon is bundled up on the seafloor. The dominant source of ALDFG lost in German Baltic waters according to participating fishers today are gillnets, which are considered one of the most hazardous forms of ALDFG (Gilman et al. 2021; Global Ghost Gear Initiative, 2021). Seabirds such as two cormorants and two long-tailed ducks were found in retrieved gillnets in two different locations (Figures 1A, B), where one of the cormorants became entangled within less than 6 days between the ghost net discovery and retrieval. Both gillnets had been overgrown with algae and contained fish skeletons as well as fresh fish and birds, suggesting they had been trapping fauna in the sea for several months.

On sensitive seafloor habitats, smothering degrades the ecosystem. While this has not been investigated in the Baltic Sea, severe disturbance of benthic communities and biogenic reefs are observed in the Mediterranean and Asian coastal seas (Moschino et al., 2019; Kim et al., 2020). Over centuries (Thompson et al., 2004), ALDFG slowly degrades into microplastic fibres. These microplastic fibres are contained in sediments and the water column (e.g., Koelmans et al., 2017) and may be ingested by filter feeders and bottom-dwelling fauna. Microplastic fibres and particles in the marine food web are found to affect the smallest zooplankton down to a depth of 7000m (*Eurythenes plasticus*, Weston et al., 2020) to the largest filter feeders including the large whales in the Mediterranean and the Gulf of Mexico (e.g., Fossi et al., 2012; Fossi et al., 2014a; Fossi et al., 2014b). How much ALDFG contributes to the density of marine mircoplastics is not known. It is paramount to remove ALDFG where possible to mitigate these long-term impacts on the marine ecosystems. In the European Union, the Marine Strategy Framework Directive (MSFD 2008/56/EC) requires Member States to mitigate the impact of plastic litter on the marine environment. Political measures are devised for the Baltic Sea in the HELCOM (Baltic Marine Environment Protection Commission, https://helcom.fi) pressure group on marine litter (https://helcom.fi/action-areas/marine-litterand-noise/marine-litter) and for the North Sea by the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic (https://www.ospar.org, https://www.ospar.org/work-areas/eiha/marine-litter).

FIGURE 1
Impressions of WWF Germany's ghost gear project: **(A)** lost gillnet on the seafloor near Rostock still catching fish and seabirds (© Martin Siegel, WWF); **(B)** same gillnet ghost fishing for several months before its dicsovery with numerous plaice and two cormorants (© Wolf Wichmann, WWF); **(C)** diver verifying a sonar position to be a lost gillnet corresponding to Figure 2B (© Christian Howe, WWF); **(D)** professional diver retrieval of a trawl bundle mixed with other nets and litter (© Christian Howe, WWF); **(E)** the "UEK 12 Bergen" - typical Baltic Sea 17m fishing vessel used for pair trawls – and ghost gear retrievals (© Andrea Stolte, WWF); **(F)** fishers working hard on vessel "SAS 107 Crampas" to get sonar-identified lost gear on board (© Andrea Stolte, WWF); **(G)** gillnet retrieval in Wismar Bay with a 9m gillnetter (© Andrea Stolte, WWF); **(H)** retrieved trawl bundle during removal from the working vessel "Fritz Reuter" with a heavy lifting crane (© Christian Howe, WWF).

In this pilot project, WWF Germany works alongside fisherfolk to mitigate the impacts of lost fishing gear on the Baltic Sea ecosystem. For fisherfolk, gear loss is an economic burden as well as a hazard to fishing grounds. Entanglement in gear lost during previous fishing sets multiplies this hazard, retrieval operations are costly, and catch in ALDFG is lost for commercial use (Brown and Macfadyen, 2007; Mouat et al., 2010; Newman et al., 2015; GESAMP, 2021 and references therein). As an inward sea, any litter entering the Baltic has no escape route. In the 1960-70s, the so-called "cod boom" led to an extensive trawler fishing fleet with a peak of 103 high-sees trawlers in Eastern Germany alone (http://www.rostocker-hochseefischerei.de/schiffe/schiffe.php). GPS positions of wrecks and other obstacles were not available at the time, and conflict between different fisheries can be assumed more common, and – with fishers still used to natural fibre materials - discarding of end-of-life nets before returning to port was not yet considered a problematic practice for the marine environment. Most of the 24 tonnes of ALDFG retrieved during this pilot project were historic netting recovered in the vicinity of Sassnitz harbour, which was one of the largest fishing ports of Eastern Germany. During a similar pilot project in 2015, WWF Poland retrieved 270 tonnes of trawl netting from offshore fishing grounds in Polish waters (WWF Poland, private communication). As ALDFG is one of the most harmful plastic litter for flora, fauna and habitats (Werner et al., 2016), WWF engaged in the development of a methodology that can lead to political implementation of lost gear mitigation measures through state authorities.

Globally, other initiatives such as the Global Ghost Gear Initiative (https://www.ghostgear.org), ghostdiving (https://www.ghostdiving.org), and many smaller, private organisations collect lost fishing gear from sensitive seafloor habitats worldwilde. One of the longest projects is carried out by the Northwest Straits Foundation in Puget Sound, USA, where since 2002, more than 5.800 nets and 6.000 crab pots were removed (https://nwstraitsfoundation.org/derelict-gear). This project utilises sonar technology developed by Fenn Enterprises since more than 25 years, which led to the collaboration for the method development in the German Baltic Sea detailed below. The longest-standing government-led project is organised by the Norwegian Fisheries Directorat since the mid 1980s, where fisherfolk are involved in the retrievals of deep-set gillnets and lobster pots in Norwegian fjords to conserve both the sensitive rocky habitats and the fishing grounds (https://www.fiskeridir.no/English/Fisheries/Marine-litter/Retrieval-of-lost-fishing-gear). In the Baltic Sea, the most consolidated initiative devising lost fishing gear mitigation measures so far was the MARELITT Baltic EU INTERREG project (2016-2019) with partners from four countries, Estonia, Germany, Poland and Sweden, in which WWF Germany was the partner on the German side (https://marelittbaltic.eu).

Since 2014, WWF Germany has developed a methodology to search for, retrieve and find a waste-management solution for lost fishing gear from the Baltic Sea. The pilot project was enabled by private-sector partnerships, the European Union Baltic Sea INTERREG programme, the German Federal Environment Agency, and other organisations (see Sec. 8 for details). From the beginning, WWF Germany was in close exchange with federal and state authorities to ensure a solution that can lead to longterm implementation. The project had several foci: 1) to ensure that mitigation activities reduce harm to the marine environment, 2) to engage local divers in the reporting of lost gear and encourage fisherfolk to participate in retrieval actions, and 3) to establish a method that can be used by state authorities for long-term mitigation of the impacts of ALDFG in the marine environment.

Developing a methodology to mitigate lost fishing gear in the Baltic Sea

Upon gear loss, fisherfolk employ steel hooks, small anchors, or chains with weighted hooks to search for and retrieve the lost gear (Predki et al., 2019, Figures 13,14). When the exact position of gear loss is unknown, this method can be unsuccessful and cause damage to the seafloor habitat. Initially, trials were made using such "search hooks" as employed by fishers to recover gear in the Baltic Sea with knowledge of historic loss hot spots from the fishing sector. This "semi-blind" search, focussing on pre-selected gear loss hot spot areas provided by regional fisherfolk, and the small area coverage with search hooks proved highly inefficient. The ecological impact of these operations has to be considered, as bottom-touching area searches have impacts on the seafloor habitat (Sahlin and Tjensvoll, 2018). Worldwide and in the Baltic Sea, recreational and tech diving teams focus their valuable efforts on cleaning ghost gear from wrecks – both for the benefit of the marine fauna and for the wreck-diving experience. Cutting loose netting from wrecks is beneficial for marine fauna, as fish seek shelter near wrecks and seals and harbour porpoises follow prey, which leads to entanglement of both prey and predator species. In the first project year, WWF Germany cut loose 850kg of netting and ropes from wrecks in a week-long at-sea operation with a team of eight scientific divers. However, the work was physically challenging for the divers and the return for a large amount of effort was comparably limited. From our observations, a large fraction of fishing gear lost over decades in the Baltic Sea is located on the plain seafloor. For instance, the majority of the 24 tonnes of ALDFG retrieved by WWF near Sassnitz, Rügen Island, was located on the sandy seabed, including one trawl bundle with a single weight of 3 tonnes. This is likely due to a mix of discards being common practice several decades ago and netting carried by currents into the quieter, shallow bay areas. Some of these nets are snagged on rocks or sunken anchors, while many are only marginally attached to obstacles or loosely lying on the seabed. With these different methods tested during the first project years, these nets were not discovered, such that WWF Germany decided in 2018 to follow another approach.

The most effective area-search providing environmentally sensitive identification of lost gear on the seafloor was found to be the search with sonar equipment (Figure 2A). High-resolution seafloor sonar scans are not bottom-touching and cover larger areas than is feasible by divers or searches with hooks. With a spatial resolution of a few centimeters, even gillnet sink- and swimlines are detected with side-scan sonar technology (Figures 2B–D). At the same time, sonar data deliver a large number of suspect positions that need to be verified by divers (Figure 1C). This confirmation is necessary to confirm suspect positions as real lost fishing gear or plastic ropes, verify exact GPS locations of the ghost gear and minimise the impact of the spot-on retrieval activity. WWF Germany has developed the "WWF Ghostdiver App" that engages divers in this verification process. Through the app, divers and other sea users can confirm sonar suspect positions in addition to regular reporting of lost gear encountered during independent diver activities. The description of the type and amount of material located on the seafloor, entanglement of animals and hence risk to marine fauna, snatching on obstacles, corrected GPS positions if needed, and images of the object on the seafloor can be transmitted through the app. In return, WWF receives the knowledge of which sonar objects are truly lost fishing gear, ropes and lines. Depending on the size and type (gillnet or trawl segment) of the identified object, this allows efficient retrieval operations with professional diving teams or fishing vessels for the exact type of lost gear that needs to be recovered from the seafloor. Over several years, a database of the amount of lost gear on the seafloor in selected fishing areas can be collected. Retrievals at exact GPS positions and with dedicated equipment avoid further damage of the seafloor and reduce the plastic pollution in the Baltic Sea.

After successful demonstration of the method, it is now the turn of German coastal state authorities to actively implement this measure into a longterm solution with the overarching aim to improve the environmental status of the Baltic Sea. The methodology and the WWF Ghostdiver app can readily be adapted to other sea regions and are presently tested in the Mediterranean.

Methods

WWF Germany has developed environmentally sensitive methods to search for, retrieve and waste manage ALDFG from the Baltic Sea. Being too small to develop lunar tides, the Baltic Sea provides the ideal testing ground with diving times exclusively depending on water depth. In tidally dominated

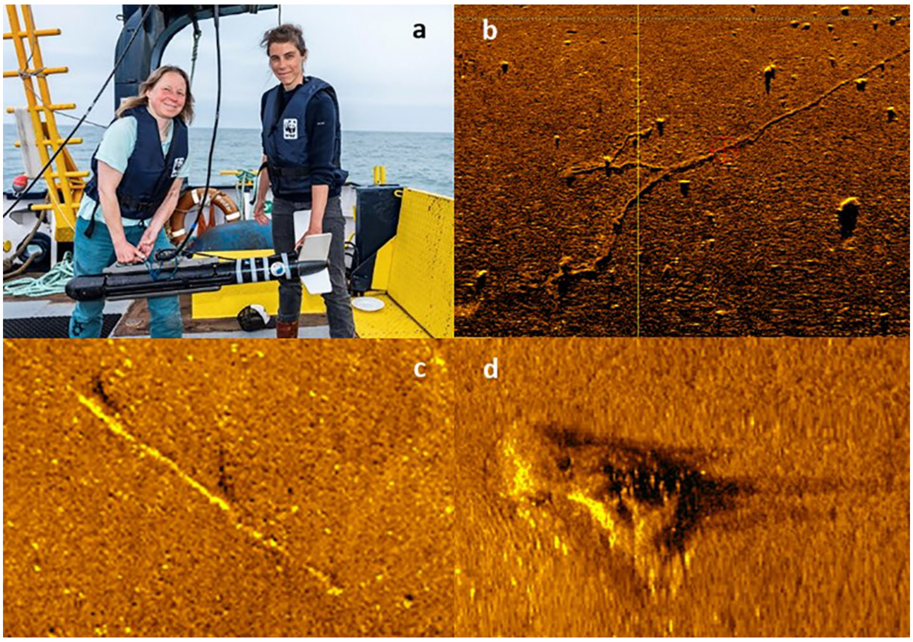

FIGURE 2
Search success using sonar technology: **(A)** project managers Andrea Stolte (left) and Gabriele Dederer (right) before deploying the sonar fish (© Uli Kunz, WWF); **(B–D)** examples of sonar images of two gillnets and one trawl bundle showing its height above the seafloor by its extended sonar shadows (© WWF Germany).

seas such as the North Sea, divers are limited to a narrow time window during the turning points of the tides to avoid the drag from tidal currents. As an inland sea only connected to the North Sea through the narrow straits of the Skagerrak and Kategatt, any pollution entering the Baltic is unlikely to escape into the North Sea or the wider Atlantic.

From the beginning of the project, fisherfolk, in particular trawlers, were employed for WWF retrieval activities and for search trials. Since March 2021, a pilot project is carried out with the support of the Environmental Ministry of Mecklenburg-Western Pomerania (MV). In this project, the key element is to employ some of the remaining fisherfolk to carry out search and retrieval activities at sea.

Search method: In 2018, WWF Germany adapted the sonar search technology for ALDFG developed by Fenn Enterprises and successfully applied by the Northwest Straits Foundation since more than 25 years in the Puget Sound (https://fennenterprises.com/projects). Towing a Marine Sonics ArcExplorer sonar fish with a transponder frequency of 600kHz as low as 5m above the seafloor at a speed of 3-4 knots, the obtained sonar spatial resolution of a few centimetres is sufficient to detect gillnet lines as thin as 1cm and other lines from trawl netting, as well as fish traps (Figure 2). This frequency is outside the hearing range of marine mammels. The swath width of 100m allows us to cover a much larger area in a few hours than could be searched by diving teams. Within the state pilot project, gillnet vessels are employed for sonar excursions in coastal fishing areas. The knowledge of present-day and historic loss areas of local fisherfolk is essential for defining sonar search areas.

Verification: Positions are visually identified during post-processing data analysis and need to be verified by divers. ALDFG suspect GPS positions are published in the WWF Ghostdiver App for verification (Figure 1C). "WWF Ghostdiver" also provides a communication platform to warn recreational divers from the risks of retrieving ALDFG from the seafloor.

Retrievals: Trawl netting is found in the Baltic Sea in large bundles weighing 1-4 tonnes each. Retrievals need to be carried out with fishing or working vessels hosting strong winches or cranes with 2-4 tonnes capacity (Figures 1D, H). Gillnets and traps are removed from shallow coastal waters (depth < 30m) with scientific divers. In contrast to recreational diving organsiations, which carry out the bulk of ghost gear retrievals worldwide on a volunteer basis, WWF retrievals are carried out with professional diving teams and not with recreational divers for efficiency and health risk minimisation. Since the beginning of the state pilot project in Mecklenburg-Western Pomerania, small 8-12m gillnetting vessels are involved in the retrieval of gillnet fragments (Figures 1G). For retrievals of trawl netting, 17m trawlers carry out the lifting of the netting from the seafloor (Figures 1E, F). In the first project year, five fishing companies were engaged for search and retrieval activities activities at sea, which is increasing in each of the two following project years.

Waste management: Recycling was found not to be viable for ALDFG retrieved from the seafloor in the Baltic Sea (Stolte and Schneider, 2018, MARELITT Baltic). Heavy contamination with organic matter, sediments, hazardous lead from sink lines and mixed plastics are prohibiting material recovery. Dismantling and cleaning are cost-, labour- and energy-intensive processes which might cause damage to machinery (Stolte and Schneider, 2018). In Germany, incineration is the only pathway for mixed plastic waste, after lead lines and metals are extracted manually for metal recycling.

Results

A map of all transects covered by the sonar survey is shown in Figure 3, with detailed results given in Table 1. A total of 326 suspect positions were identified in the German coastal state of Schleswig-Holstein (SH), of which 93 were verified until February 2022, and while 40 were ALDFG (success rate 43%), 53 were other objects or active nets (false suspect rate 57%, Table 1). In Mecklenburg-Western Pomerania, near Rügen Island, 83 of 223 sonar positions were verified with 54 ALDFG retrieved before December 2021. In a testbed area (Figure 4) near Neustadt, SH, after 3 days of sonar charting, 22 of 49 sonar positions verified during 5 diving days were confirmed as ALDFG, a success rate of 45%. All 22 nets could be retrieved within 9 recovery days with scientific divers. When all sonar data verified in both states so far are considered, the total success rate is 52%. The sonar success rate has to be compared to the blind search approach commonly used by fisherfolk after loosing a net, where a search hook is dragged over the seafloor in the area where the presumed loss occured. In the case of a trawl net, this can be hundreds of metres from the actual snagging point. In addition, nets lost or discarded decades ago cannot be located in blind searches unless vast areas of seafloor are covered with ground-touching gear, which is ecologically not warranted (Sahlin and Tjensvoll, 2018). Diver searches, on the other hand, focus on wrecks or on submarine structures. The sonar technology fills the gap to cover extended areas and re-locate lost gear in regions where divers are not active. Hence, a success rate of more than 50% is an excellent result for this approach. The 100m sonar swath with a total area of 4425 ha covered in Schleswig-Holstein in coastal fishing areas and 1395 ha in Mecklenburg-Western Pomerania in 45 days at sea, implies that an average area of at least 130 ha per day could be searched. This is a lower limit as no area estimation is available for the 7 days in 2018.

In comparison, scientific divers can search a circumference around a single, expected lost gear GPS position, or carry out a scooter search along a strip. In a circular area around a single point, a one-hour scientific dive covers a radius of approximately 30m and a search area of 2827m^2. Rounding this to 3000m^2, a day search with a rotating scientific diving team of four divers and six dives yields an area coverage of 18.000m^2, less than 2

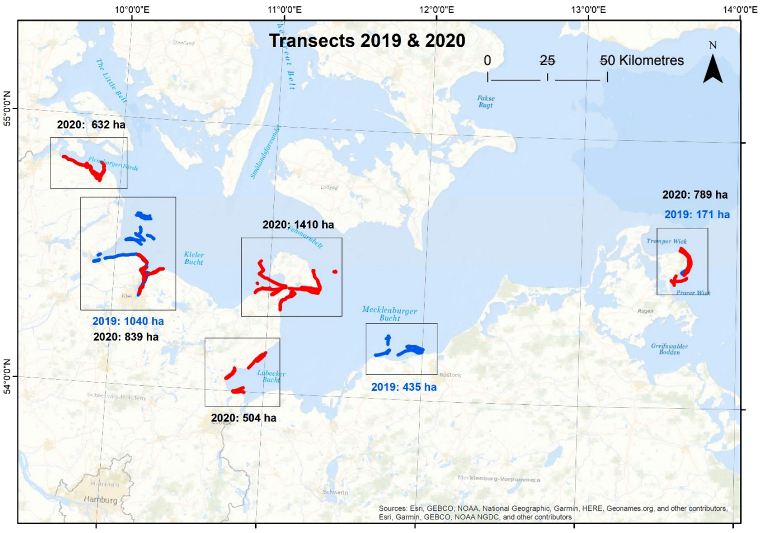

FIGURE 3
Sonar transects in the German Baltic Sea in 2019 and 2020. The area of each search region is given in hectars next to each regional box. The total charted area was 5820 ha on 45 days at sea, as summarised in Table 1. © Jutta Beher, WWF.

TABLE 1 Summary of pilot sonar searches and retrievals carried out during WWF Germany's ghost gear project in the years 2018 to 2021.

Search area	Sonar area (hectar)	Days at Sea	Sonar ALDFG suspect positions	Diver verification	ALDFG (retrieved)
Schleswig-Holstein (SH)					
Bay of Lübeck	504 ha	6	63	49	22 (20)
Fehmarn, Hohwacht Bay	1410 ha	5	61	17	7 (5)
Bay of Kiel & Eckernförde 2020	839 ha	7	56	16	4 (0)
Bay of Flensburg	632 ha	5	67	4	3 (3)
Total SH 2020	**3385 ha**	**23**	**247**	**86**	**36 (28)**
Bay of Kiel & Eckernförde 2019	1040 ha	5	79	7	4 (4)
Total SH 2019-2020	**4425 ha**	**28**	**326**	**93**	**40 (32)**
Mecklenburg-Western Pomerania (MV)					
Rügen Island 2020	789 ha	6	81	48	22 (22)
Rügen Island 2019	171 ha	2	70	29	28 (28)
Rügen Island 2018	–	7	70	6	4 (4)
Bay of Mecklenburg 2019	435 ha	2	2	0	0
Total MV 2018-2020	**1395 ha[a]**	**17**	**223**	**83**	**54 (54)**
Schleswig-Holstein plus Mecklenburg-Western Pomerania combined					
Total Sonar area	**5820 ha**	**45**	**549**	**176**	**94 (86)**
Efficieny / Average	**130 ha / day**			**Percentage of ALDFG among verified suspect positions:**	**52%**

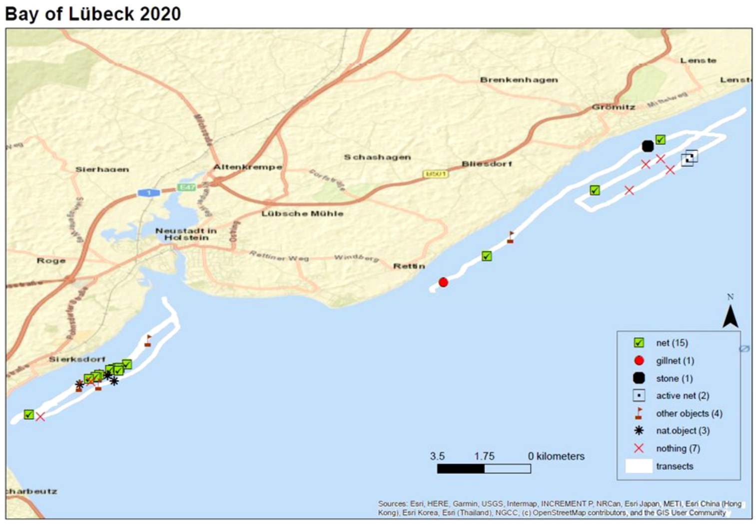

FIGURE 4
Test area in the Bay of Lübeck, with analysis of sonar supect positions, annotated with type of objects found at each suspect location. Sonar charting of 3 days led to 49 suspect positions in this test area, of which 22 were confirmed as lost gear or ropes on 5 scientific diving days. All 22 ALDFG could be retrieved on 9 days of recovery operations. © Jutta Beher, WWF.

hectares or just 1.5% of the average daily sonar area. During a scooter search, divers cover extended swathes. Assuming a strip length of 1km and visibility of 3m as an upper limit in the Baltic summer months implying a strip width of 6m, a single dive might cover 4 strips or an area of 24.000m^2. If six dives can be achieved, a total area of 14.4 ha can be covered in a single day during scooter searches. or just 11% of the average search area of 130 ha/day with the sonar, rendering the sonar charting followed by exactly positioned verification dives the most efficient search methodology. Sonar searches require a smaller team of 2-3 crew, compared to 4-5 members in a scientific diving team, and cover substantially more area, yielding economic benefits. The sonar is operated for 4-5 hours during a typical sonar cruise, implying an efficiency of 4.5h/130 ha or 2 minutes per hectar compared to 25 min/ha for 6 diving hours with scooters. Charter cost depends on vessel type, small diving or gillnetting vessels operate at lower charter and fuel costs than working or larger fishing vessels. Assuming a smaller vessel cost of at most 1000 Euros/130 ha results in a cost efficiency of 8 Euros per hectar. This cost has to be compared to a full scientific diving team with a maximum area coverage of 14.4 ha/day with scooters with at least 3 divers and a skipper, where professional costs depend on country and region and in Germany, are typically between 2000 and 4000 Euros/day or at least 140 Euros per hectar. The sonar search turns out to be 12 times more efficient in time and 17 times more efficient in cost than the diver search, in addition to the larger area covered by sonar charting. Even with a success rate of 50%, the chances are much higher to detect lost gear in fishing areas where exact loss positions are not known.

The ArcExplorer sonar and examples of ghost gear detection images are shown in Figure 2. The efficiency of the WWF methodology allowed 94 ALDFG to be retrieved from the Baltic seafloor during consolidated retrieval campaigns on accurate GPS positions. The 54 collected ALDFG in front of Rügen Island were comprised mainly of trawl netting, mixed with other forms of fisheries and marine litter, including metals, anchors, cables, tires, and gillnets (Figures 1D, F, H). While the focus of the state pilot project lies on retrieval with 9-17m class fishing vessels (Figures 1E-G), working vessels with heavy lifting cranes have to be employed for large trawl nets (Figure 1H). The total wet weight collected during the pilot project from 2014 to 2021 added to at least 24 tonnes. In Schleswig-Holstein, sonar searches were focussing on the coastal fisheries areas operating predominantly gillnets and traps. These smaller and lower-weight items were retrieved from the seafloor by scientific diving teams. While total weight estimates are not available for ALDFG collected in this coastal state, more than 2000m of gillnet fragments could be retrieved.

Discussion and limitations of the method

The methodology to search for and retrieve lost fishing gear from the Baltic Sea was developed to present a concept to state authorities, such as the Federal Environment Agency and the ministries of the German coastal states. In the European Union, all member states are required to achieve "good environmental status" under the Marine Strategy Framework Directive (MSFD

2008/56/EC). Cleaning actions to improve seafloor habitats and remove plastic litter as a longterm hazard to marine species are explicit measures implemented in Germany under the MSFD (BMUB 2016, Annex 1, p. 22). The Baltic Sea, in particular, is a marine environment under severe multiple stressors: temperature inrease as a direct consequence of climate change invokes oxygen-depleted zones potentially affecting fish nursery grounds (see Meier et al., 2022 for an in-depth review), enhanced by severe eutrophication from intensive agriculture causing algae blooms (Löptien and Dietze, 2022; Meier et al., 2022), contamination with toxins from ammunitions and other historic contaminants from at-sea disposal (Vanninen et al., 2020). The high density of shipping routes adds to the pressure on the ecosystem along with decades of intensive fishing without ecological consideration. Relieving the seafloor from lost fishing gear is a comparably low-cost measure to improve seafloor habitats without negative impact for any of the economic sectors, while providing benefits for the fishing sector. Incorporating the fishing sector for mitigation measures has the added benefit that fisheries contribute to the mitigation of longterm negative impacts caused by this industry. In Mecklenburg-Western Pomerania, a state-funded pilot project is already implemented with the aim to evaluate options for regular retrieval operations with fishing vessels. This community case study provides the foundation for the state projects outlined below and the insights necessary for its evalulation.

Despite the success in detecting and retrieving substantial amounts of trawl netting and gillnets, several challenges remain in the presented method.

Challenges of ghost gear in sonar data

The interpretation of sonar data is limited especially in areas with soft seabed habitats, where the sound penetration into the sediments delivers a similar reflectivity signal as a larger lost trawl net. Structured seafloors with rich underwater flora, but also natural structures such as edges and reefs can render data interpretation complex. Most coastal fishing grounds in the German Baltic Sea are located at depths of less than 15 metres, with typical depths of 8-12m. At present, WWF Germany has employed the sonar search methodology mainly in waters shallower than 25m, easy access for recreational and professional divers. The Northwest Straits Foundation and Fenn Enterprises are deploying sonar search technology down to depths of 200m and more in highly structured environments in search for ghost gear, e.g., in the North American Puget Sound (https://nwstraitsfoundation.org/derelict-gear, https://fennenterprises.com/projectsweath). With more than 25 years of experience, their detection rate for lost traps, pots and gillnets is very high. However, teams with less experience in the interpretation of sonar scan data cannot expect to obtain similarly high recovery rates.

Adaptation to other marine environments

In June 2021, WWF Germany in collaboration with the Federal Environment Agency has carried out a pilot search for lost fishing gear in the North Sea. In contrast to the Baltic Sea, high-density gillnet coastal fisheries do not exist along the German North Sea coast. The fisheries regions are much more extended and the swath width of 100m, covering substantially more area than diving teams could, becomes comparably small. No lost trawl netting could be identified in 8 days at sea during this pilot sonar search. The only places where ALDFG suspect positions were identified was 1) the Danish Limfjord, where intense recreational trap and gillnet fisheries spatially overlap with professional fishing activities, and 2) the rocky seabed near Heligoland Island, where one candidate gillnet or lobster trap line position was found in areas closed to professional fishing today, with only lobster pots still permitted. These positions could not be dived immediately due to tidal currents, and hence remain unconfirmed. The sonar scans of the seafloor down to 35 meters depth delivered excellent data quality under the tidal current conditions and in unfavourable weather with 1.5m waves. However, as hardly any ALDFG was found, it needs to be acknowledged that this search methodology has its limitations in extended fishing grounds where ALDFG hot spots are not known. This limitation has to be expected in other seas and ecoregions as well. Because the search area – though less limited in spatial coverage than diver or visual camera searches – with high-resolution sonar technology is limited to a swath width of 100 metres in the case of the 600kHz ArcExplorer, good knowledge of lost gear hot spots from regional fisheries is still a prerequisite for a successful and efficient search and retrieval campaign.

ALDFG as hazardous waste

Waste management remains problematic: ALDFG is delivered to a sorting facility in North Germany (Schleswig-Holstein) for dismantling and metal recycling. The organic and synthetic components are shredded for incineration. With the implementation of the revised European Port Reception Facilities Directive (EU 2019/883), collection of end-of-life fishing gear will be legal common practice in all fishing harbours. The producer responsibility scheme anticipated in the Single-Use Plastics Directive (EU 2019/904) provides a funding concept for waste management of all fishing gears brought into the European market. Both legislations serve to decrease the waste management problem, but do explicitely not account for actively retrieved ALDFG. For this hazardous waste, individual solutions will remain necessary.

WWF Germany's pilot project in the context of other retrieval campaigns

Lost fishing gear is retrieved by a wide range of organisations worldwide, mostly by recreational diving teams. Recreational divers have a strong motivation to keep their diving environment clean, as is evidenced e.g. by the PADI special course "Dive against debris" training divers in marine litter removal (https://www.diveagainstdebris.org). Ghostdiving.org offers dedicated ghost net retrieval trainings for experienced divers, as cutting nets or ropes from the seafloor harbours the risk of entanglement as a severe health risk for divers. For legal reasons, WWF is not entitled to work with recreational divers for retrieval activities because of liability issues. According to German labour law, even voluntary divers working in the context of a WWF-coordinated retrieval activity require insurance through a professional insurance organisation. More importantly, the method was developed to enable regular retrieval programmes by German environmental authorities to implement required measures for cleaner European Seas as set out in the Marine Strategy Framework Directive (2008/56/EC), where working with professional diving teams is required. Recreational divers play a key role in verification dives, where gear is observed but not handled. The WWF Ghostdiver App (see summary below) provides a public communication platform of positions and verification dives. Through verification dives, only confirmed lost gear positions are targeted with larger vessels, saving fuel, time and cost.

In the past years, several organisations, e.g., ghostdiving Germany, have removed nets, ropes and lines from wrecks. As was demonstrated in the first WWF project year, where 850kg of nets and ropes were cut from wrecks, this work is labourious and time-consuming, and the large amounts of lost trawls and gillnets on the seafloor cannot be captured in this way. A common database collecting the amounts of ghost gear retrieved is currently not available. Recreational and professional divers are encouraged to feed data into WWF's Ghostdiver App to monitor ghost gear locations and information, leading to a more complete picture of gear losses and retrieval success. WWF Germany highly values the effort of private organisations to clean ghost gear from wrecks and contribute to a safer, healthier marine environment in the Baltic Sea.

Comparison to North European ALDFG mitigation efforts

The MARELITT Baltic project (2016-2019), with WWF Germany as one of the initialising partners, led to recommendations on the political implementation of ALDFG mitigation measures in the Baltic Sea ecoregion (Tschernij et al., 2019, https://marelittbaltic.eu/documentation). Methodology testing results of search, retrieval, processing and recycling options are incorporated in the pilot project reported here and considered for future longterm implementation in Germany. Clean Nordic Oceans (CNO) is a network of all Scandinavian countries with the aim to reduce the impact of fisheries and other marine litter on the Nordic seas (http://cnogear.org/about). During CNO projects, the retrieval experiences of Scandinavian countries together with fisherfolk and waste management options were investigated. One particularly successful initiative is the dismantling of fishing gear for recycing pathways in the Fisheries Association Norden (https://www.ffnorden.se), where end-of-life netting and lobster pots are separated into individual polymer and metal types and shipped to recyclers. Recycling is only available for pre-cleaned and sorted materials and not an option for most ALDFG (https://plastixglobal.com, https://nofir.no), but the effort of this Swedish fishing community demonstrates the best-practice feasibility of dealing with fishing gear and awareness raising. The Danish fisheries research institute DTU Aqua has recently conducted a sonar, diver and underwater video survey of lost fishing gear in conflict areas (Pedersen et al., 2021). An overabundance of ALDFG in areas with trawl and gillnet gear conflict could not be confirmed for Danish fishing zones, and only two ghost nets were identified. In Nothern Europe, Norway is the only country carrying out regular retrieval operations of ALDFG in North Sea fjords since more than three decades. In Norwegian deep fjord fisheries, lobster pots are costly and from the beginning, fisherfolk have reported lost pots because of their high economic value and the benefit of keeping fishing grounds clean. The implementation in Norway through the Fisheries Directorat serves as a template for longterm implementation of lost gear retrievals in collaboration with the fishing sector (https://www.fiskeridir.no/English/Fisheries/Marine-litter/Retrieval-of-lost-fishing-gear). The key to success is the reporting of loss positions by fishers, which requires that fishers are not discouraged by possible economic consequences of reporting of their own and other fishers lost gear encountered at sea. With the first state-funded project in Mecklenburg-Western Pomerania, fishers are reimbursed for search and retrieval activities for the first time in Germany, encouraging reporting and allowing mitigation of the impact of both historic and contemporary ALDFG and a healthier Baltic Sea seafloor ecosystem.

Outlook and summary

Pilot projects by German coastal states

The European Marine Strategy Framework Directive requires Member States to establish good environmental status in the European Seas (MSFD 2008/56/EC, https://www.msfd.eu). Since 2021, the environmental ministry of Mecklenburg-

Western Pomerania supports the retrieval of ALDFG by WWF in cooperation with fishing vessels. A similar project is planned from 2023 onwards in Schleswig-Holstein. ALDFG has accumulated in the Baltic Sea since the introduction of plastic nylon netting in the 1960s (Predki et al., 2011; Tschernij et al., 2019, see also https://britishseafishing.co.uk/ghost-nets, Radhalekshmy and Nayar, 1973). Most of the trawl netting retrieved during the project is historical from pre-GPS losses, where accurate locations of wrecks and rocks were not available to trawlers. This is confirmed by the retrieving fishers and is evidenced in the mesh width in the case of trawl cod ends, which was narrower 30 years ago than is allowed today, and in fibre abrasion. Gillnets are still lost today during sport boat accidents, storms, and winter ice (see also Richardson et al., 2021 for causes of loss in other European fisheries). Fisheries benefit from clean fishing grounds, but retrievals are costly and the locations of lost nylon gear on the seafloor are unknown. The pilot projects encourage fisherfolk to participate in retrieval activities and reimburse labour, fuel, and harbour costs with the overarching aim to mitigate ALDFG impact. During the first project year, five small fishing enterprises were actively involved with their vessels in the project, either through sonar charting trips or through ALDFG retrieval activities at sea, or both.

Fisherfolk in Germany and throughout Europe are aware of plastic marine litter through passively fished waste supported by state authorities, including at the German Baltic Sea. The Fishing for Litter scheme (F4L), coordinated by NABU and now in its 11th year in Germany, receives wide participation in the fisheries communities. Originally coordinated through KIMO International in the Netherlands (https://fishingforlitter.org), eight countries and one ecoregion participate today. For F4L UK, it was shown that litter collection at sea increases awareness and best practice behaviour among fisherfolk (DEFRA, 2014; Wyles et al., 2019). However, passively fished gear segments tend to be small (Dau et al., 2014), and complete ALDFG is not captured in passively fished waste during regular fishing operations. In contrast, during this pilot project, extended gillnet segments of several hundred meters in length and trawl fragments exceeding one tonne of weight were retrieved by fishing vessels.

WWF Ghostdiver App

The internationalised WWF Ghostdiver App, with support from the Federal Ministry for the Environment through the European Environment Initiative EURENI (https://www.z-u-g.org/aufgaben/europaeische-umweltschutzinitiative), is available since August 2022. In contrast to other digital applications and databases, such as e.g., the recorder app and database for ghost gear of the Global Ghost Gear Initiative (https://www.ghostgear.org), of which WWF is a partner, the Ghostdiver App incorporates the sonar methodology. WWF's app allows recreational divers to participate in the verification of ALDFG suspect sonar positions generated during sonar area searches. In addition, "WWF Ghostdiver" encourages reporting of lost gear and warns divers against self-commissioned retrievals, as these 1) can be a dangerous health and life risk for divers when getting entangled, and 2) state authorities are held responsible for cleaning actions on the seafloor to improve the good environmental status according to the EU Marine Strategy Framework Directive. For the methodology development and the definition of implementation measures for lost gear retrievals, the German Federal Environment Agency has contributed to this effort. With the initiated and announced state projects, Mecklenburg-Western Pomerania and Schleswig-Holstein are accepting responsibility for lost fishing gear, including historic plastic wastes, in their coastal waters for the first time.

The internationalised version of this citizen diver approach can be adapted by NGOs worldwide. Precise, verified positions of ALDFG will enable dedicated retrieval operations coordinated by state or regional authorities. In collaboration with WWF Mediterranean, France and Italy, WWF Germany's methodology was tested in the heavily polluted Mediterranean Sea in late summer 2022 for the first time.

Summary of case study results

With a total of 24 tonnes of ALDFG retrieved near Rügen Island alone from the project initiation in 2014 until the end of 2021, and more than 30 recovered gillnet fragments, the combination of sonar searches, diver verification and retrievals with fishing vessels has turned out highly effective in reducing the impact of ALDFG in the German Baltic Sea. An ecologically viable waste management pathway needs to be established prior to retrieval actions to ensure that ALDFG does not contaminate landfills. Efficient removal fosters healthy seabed habitats and mitigates the long-term contamination of the marine food web with microplastic fibres and particles, from which divers, fisherfolk and seafood consumers benefit in addition to the marine ecosystem.

Data availability statement

The datasets presented in this article are not readily available because the sonar data employed in this article are proprietary to WWF Germany and not publicly available. Requests to access the datasets should be directed to andrea.stolte@wwf.de.

Author contributions

AS: lead project manager, coordination of sonar excursions, retrieval campaigns, waste management solutions, data analysis. GD: co-project manager, lead WWF Ghostdiver app development, coordination of diving activities, sonar and retrieval campaigns. JL: project initiator and project leader 2014-2020, political implementation and initiation of state pilot projects. ML: coordinator WWF Ghostdiver app and data management. MG: development of analysis script for sonar data positions and first data base. CF: sonar trainer and long-term sonar search for ALDFG expert with Northwest Straits Foundation. WF: sonar driver and chief sonar analyst, verification diver and support of retrieval campaigns. CH: sonar driver and scientific diver including sonar data analysis and gear retrieval campaigns. HV: head of WWF international marine centre, funding and overarching project support. SW: lead scientist German Federal Environment Agency on marine litter and ALDFG, expert harm of plastic litter in the marine environment, scientific verification diver.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Bergmann, M., Lutz, B., Tekman, M. B., and Gutow, L. (2017). Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wild life. *Mar. pollut. Bull.* 1251–2, 535–540. doi: 10.1016/j.marpolbul.2017.09.055

BMUB (Federal Ministry of the Environment, Nature Conservation, Construction and Nuclear Safety (2016) *MSFD programme of measures for marine protection in the German parts of the north Sea and the Baltic Sea.* Available at: http://www.meeresschutz.info/berichte-art13.html?file=files/meeresschutz/berichte/art13-massnahmen/MSFD_Art13_Programme_of_Measures_English-Summary.pdf.

British Sea Fishing. Available at: https://britishseafishing.co.uk/ghost-nets (Accessed Aug 12th, 2022).

Brown, J., and Macfadyen, G. (2007). Ghost fishing in European waters: Impacts and management responses. *Mar. Policy* 31 (4), 488–504. doi: 10.1016/j.marpol.2006.10.007

Clean Nordic ocean. Available at: http://cnogear.org/about (Accessed Aug 10th, 2022).

Dau, K., Millat, G., Brandt, T., and Möllmann, N. (2014) Pilotprojekt fishing for litter in Niedersachsen. *Final report 2013 – 2014.* Available at: https://muell-im-meer.de/sites/default/files/2020-08/Fishing%20for%20Litter%20in%20NI_2013-2014-web.pdf.

DEFRA (2014) *Evaluation of the fishing for litter scheme.* Available at: http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=17938.

Dive against debris – PADI training programme. Available at: https://www.diveagainstdebris.org (Accessed Aug 12th, 2022).

European Environment initiative EURENI. Available at: https://www.z-u-g.org/aufgaben/europaeische-umweltschutzinitiative (Accessed Aug 11th, 2022).

Fenn Enterprises Sonar Search & ALDFG removals (2022). Available at: https://fennenterprises.com/projects (Accessed June 21st, 2022).

Fisheries Association Norden, Smögen Municipality, Sweden. Available at: https://www.ffnorden.se (Accessed Aug 10th, 2022).

Fisheries history & high-seas trawler statistics in Eastern Germany. Available at: http://www.rostocker-hochseefischerei.de/schiffe/schiffe.php (Accessed Aug 10th, 2022).

Fossi, M. C., Baini, M., Panti, C., Galli, M., Jiménez, B., Muñoz-Arnan, J., et al. (2014). Are whale sharks exposed to persistent organic pollutants and plastic pollution in the gulf of California (Mexico)? First ecotoxicological investigation using skin biopsies. *Comp. Biochem. Physiol. C Toxicol. Pharmacol.* 199, 48–58. doi: 10.1016/j.cbpc.2017.03.002

Fossi, M. C., Coppola, D., Baini, M., Galli, M., Jiménez, B., Muñoz-Arnan, J., et al. (2014a). Large Filter feeding marine organisms as indicators of microplastic in the pelagic environment: the case studies of the Mediterranean basking shark (Cetorhinus maximus) and fin whale (Balaenoptera physalus). *Mar. Environ. Res.* 100, 17–24. doi: 10.1016/j.marenvres.2014.02.002

Fossi, M. C., Panti, C., Baini, M., and Lavers, J. L. (2018). A review of plastic-associated pressures: Cetaceans of the Mediterranean Sea and Eastern Australian shearwaters as case studies. *Front. Mar. Sci.* 5. doi: 10.3389/fmars.2018.00173

Fossi, M. C., Panti, C., Guerranti, C., Coppola, D., Giannetti, M., Marsili, L., et al (2012). Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (Balaenoptera physalus). *Mar. pollut. Bull.* 64 (11), 2374–2379. doi: 10.1016/j.marpolbul.2012.08.013

Galgani, F., Hanke, G., and Maes, T. (2015). "Global distribution, composition and abundance of marine litter," in *Marine anthropogenic litter.* Eds. M. Bergmann, L. Gutow and M. Klages (Cham, Switzerland: Springer). doi: 10.1007/978-3-319-16510-3_2

GESAMP (2021). "Sea-based sources of marine litter," in *(IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA joint group of experts on the scientific aspects of marine environmental protection).* Ed. K. Gilardi. London: International Maritime Organization (IMO). Available at: http://www.gesamp.org/publications/sea-based-sources-of-marine-litter

Ghostdiving – organisation of recreational divers retrieving ghost gear. Available at: https://www.ghostdiving.org (Accessed Aug 10th, 2022).

Gilman, E., Musyl, M., Suuronen, P., Chaloupka, M., Gorgin, S., Wilson, J., et al. (2021). Highest risk abandoned, lost and discarded fishing gear. *Sci. Rep.* 11, 7195. doi: 10.1038/s41598-021-86123-3

Global Ghost Gear Initiative (GGGI). Available at: https://www.ghostgear.org (Accessed Aug 10th, 2022).

Global Ghost Gear Initiative (GGGI) (2021) *Best practice framework for the management of fishing gear.* Available at: https://www.ghostgear.org/news/2021/6/25/best-practice-framework-refresh.

HELCOM pressure group on marine litter. Available at: https://helcom.fi/action-areas/marine-litter-and-noise/marine-litter (Accessed Aug 10th, 2022).

Helsinki Commission (HELCOM) *Baltic Marine environment protection commission.* Available at: https://helcom.fi (Accessed Aug 10th, 2022).

Jacobsen, J. K., Massey, L., and Gulland, F. (2010). Fatal ingestion of floating net debris by two sperm whales (Physeter macrocephalus). *Mar. pollut. Bull.* 60, 765–767. doi: 10.1016/j.marpolbul.2010.03.008

Kim, D., Kwon, B.-O., and Choi, K. (2020). Impact of derelict fishing gear on the seafloor integrity and benthic communities in the macrotidal flats from northern gyeonggi bay, west coast of Korea. *Sci. Total Environ.* 745, 141168. doi: 10.1016/j.scitotenv.2020.141168

KIMO *International fishing for litter scheme.* Available at: https://fishingforlitter.org/ (Accessed Aug 9th, 2022).

Koelmans, A. A., Kooi, M. L., Kara, L., and van Sebille, E. (2017). All is not lost: deriving a top-down mass budget of plastic at sea. *Environ. Res. Lett.* 12, 114028. doi: 10.1088/1748-9326/aa9500

Kühn, S., and van Franeker, J. A. (2020). Quantitative overview of marine debris ingested by marine megafauna. *Mar. pollut. Bull.* 151, 110858. doi: 10.1016/j.marpolbul.2019.110858

Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Atiken, J., Marthouse, R., et al. (2018). Evidence that the great pacific garbage patch is rapidly accumulating plastic. *Sci. Rep.* 8, 4666. doi: 10.1038/s41598-018-22939-w

Löptien, U., and Dietze, H. (2022). Retracing cyanobacteria blooms in the Baltic Sea. *Sci. Rep.* 12, 10873. doi: 10.1038/s41598-022-14880-w

Macfadyen, G., Huntington, T., Cappell, R. UNEP/FAO, FAO FISHERIES AND AQUACULTURE TECHNICAL PAPER and UNEP REGIONAL SEAS REPORTS AND STUDIES (2009). *Abandoned, lost or otherwise discarded fishing gear.* FAO, Rome: UNEP.

MARELITT *Baltic Project reports.* Available at: https://marelittbaltic.eu/documentation (Accessed Aug 9th, 2022).

Marine strategy framework directive. Available at: https://www.msfd.eu (Accessed Aug 15th, 2022).

Meier Markus, H. E., Kniebusch, M., Dieterich, C., Gröger, M., Zorita, E., Elmgren, R., et al. (2022). Climate change in the Baltic Sea region: A summary. *Earth Syst. Dynam.* 13, 457–593. doi: 10.5194/esd-13-457-2022

Moschino, V., Riccato, F., Fiorin, R., Nesto, N., Picone, M., Boldrin, A., et al. (2019). Is derelict fishing gear impacting the biodiversity of the northern Adriatic Sea? an answer from unique biogenic reefs. *Sci. Total Environ.* 663, 387–399. doi: 10.1016/j.scitotenv.2019.01.363

Mouat, J., Lozano, L., Rebeca, B., Hannah, KIMO (2010) *Economic impacts of marine litter.* Available at: https://www.kimointernational.org/wp/wp-content/uploads/2017/09/KIMO_Economic-Impacts-of-Marine-Litter.pdf.

Newman, S., Watkins, E., Farmer, A., ten Brink, P., and Schweitzer, J.-P. (2015). "The economics of marine litter," in *Marine anthropogenic litter.* Eds. M. Bergmann, L. Gutow and M. Klages (Springer, Cham). doi: 10.1007/978-3-319-16510-3_14

NOFIR *Recycling of end-of-life fishing gear.* Available at: https://nofir.no (Accessed Aug 15th, 2022).

Northwest Straits Foundation. Available at: https://nwstraitsfoundation.org/https://nwstraitsfoundation.org/derelict-gear (Accessed June 21st, 2022).

Norwegian Fisheries Directorat lost gear retrieval campaigns. Available at: https://www.fiskeridir.no/English/Fisheries/Marine-litter/Retrieval-of-lost-fishing-gear (Accessed Aug 10th, 2022).

OSPAR *Convention for the protection of the marine environment of the north-East Atlantic.* Available at: https://www.ospar.org/work-areas/eiha/marine-litter (Accessed Aug 10th, 2022).

Pedersen, E. M., Andersen, N. G., Egekvist, J., Nielsen, A., Olsen, J., Fletcher, T., et al. (2021). Ghost nets in Danish waters. DTU Aqua Report No.394-2021. *Natl. Institute Aquat. Resour.* Technical University of Denmark. 83 pp. Available at: https://orbit.dtu.dk/files/272867717/394_2021_Ghost_nets_in_Danish_waters.pdf

Pham, C. K., Ramirez-Llodra, E., Alt, C. H. S., Amaro, T., Bergmann, M., Canals, M., et al. (2014). Marine litter distribution and density in European seas, from the shelves to deep basins. *PloS One* 9 (4), e95839. doi: 10.1371/journal.pone.0095839

Plastix Global *Recycling of end-of-life fishing gear and other litter.* Available at: https://plastixglobal.com (Accessed Aug 15th, 2022).

Prędki, P., Kalinowska, M., Migdał, S. WWF Poland (2019) *MARELITT Baltic report 1: Derelict fishing gear mapping and retrieval methodologies.* Available at: https://www.marelittbaltic.eu/documentation.

Predki, P., Kasperek, Stanisław, Hac, B., Stanuch, K., Szulc, M. WWF Poland (2011) *Ecological effects on ghost net retrieval in the Baltic sea. BalticSea2020, pilot project: Collecting ghost nets final project report*. Available at: https://www.balticsea2020.org/english/alla-projekt/rovfisken/fishery-completed-projects/214-collecting-ghost-nets-in-the-baltic-sea

Radhalekshmy, K., and Gopalan Nayar, S. (1973). Synthetic fibres for fishing gear. fishery technology. *Fish. Institute India*. 142–165. Available at: https://aquadocs.org/mapping/18232/1/FT10.2_142.pdf

Richardson, K., Hardesty, B. D., Vince, J. Z., and Wilcox, C. (2021). Global causes, drivers, and prevention measures for lost fishing gear. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.690447

Sahlin, J., and Tjensvoll, I. (2018) *Environmental impact assessment: Retrieval of derelict fishing gear from the Baltic sea. MARELITT Baltic project report no. 9*. Available at: https://www.marelittbaltic.eu/documentation.

Sherrington, C., Darrah, C., Hann, S., Cole, G., and Corbin, M. (2016) *Study to support the development of measures to combat a range of marine litter sources. report for the European commission DG environment*. Available at: https://www.eunomia.co.uk/reports-tools/study-to-support-the-development-of-measures-to-combat-a-range-of-marine-litter-sources.

Stolte, A., and Schneider, F. (2018) *Recycling options for derelict fishing gear. MARELITT Baltic project report no. 5*. Available at: https://www.marelittbaltic.eu/documentation.

Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., Steven, J., et al. (2004). Lost at Sea: Where is all the plastic? *Sci. 304 Issue* 5672, 838. doi: 10.1126/science.1094559

Tschernij, V., Press, M., Migdal, S., Stolte, A., and Lamp, J. (2019). *The Baltic Sea blueprint, final report of the MARELITT Baltic EU INTERREG project*. Available at: https://marelittbaltic.eu/documentation.

Vanninen, P., Östin, A., Bełdowski, J., Pedersen, E. A., Söderström, M., Szubska, M., et al. (2020). Exposure status of sea-dumped chemical warfare agents in the Baltic Sea. *Mar. Environ. Res.* 161, 105112. doi: 10.1016/j.marenvres.2020.105112

Werner, S., Budziak, A., van Franeker, J. A., Galgani, F., Hanke, G., Maes, T., et al. (2016). *Harm caused by marine litter; European commission, joint research centre, marine strategie framework directive working group on marine litter - thematic report*. Available at: https://data.europa.eu/doi/10.2788/690366.

Weston, J. N.J., Carrillo-Barragan, P., Linley, T. D., Reid, W. D.K., and Jamieson, A. J. (2020). New species of eurythenes from hadal depths of the Mariana trench, pacific ocean (Crustacea: Amphipoda). *Zootaxa* 4748, 1. doi: 10.11646/zootaxa.4748.1.9

Wyles, K. J., Pahl, S., Carroll, L., and Thompson, R. C. (2019). An evaluation of the fishing for litter (FFL) scheme in the UK in terms of attitudes, behavior, barriers and opportunities. *Mar. pollut. Bull.* 144, 48–60. doi: 10.1016/j.marpolbul.2019.04.035

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A transdisciplinary approach to reducing global plastic pollution

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Introduction

Plastic waste is ubiquitous in the environment – it can be found in sediments (Brandon et al., 2019), the atmosphere (Brahney et al., 2020; Evangeliou et al., 2020; Brahney et al., 2021), polar ice (Materić et al., 2022), the oceans (Eriksen et al., 2014; Fischer et al., 2015; Courtene-Jones et al., 2021), the human body (Ragusa et al., 2021; Zhang et al., 2021; Leslie et al., 2022), and in organisms across taxa. Without a new approach, about 710 million metric tons of plastics will enter the environment between 2016 and 2040 (Lau et al., 2020), leading to negative repercussions at all levels of biological organization (Bucci et al., 2020).

Global plastics production without sufficient waste management constitutes an "uncontrolled experiment" by humanity (Geyer et al., 2017). Based on trends in plastics production, plastics entering the environment, unwanted impacts on Earth system processes, and insufficient monitoring and safety assessment, Persson et al. (2022) assert that society has exceeded the planetary boundary for plastics. Though scientists are still determining proper control variables to measure the exceedance of this planetary boundary, immediate action is needed (Lau et al., 2020; Persson et al., 2022). Consistent with research needs (Villarrubia-Gómez et al., 2018; Persson et al., 2022), this article aims to 1) summarize the physical and chemical burdens posed by plastic pollution, focusing on the marine environment and society; 2) utilize the planetary boundaries approach as a call-to-action for global protection; and 3) suggest novel interventions to reduce plastic pollution, organized for the first time to our knowledge, by the four pathways toward global sustainability (Folke et al., 2021). We focus on the marine environment and society to understand impacts from plastics' source, society, to a major sink – the ocean (Weiss et al., 2021).

Plastics, plastics, everywhere

Plastics are synthetic organic polymers that provide many societal benefits (Andrady and Neal, 2009). Plastics are categorized by chemical/material properties and size. Macroplastics are >5 mm^3 and include everyday items (*e.g.*, furniture, textiles) (Khalid Ageel et al., 2022), fishing gear (Valderrama Ballesteros et al., 2018; Kuczenski et al., 2022), roads (Evangeliou et al., 2020; Brahney et al., 2021), pipes (Al-Malack, 2001), housing insulation (Huang and Tsuang, 2014), and paints (Dibke et al., 2021; Paruta et al., 2022) – plastics are ubiquitous.

Microplastics are < 5 mm^3 (Arthur et al., 2009). Primary microplastics are intentionally produced (Rochman et al., 2019) and include pre-production pellets, synthetic turf (Thomas et al., 2019), and microbeads (Rochman et al., 2015). Secondary microplastics are generated through use or weathering (*e.g.*, tire wear, microfibers) (Jahnke et al., 2017; Sobhani et al., 2020). Some ship hull coatings (Dibke et al., 2021; Turner, 2021) and biodegradable plastics (Wei et al., 2021) are engineered to produce microplastics.

The physical and chemical burdens of marine plastic pollution

Microplastics enter the food web at all trophic levels (Cole et al., 2013; Desforges et al., 2015; Cox et al., 2019). Plastic ingestion can lead to abrasion, scarring (Neilson et al., 2009), perforation (Brandão et al., 2011; Wilcox et al., 2018), dismemberment (Law, 2017), restricted mobility (Neilson et al., 2009), suffocation (Gregory, 2009), and gastrointestinal obstruction (Stamper et al., 2009). Microplastics and nanoplastics (<100 nm) internalized *via* respiration or ingestion may translocate within the body (Browne et al., 2013; Pitt et al., 2018; Messinetti et al., 2019; Zeytin et al., 2020) and transfer across trophic levels (Nelms et al., 2018; Athey et al., 2020). Plastics ingestion and translocation may ultimately result in death (Bucci et al., 2020). Susceptibility depends on an animal's life history, foraging ecology, and behavior, as well as plastics' chemical composition, size, shape, and distribution (Allen et al., 2017; Savoca et al., 2017; Bucci et al., 2020; Diana et al., 2020).

At least 2,400 of the 10,000 compounds associated with plastics are toxins, endocrine disruptors, teratogens, or carcinogens (Hahladakis et al., 2018; Groh et al., 2019; Wiesinger et al., 2021). Depending on environmental conditions and chemical properties, plastics can leach plasticizers, contaminants, and proprietary compounds that are toxic to marine larvae (Li et al., 2016; Ward et al., 2022), impair embryonic development in fish, sea urchin, and mussels (Feng et al., 2012; Nobre et al., 2015; Gandara e Silva et al., 2016), and decrease the growth and photosynthetic capacity of important marine cyanobacteria (Tetu et al., 2019).

Proprietary organotins are used to produce certain plastics (e.g., polyesters, polyvinyl chloride) (Piver, 1973). Organotins are acutely toxic to marine animals at low concentrations (micrograms/liter), chronically toxic at lower concentrations (tens of nanograms/liter), and teratogenic and endocrine disrupting at very low levels (<10 nanograms/liter) (McClellan-Green et al., 2006). Plastics can adsorb environmental pollutants (*e.g.*, heavy metals, persistent organic pollutants) (Rochman et al., 2013; Rochman et al., 2014), which may undergo trophic transfer (Athey et al., 2020). Society is not keeping pace with the safety assessments needed for chemicals associated with plastics (Wiesinger et al., 2021).

The societal burden of plastic pollution: Human health and environmental justice

Microplastics have been reported in human lung tissue (Amato-Lourenço et al., 2021), stool and colectomy samples (Schwabl et al., 2019; Ibrahim et al., 2021), blood (Leslie et al., 2022), and placentas (Ragusa et al., 2021). Plastics impact humans health across levels of biological organization (Morrison et al., 2022), including molecular and cellular processes (Banerjee and Shelver, 2021), tissue and organ systems (Wright and Kelly, 2017), and physiological responses (Karbalaei et al., 2018). Studies characterizing plastics' impact on human health are preliminary and primarily rely on laboratory experiments that simplify real-world exposures (WHO, 2022).

Marginalized communities are disproportionately exposed to plastic-associated pollutants (Calafat et al., 2008), which has recently received high-profile attention, including from the Biden administration in the United States (U.S.) (Singer, 2011; Keehan, 2018; Castellon, 2021). For example, "Cancer Alley" in Louisiana is an industrialized corridor of concentrated petrochemical and plastics manufacturing industries (U.S. EPA, 2014; Terrell and James, 2020). Residents have an increased cancer risk from air pollution compared to 95% of the U.S. population (U.S. EPA, 2014; Terrell and James, 2020). Over 20% of Cancer Alley residents live in poverty (Terrell and James, 2020), while the U.S. average in 2020 was 11.4%

(Census.gov, 2022). Other environmental injustices include high-income countries exporting plastic waste to lower-income countries (Brooks et al., 2018; Kaza et al., 2018; Law et al., 2020), landfill citing locations (Bullard, 2018), impacts to indigenous peoples (*e.g.*, land take, ecosystem destruction) (UNEP, 2021a), and occupational hazards to waste pickers (UNEP, 2021a). Marginalized communities often live and work in unsafe conditions due to exposure to transboundary plastic-associated pollutants.

Discussion

Here we detail interventions to reduce plastic pollution (Figure 1), which are organized for the first time (to our knowledge) by the four pathways toward global sustainability (Folke et al., 2021). This framework incorporates the interconnectedness of humans and nature to promote resilient, sustainable change (Folke et al., 2021). We focus on interventions infrequently discussed in the scientific literature because further innovation is needed to reduce plastic waste (Lau et al., 2020). Interventions should undergo small-scale experimentation to inform change at broader levels of governance (Folke et al., 2021). For this study, a team of interdisciplinary plastic pollution researchers selected interventions through discussion and review.

Pathway 1: "Recognize and act on the fact that societal development is embedded in and critically dependent on the biosphere" (Folke et al., 2021).

I. *Raise public awareness about major sources of microplastics*. Scientists recently found that paints (Dibke et al., 2021; Turner, 2021) and roads (Evangeliou et al., 2020) are significant microplastics sources (Lau et al., 2020; Paruta et al., 2022). Nongovernmental organizations should run campaigns or outreach programs to raise public awareness. Although non-plastic alternatives may not be available (or widespread) yet for paints and roads, awareness may help to spur action (*e.g.*, research and development grants for alternatives). For example, social norms contributed to the voluntary phaseout of plastic microbeads in personal care products (Dauvergne, 2018a).

II. *Create transparent disclosure systems*. Management systems that provide transparency and accountability for the plastics value chain should be created, building on the Plastic Disclosure Project (2022). Corporate

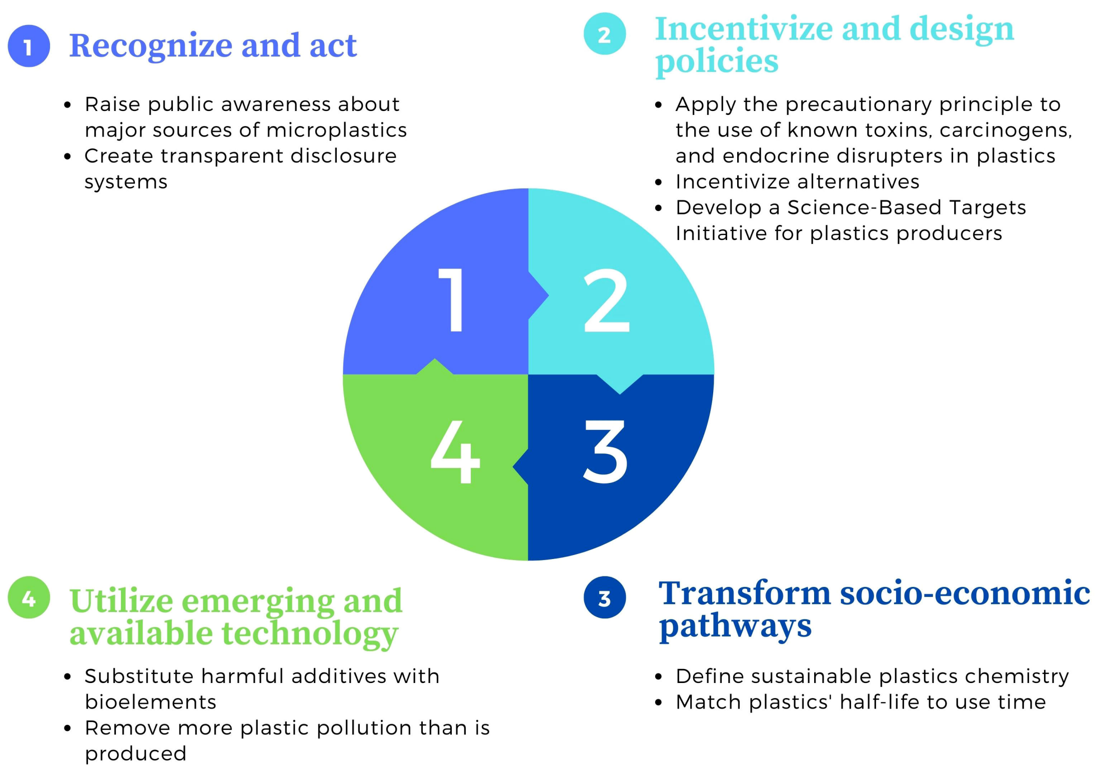

FIGURE 1
Suggested interventions organized by the four pathways toward global sustainability developed by Folke et al. (2021).

disclosures may accelerate science-based policy by reducing the opaqueness of global supply chains (Dauvergne, 2018b).

Pathway 2: "Create incentives and design policies that enable societies to collaborate towards just and sustainable futures within planetary boundaries" (Folke et al., 2021).

I. *Apply the precautionary principle to the use of known toxins, carcinogens, and endocrine disrupters in plastics.* Policies should require independent labs to test additives with unknown environmental and human health impacts before use, similar to the European Commission Regulation No 1223/2009 for cosmetics (EC, 2009). Findings should be shared publicly, potentially reducing the chances of regrettable substitution.

II. *Incentivize alternatives.* Policies that tax plastic products nudge consumer behavior to avoid plastics rather than to reflect its' social cost (Rivers et al., 2017; Mogomotsi et al., 2019; Diana et al., 2022). Because determining plastics' social cost is difficult, plastic should be priced at an estimate of the price necessary to meet plastics reduction targets by making alternatives more cost-effective (Monast and Virdin, 2022). Further investment should promote reusable alternatives. Governments should consider reducing perverse incentives (Sterner, 2003), such as subsidies or tax exemptions supporting unnecessary, problematic, or harmful plastics (UNEP, 2021b).

III. *Develop a Science-Based Targets Initiative for plastics producers.* Modeled off the Science-Based Targets Initiative (2021) for greenhouse gases, companies should adopt sector-specific targets backed by independent scientists to reduce plastic pollution. Targets should be specific, measurable, assignable, realistic, time-related (Doran, 1981), and adaptive.

Pathway 3: "Transform the current pathways of social, economic, cultural development into financially incentivized stewardship of human actions that enhance the resilience of the biosphere" (Folke et al., 2021).

I. *Define sustainable plastics chemistry.* Stakeholders should contribute to defining sustainable chemistry (Hogue, 2019) to inform safer plastics production (Anastas et al., 2021). Financial incentives could incentivize safer plastics production.

II. *Match plastics' half-life to use time.* Governments should subsidize products that match plastic's half-life to its approximate use time. For example, a plastic bag has a half-life of 4.6 years when buried on land (Chamas et al., 2020) but may only be used for hours. Measurement and reporting of plastics degradation time, microplastic generation, and degradation products should be standardized.

Pathway 4: "Make active use of emerging and converging technologies for enabling the societal stewardship transformation" (Folke et al., 2021).

I. *Substitute harmful additives with bioelements.* Biologically compatible elements (*i.e.*, bioelements) should be used to generate polymers (Gadomska-Gajadhur and Ruśkowski, 2020) because biological systems use and maintain these molecules. Substantial removal of non-biocompatible compounds before selling a product should be required. Financial incentives could improve affordability.

II. *Remove more plastic pollution than is produced.* Similar to the CEO Water Mandate, which dictates a net positive impact on stressed watersheds (UN Global Compact, 2022), a voluntary program (van't Veld and Kotchen, 2011) should be developed that requires companies to responsibly clean-up an excess of the plastic types produced. Plastic types should be organized by recycling category, a measure (e.g., weight per surface area), or product types. Clean-ups that utilize technologies to collect marine debris (Schmaltz et al., 2020; Dijkstra et al., 2021) should minimize bycatch and ecological impacts (Falk-Andersson et al., 2020). Recovered plastics should be recycled, repurposed, bioremediated (Sheth et al., 2019), or stored responsibly. This program may disincentivize unnecessary plastics production because plastics clean-up can be difficult and costly (Cordier and Uehara, 2019; Falk-Andersson et al., 2020). Monitoring and enforcement should supplement the program.

Conclusions

Society has exceeded the planetary boundary for plastics – this can result in irreversible damage to the marine environment and human health due to physical and chemical burdens. The enormity of the problem and the remaining uncertainties of its effects should not deter us from action. Rather, we should redouble our efforts by connecting with experts across fields through open communication and a shared commitment to solutions. We must incorporate diverse viewpoints, including industry representatives and experts who are geographically distributed and be unafraid to test innovative approaches. This article shares novel strategies to add to the growing discourse (e.g., Bergmann et al., 2022; Zhu and Rochman, 2022) on tools to consider as we draft an international treaty to reduce plastic pollution (Simon et al., 2021). Through extensive cross-sector and transdisciplinary collaboration and transboundary coordination, society can begin to pave the way toward global plastics sustainability.

Author contributions

ZD, DR, JV, JS and MD-D. conceived of the article. ZD, DR, MD-D, JV, EH-S, GM, JS, JP, KC, MM and RK contributed to writing the article. All authors contributed to the article and approved the submitted version.

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References

Allen, A. S., Seymour, A. C., and Rittschof, D. (2017). Chemoreception drives plastic consumption in a hard coral. *Mar. pollut. Bull.* 124, 198–205. doi: 10.1016/j.marpolbul.2017.07.030

Al-Malack, M. H. (2001). Migration of lead from unplasticized polyvinyl chloride pipes. *J. Hazard Mater* 82, 263–274. doi: 10.1016/s0304-3894(00)00366-6

Amato-Lourenço, L. F., Carvalho-Oliveira, R., Júnior, G. R., dos Santos Galvão, L., Ando, R. A., and Mauad, T. (2021). Presence of airborne microplastics in human lung tissue. *J. Hazardous Materials* 416, 126124. doi: 10.1016/j.jhazmat.2021.126124

Anastas, P. T., Saltzberg, M., and Subramaniam, B. (2021). Plastics are not bad. bad plastics are bad. *ACS Sustain. Chem. Eng.* 9, 9150–9150. doi: 10.1021/acssuschemeng.1c03046

Andrady, A. L., and Neal, M. A. (2009). Applications and societal benefits of plastics. *Philos. Trans. R Soc. Lond B Biol. Sci.* 364, 1977–1984. doi: 10.1098/rstb.2008.0304

Arthur, C., Baker, J., and Bamford, H. (2009) *Proceedings of the international workshop on the occurrence, effects, and fate of microplastic marine debris* (National Oceanic and Atmospheric Administration). Available at: https://marinedebris.noaa.gov/sites/default/files/publications-files/TM_NOS-ORR_30.pdf (Accessed March 5, 2020).

Athey, S. N., Albotra, S. D., Gordon, C. A., Monteleone, B., Seaton, P., Andrady, A. L., et al. (2020). Trophic transfer of microplastics in an estuarine food chain and the effects of a sorbed legacy pollutant. *Limnol. Oceanogr. Lett.* 5, 154–162. doi: 10.1002/lol2.10130

Banerjee, A., and Shelver, W. L. (2021). Micro- and nanoplastic induced cellular toxicity in mammals: A review. *Sci. Total Environ.* 755, 142518. doi: 10.1016/j.scitotenv.2020.142518

Bergmann, M., Almroth, B. C., Brander, S. M., Dey, T., Green, D. S., Gundogdu, S., et al. (2022). A global plastic treaty must cap production. *Science* 376, 469–470. doi: 10.1126/science.abq0082

Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., and Sukumaran, S. (2020). Plastic rain in protected areas of the united states. *Science* 368, 1257–1260. doi: 10.1126/science.aaz5819

Brahney, J., Mahowald, N., Prank, M., Cornwell, G., Klimont, Z., Matsui, H., et al. (2021). Constraining the atmospheric limb of the plastic cycle. *Proc. Natl. Acad. Sci. U.S.A.* 118, e2020719118. doi: 10.1073/pnas.2020719118

Brandão, M. L., Braga, K. M., and Luque, J. L. (2011). Marine debris ingestion by magellanic penguins, spheniscus magellanicus (Aves: Sphenisciformes), from the Brazilian coastal zone. *Mar. Pollut. Bull.* 62, 2246–2249. doi: 10.1016/j.marpolbul.2011.07.016

Brandon, J. A., Jones, W., and Ohman, M. D. (2019). Multidecadal increase in plastic particles in coastal ocean sediments. *Sci. Adv.* 5, eaax0587. doi: 10.1126/sciadv.aax0587

Brooks, A. L., Wang, S., and Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. *Sci. Adv.* 4, eaat0131. doi: 10.1126/sciadv.aat0131

Browne, M. A., Niven, S. J., Galloway, T. S., Rowland, S. J., and Thompson, R. C. (2013). Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. *Curr. Biol.* 23, 2388–2392. doi: 10.1016/j.cub.2013.10.012

Bucci, K., Tulio, M., and Rochman, C. M. (2020). What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. *Ecol. Appl.* 30, e02044. doi: 10.1002/eap.2044

Bullard, R. D. (2018). *Dumping in Dixie: Race, class, and environmental quality. 3rd Edition* (Routledge: Westview Press).

Calafat, A. M., Ye, X., Wong, L.-Y., Reidy, J. A., and Needham, L. L. (2008). Exposure of the U.S. population to bisphenol a and 4-tertiary-octylphenol: 2003-2004. *Environ. Health Perspect.* 116, 39–44. doi: 10.1289/ehp.10753

Castellón, I. G. (2021). Cancer alley and the fight against environmental racism. *Vill. Envtl. LJ* 32, 15.

Census.gov (2022). *Income and Poverty in the United States: 2020.* Accessed: https://www.census.gov/library/publications/2021/demo/p60-273.html#:~:text=The%20official%20poverty%20rate%20in,from%2010.5%20percent%20in%202019.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., et al. (2020). Degradation rates of plastics in the environment. *ACS Sustain. Chem. Eng.* 8, 3494–3511. doi: 10.1021/acssuschemeng.9b06635

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., et al. (2013). Microplastic ingestion by zooplankton. *Environ. Sci. Technol.* 47, 6646–6655. doi: 10.1021/es400663f

Cordier, M., and Uehara, T. (2019). How much innovation is needed to protect the ocean from plastic contamination? *Sci. Total Environ.* 670, 789–799. doi: 10.1016/j.scitotenv.2019.03.258

Courtene-Jones, W., Maddalene, T., James, M. K., Smith, N. S., Youngblood, K., Jambeck, J. R., et al. (2021). Source, sea and sink–a holistic approach to understanding plastic pollution in the southern Caribbean. *Sci. Total Environ.* 797, 149098. doi: 10.1016/j.scitotenv.2021.149098

Cox, K. D., Covernton, G. A., Davies, H. L., Dower, J. F., Juanes, F., and Dudas, S. E. (2019). Human consumption of microplastics. *Environ. Sci. Technol.* 53, 7068–7074. doi: 10.1021/acs.est.9b01517

Dauvergne, P. (2018a). The power of environmental norms: Marine plastic pollution and the politics of microbeads. *Environ. Politics* 27, 579–597. doi: 10.1080/09644016.2018.1449090

Dauvergne, P. (2018b). Why is the global governance of plastic failing the oceans? *Global Environ. Change* 51, 22–31. doi: 10.1016/j.gloenvcha.2018.05.002

Desforges, J. W., Galbraith, M., and Ross, P. S. (2015). Ingestion of microplastics by zooplankton in the northeast pacific ocean. *Arch. Environ. Contamination Toxicol. New York* 69, 320–330. doi: 10.1007/s00244-015-0172-5

Diana, Z., Sawickij, N., Rivera, N. A., Hsu-Kim, H., and Rittschof, D. (2020). Plastic pellets trigger feeding responses in sea anemones. *Aquat. Toxicol.* 222, 105447. doi: 10.1016/j.aquatox.2020.105447

Diana, Z., Vegh, T., Karasik, R., Bering, J., D. Llano Caldas, J., Pickle, A., et al. (2022). The evolving global plastics policy landscape: An inventory and effectiveness review. *Environ. Sci. Policy* 134, 34–45. doi: 10.1016/j.envsci.2022.03.028

Dibke, C., Fischer, M., and Scholz-Böttcher, B. M. (2021). Microplastic mass concentrations and distribution in German bight waters by pyrolysis–gas chromatography–mass Spectrometry/Thermochemolysis reveal potential impact of marine coatings: Do ships leave skid marks? *Environ. Sci. Technol.* 55, 2285–2295. doi: 10.1021/acs.est.0c04522

Dijkstra, H., van Beukering, P., and Brouwer, R. (2021). In the business of dirty oceans: Overview of startups and entrepreneurs managing marine plastic. *Mar. Pollut. Bull.* 162, 111880. doi: 10.1016/j.marpolbul.2020.111880

Doran, G. (1981) *There's a S.M.A.R.T. way to write management's goals and objectives*. Available at: https://community.mis.temple.edu/mis0855002fall2015/files/2015/10/S.M.A.R.T-Way-Management-Review.pdf.

Eriksen, M., Lebreton, L. C. M., Carson, H. S., Thiel, M., Moore, C. J., Borerro, J. C., et al. (2014). Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at Sea. *PloS One* 9, e111913. doi: 10.1371/journal.pone.0111913

European Commission (2009) *Regulation (EC) no 1223/2009 of the European parliament and of the council of 30 November 2009 on cosmetic products (recast) (Text with EEA relevance)Text with EEA relevance*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02009R1223-20190813.

Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., et al. (2020). Atmospheric transport is a major pathway of microplastics to remote regions. *Nat. Commun.* 11, 3381. doi: 10.1038/s41467-020-17201-9

Falk-Andersson, J., Larsen Haarr, M., and Havas, V. (2020). Basic principles for development and implementation of plastic clean-up technologies: What can we learn from fisheries management? *Sci. Total Environ.* 745, 141117. doi: 10.1016/j.scitotenv.2020.141117

Feng, D., Rittschof, D., Orihuela, B., Kwok, K. W. H., Stafslien, S., and Chisholm, B. (2012). The effects of model polysiloxane and fouling-release coatings on embryonic development of a sea urchin (*Arbacia punctulata*) and a fish (*Oryzias latipes*). *Aquat. Toxicol.* 110–111, 162–169. doi: 10.1016/j.aquatox.2012.01.005

Fischer, V., Elsner, N. O., Brenke, N., Schwabe, E., and Brandt, A. (2015). Plastic pollution of the kuril–kamchatka trench area (NW pacific). *Deep Sea Res. Part II: Topical Stud. Oceanogr.* 111, 399–405. doi: 10.1016/j.dsr2.2014.08.012

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., et al. (2021). Our future in the anthropocene biosphere. *Ambio* 50, 834–869. doi: 10.1007/s13280-021-01544-8

Gadomska-Gajadhur, A., and Ruśkowski, P. (2020). Biocompatible catalysts for lactide polymerization–catalyst activity, racemization effect, and optimization of the polymerization based on design of experiments. *Organic Process Res. Dev.* 24, 1435–1442. doi: 10.1021/acs.oprd.0c00149

Gandara e Silva, P. P., Nobre, C. R., Resaffe, P., Pereira, C. D. S., and Gusmão, F. (2016). Leachate from microplastics impairs larval development in brown mussels. *Water Res.* 106, 364–370. doi: 10.1016/j.watres.2016.10.016

Geyer, R., Jambeck, J. R., and Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Sci. Adv.* 3, e1700782. doi: 10.1126/sciadv.1700782

Gregory, M. R. (2009). Environmental implications of plastic debris in marine settings- entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philos. Trans. R. Soc. B: Biol. Sci.* 364, 2013–2025. doi: 10.1098/rstb.2008.0265

Groh, K. J., Backhaus, T., Carney-Almroth, B., Geueke, B., Inostroza, P. A., Lennquist, A., et al. (2019). Overview of known plastic packaging-associated chemicals and their hazards. *Sci. Total Environ.* 651, 3253–3268. doi: 10.1016/j.scitotenv.2018.10.015

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., and Purnell, P. (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J. Hazardous Materials* 344, 179–199. doi: 10.1016/j.jhazmat.2017.10.014

Hogue, C. (2019). "Differentiating between green chemistry and sustainable chemistry in congress," in *Chemical & engineering news*. Available at: https://cen.acs.org/environment/green-chemistry/Differentiating-between-green-chemistry-sustainable/97/web/2019/07.

Huang, Y.-C. T., and Tsuang, W. (2014). Health effects associated with faulty application of spray polyurethane foam in residential homes. *Environ. Res.* 134, 295–300. doi: 10.1016/j.envres.2014.07.015

Ibrahim, Y. S., Tuan Anuar, S., Azmi, A. A., Wan Mohd Khalik, W. M. A., Lehata, S., Hamzah, S. R., et al. (2021). Detection of microplastics in human colectomy specimens. *JGH Open* 5, 116–121. doi: 10.1002/jgh3.12457

Jahnke, A., Arp, H. P. H., Escher, B. I., Gewert, B., Gorokhova, E., Kühnel, D., et al. (2017). Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. *Environ. Sci. Technol. Lett.* 4, 85–90. doi: 10.1021/acs.estlett.7b00008

Karbalaei, S., Hanachi, P., Walker, T. R., and Cole, M. (2018). Occurrence, sources, human health impacts and mitigation of microplastic pollution. *Environ Scie Poll Res* 25 (36), 36046–36063.

Kaza, S, Yao, LC, Bhada-Tata, P, and Van Woerden, F (2018). *A Global Snapshot of Solid Waste Management to 2050*. Urban Development;. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/30317. License: CC BY 3.0 IGO.

Keehan, C. J. (2018). Lessons from cancer alley: How the clean air act has failed to protect public health in southern Louisiana. *Colo. Nat. Resour. Energy Envtl. L. Rev.* 29, 341.

Khalid Ageel, H., Harrad, S., and Abou-Elwafa Abdallah, M. (2022). Occurrence, human exposure, and risk of microplastics in the indoor environment. *Environ. Science: Processes Impacts* 24, 17–31. doi: 10.1039/D1EM00301A

Kuczenski, B., Vargas Poulsen, C., Gilman, E. L., Musyl, M., Geyer, R., and Wilson, J. (2022). Plastic gear loss estimates from remote observation of industrial fishing activity. *Fish Fish.* 23, 22–33. doi: 10.1111/faf.12596

Lau, W. W. Y., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., et al. (2020). Evaluating scenarios toward zero plastic pollution. *Science* 369, 1455–1461. doi: 10.1126/science.aba9475

Law, K. L. (2017). Plastics in the marine environment. *Annu. Rev. Mar. Sci.* 9, 205–229. doi: 10.1146/annurev-marine-010816-060409

Law, K. L., Starr, N., Siegler, T. R., Jambeck, J. R., Mallos, N. J., and Leonard, G. H. (2020). The united states' contribution of plastic waste to land and ocean. *Sci. Adv.* 6, eabd0288. doi: 10.1126/sciadv.abd0288

Leslie, H. A., van Velzen, M. J. M., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., and Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environ. Int.* 163, 107199. doi: 10.1016/j.envint.2022.107199

Li, H.-X., Getzinger, G. J., Ferguson, P. L., Orihuela, B., Zhu, M., and Rittschof, D. (2016). Effects of toxic leachate from commercial plastics on larval survival and settlement of the barnacle amphibalanus amphitrite. *Environ. Sci. Technol.* 50, 924–931. doi: 10.1021/acs.est.5b02781

Materić, D., Kjær, H. A., Vallelonga, P., Tison, J.-L., Röckmann, T., and Holzinger, R. (2022). Nanoplastics measurements in northern and southern polar ice. *Environ. Res.* 208, 112741. doi: 10.1016/j.envres.2022.112741

McClellan-Green, P., Romano, J., and Rittschof, D. (2006). Imposex Induction in the Mud Snail, Ilyanassa obsoleta by Three Tin Compounds. *Bull Environ Contam Toxicol* 76, 581–588. doi: 10.1007/s00128-006-0959-1

Messinetti, S., Mercurio, S., Scarì, G., Pennati, A., and Pennati, R. (2019). Ingested microscopic plastics translocate from the gut cavity of juveniles of the ascidian Ciona intestinalis. *The European Zoological Journal* 86, 189–195. doi: 10.1080/24750263.2019.1616837

Mogomotsi, P. K., Mogomotsi, G. E., and Phonchi, N. D. (2019). Plastic bag usage in a taxed environment: Investigation on the deterrent nature of plastic levy in maun, Botswana. *Waste Manag Res.* 37, 20–25. doi: 10.1177/0734242X18801495

Monast, J., and Virdin, J. (2022). "Pricing plastics pollution: Lessons from three decades of climate policy," in *Connecticut Law review*. Connecticut Law Review. Available at: https://opencommons.uconn.edu/law_review/524.

Morrison, M., Trevisan, R., Ranasinghe, P., Merril, G. B., Santos, J., Hong, A., et al. (2022). A growing crisis for One Health: impacts of plastic pollution across layers of biological function. *Frontiers in Marine Science*. doi: 10.3389/fmars.2022.980705

Neilson, J. L., Straley, J. M., Gabriele, C. M., and Hills, S. (2009). A non-lethal entanglement of humpback whales (megaptera novaeangliae) in fishing gear in northern southeast Alaska. *J. Biogeogr.* 36, 452–464. doi: 10.1111/j.1365-2699.2007.01820.x

Nelms, S. E., Galloway, T. S., Godley, B. J., Jarvis, D. S., and Lindeque, P. K. (2018). Investigating microplastic trophic transfer in marine top predators. *Environ. pollut.* 238, 999–1007. doi: 10.1016/j.envpol.2018.02.016

Nobre, C. R., Santana, M. F. M., Maluf, A., Cortez, F. S., Cesar, A., Pereira, C. D. S., et al. (2015). Assessment of microplastic toxicity to embryonic development of the sea urchin *Lytechinus variegatus* (Echinodermata: Echinoidea). *Mar. pollut. Bull.* 92, 99–104. doi: 10.1016/j.marpolbul.2014.12.050

Paruta, P., Pucino, M., and Boucher, J. (2022). *Plastic paints the environment, EA- environmental action*, ISBN 978-2-8399-3494-7. EA - Environmental Action.

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., et al. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environ. Sci. Technol.* 56, 1510–1521. doi: 10.1021/acs.est.1c04158

Pitt, J. A., Kozal, J. S., Jayasundara, N., Massarsky, A., Trevisan, R., Geitner, N., et al. (2018). Uptake, tissue distribution, and toxicity of polystyrene nanoparticles in developing zebrafish (Danio rerio). *Aquat. Toxicol.* 194, 185–194. doi: 10.1016/j.aquatox.2017.11.017

Piver, W. (1973). Organotin compounds: industrial applications and biological investigation. *Environ. Health Perspect.* 19, 61–79. doi: 10.1289/ehp.730461

Plastic Disclosure Project (2022). Available at: https://www.plasticdisclosure.org/understake-the-pdp.

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., et al. (2021). Plasticenta: First evidence of microplastics in human placenta. *Environ. Int.* 146, 106274. doi: 10.1016/j.envint.2020.106274

Rivers, N., Shenstone-Harris, S., and Young, N. (2017). Using nudges to reduce waste? the case of toronto's plastic bag levy. *J. Environ. Manage.* 188, 153–162. doi: 10.1016/j.jenvman.2016.12.009

Rochman, C. M., Brookson, C., Bikker, J., Djuric, N., Earn, A., Bucci, K., et al. (2019). Rethinking microplastics as a diverse contaminant suite. *Environ. Toxicol. Chem.* 38, 703–711. doi: 10.1002/etc.4371

Rochman, C. M., Hentschel, B. T., and Teh, S. J. (2014). Long-term sorption of metals is similar among plastic types: Implications for plastic debris in aquatic environments. *PloS One; San Francisco* 9, e85433. doi: 10.1371/journal.pone.0085433

Rochman, C. M., Hoh, E., Hentschel, B. T., and Kaye, S. (2013). Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: Implications for plastic marine debris. *Environ. Sci. Technol.* 47, 1646–1654. doi: 10.1021/es303700s

Rochman, C. M., Kross, S. M., Armstrong, J. B., Bogan, M. T., Darling, E. S., Green, S. J., et al. (2015). Scientific evidence supports a ban on microbeads. *Environ. Sci. Technol.* 49, 10759–10761. doi: 10.1021/acs.est.5b03909

Savoca, M. S., Tyson, C. W., McGill, M., and Slager, C. J. (2017). Odours from marine plastic debris induce food search behaviours in a forage fish. *Proc. Biol. Sci.* 284, 20171000. doi: 10.1098/rspb.2017.1000

Schmaltz, E., Melvin, E. C., Diana, Z., Gunady, E. F., Rittschof, D., Somarelli, J. A., et al. (2020). Plastic pollution solutions: emerging technologies to prevent and collect marine plastic pollution. *Environ. Int.* 144, 106067. doi: 10.1016/j.envint.2020.106067

Schwabl, P., Köppel, S., Königshofer, P., Bucsics, T., Trauner, M., Reiberger, T., et al. (2019). Detection of various microplastics in human stool. *Ann. Intern. Med.* 171, 453–457. doi: 10.7326/M19-0618

Science-Based Targets Initiative (2021)Ambitious corporate climate action. In: *Science based targets*. Available at: https://sciencebasedtargets.org/ (Accessed April 8, 2021).

Sheth, M. U., Kwartler, S. K., Schmaltz, E. R., Hoskinson, S. M., Martz, E. J., Dunphy-Daly, M. M., et al. (2019). Bioengineering a future free of marine plastic waste. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00624

Simon, N., Raubenheimer, K., Urho, N., Unger, S., Azoulay, D., Farrelly, T., et al. (2021). A binding global agreement to address the life cycle of plastics. *Science* 373, 43–47. doi: 10.1126/science.abi9010

Singer, M. (2011). Down cancer alley: The lived experience of health and environmental suffering in louisiana's chemical corridor. *Med. Anthropol. Q.* 25 (2), 141–163. doi: 10.1111/j.1548-1387.2011.01154.x

Sobhani, Z., Lei, Y., Tang, Y., Wu, L., Zhang, X., Naidu, R., et al. (2020). Microplastics generated when opening plastic packaging. *Sci. Rep.* 10, 1–7. doi: 10.1038/s41598-020-61146-4

Stamper, M. A., Spicer, C. W., Neiffer, D. L., Mathews, K. S., and Fleming, G. J. (2009). Morbidity in a juvenile green sea turtle (Chelonia mydas) due to ocean-borne plastic. *J. Zoo wildlife Med.* 40, 196–198. doi: 10.1638/2007-0101.1

Sterner, T. (2003). *Policy instruments for environmental and natural resource management* (Washington, DC: Resources for the Future: World Bank; Stockholm, Sweden : Swedish International Development Cooperation Agency, c2003). Available at: https://find.library.duke.edu/catalog/DUKE008570824.

Terrell, K. A., and James, W. (20221). Racial disparities in air pollution burden and COVID-19 deaths in Louisiana, USA, in the context of long-term changes in fine particulate pollution. *Environ. Justice* 15, env.2020.0021. doi: 10.1089/env.2020.0021

Tetu, S. G., Sarker, I., Schrameyer, V., Pickford, R., Elbourne, L. D., Moore, L. R., et al. (2019). Plastic leachates impair growth and oxygen production in prochlorococcus, the ocean's most abundant photosynthetic bacteria. *Commun. Biol.* 2, 1–9. doi: 10.1038/s42003-019-0410-x

Thomas, K., Irvin-Barnwell, E., Guiseppi-Elie, A., Ragin-Wilson, A., and Zambrana, J. (2019). "Synthetic turf field recycled tire crumb rubber research under the federal research action plan," in *Final report part 1 - tire crumb rubber characterization appendices*, vol. Volume 2. (Washington, DC: U.S. Environmental Protection Agency). Available at: https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NERL&dirEntryId=346618. EPA/600/R-19/051.2.

Turner, A. (2021). Paint particles in the marine environment: An overlooked component of microplastics. *Water Res. X* 12, 100110. doi: 10.1016/j.wroa.2021.100110

UNEP (2021a). *NEGLECTED: Environmental justice impacts of marine litter and plastic pollution* (Nairobi: UNEP - UN Environment Programme). Available at: http://www.unep.org/resources/report/neglected-environmental-justice-impacts-marine-litter-and-plastic-pollution.

UNEP (2021b). "From pollution to solution," in *A global assessment of marine litter and plastic pollution*(Nairobi: The United Nations Environment Programme).

UN Global Compact (2022) *CEO Water mandate*. Available at: https://ceowatermandate.org.

U.S. EPA (2014) *EJSCREEN: Environmental justice screening and mapping tool* (US EPA). Available at: https://www.epa.gov/ejscreen (Accessed October 25, 2020).

Valderrama Ballesteros, L., Matthews, J. L., and Hoeksema, B. W. (2018). Pollution and coral damage caused by derelict fishing gear on coral reefs around koh Tao, gulf of Thailand. *Mar. pollut. Bull.* 135, 1107–1116. doi: 10.1016/j.marpolbul.2018.08.033

van't Veld, K., and Kotchen, M. J. (2011). Green clubs. *J. Environ. Economics Manage.* 62, 309–322. doi: 10.1016/j.jeem.2011.03.009

Villarrubia-Gómez, P., Cornell, S. E., and Fabres, J. (2018). Marine plastic pollution as a planetary boundary threat–the drifting piece in the sustainability puzzle. *Mar. Policy* 96, 213–220.

Ward, C. S., Diana, Z., Ke, K. M., Orihuela, B., Schultz, T. P., and Rittschof, D. (2022). Microbiome development of seawater-incubated pre-production plastic pellets reveals distinct and predictive community compositions. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.807327

Wei, X.-F., Bohlén, M., Lindblad, C., Hedenqvist, M., and Hakonen, A. (2021). Microplastics generated from a biodegradable plastic in freshwater and seawater. *Water Res.* 198, 117123. doi: 10.1016/j.watres.2021.117123

Wiesinger, H., Wang, Z., and Hellweg, S. (2021). Deep dive into plastic monomers, additives, and processing aids. *Environmental science & technology* 55 (13), 9339-9351.

Weiss, L., Ludwig, W., Heussner, S., Canals, M., Ghiglione, J.-F., Estournel, C., et al (2021). The missing ocean plastic sink: Gone with the rivers. *Science* 373, 107–111. doi: 10.1126/science.abe0290

Wilcox, C., Puckridge, M., Schuyler, Q. A., Townsend, K., and Hardesty, B. D. (2018). A quantitative analysis linking sea turtle mortality and plastic debris ingestion. *Sci. Rep.* 8 (1), 1–11.

World Health Organization (WHO) (2022). *Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health* (Geneva: World Health Organization). Licence: CC BY- NC-SA 3.0 IGO.

Wright, S. L., and Kelly, F. J. (2017). Plastic and human health: A micro issue? *Environ. Sci. Technol.* 51, 6634–6647.

Zeytin, S., Wagner, G., Mackay-Roberts, N., Gerdts, G., Schuirmann, E., Klockmann, S., et al. (2020). Quantifying microplastic translocation from feed to the fillet in European sea bass dicentrarchus labrax. *Mar. pollut. Bull.* 156, 111210.

Zhang, N., Li, Y. B., He, H. R., Zhang, J. F., and Ma, G. S. (2021). You are what you eat: Microplastics in the feces of young men living in Beijing. *Sci. Total Environ.* 767, 144345. doi: 10.1016/j.scitotenv.2020.144345

Zhu, X., and Rochman, C. (2022). Emissions inventories of plastic pollution: A critical foundation of an international agreement to inform targets and quantify progress. *Environ. Sci. Technol*, 3309–12. doi: 10.1021/acs.est.2c01038

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A growing crisis for One Health: Impacts of plastic pollution across layers of biological function

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The global accumulation of plastic waste has reached crisis levels. The diverse and multilayered impacts of plastic on biological health prompts an evaluation of these effects from a One Health perspective, through which the complexity of these processes can be integrated and more clearly understood. Plastic particles ranging from nanometers to meters in size are found throughout every ecosystem on Earth, from the deepest marine trenches to the highest mountains. Plastic waste affects all layers of biological organization, from the molecular and cellular to the organismal, community, and ecosystem-levels. These effects are not only mediated by the physical properties of plastics, but also by the chemical properties of the plastic polymers, the thousands of additives combined with plastics during manufacturing, and the sorbed chemicals and microbes that are transported by the plastic waste. Using a One Health framework we provide an overview of the following themes: 1) ways in which plastic impacts global health across levels of biological organization, 2) how the effects of plastic interact between layers of biology, and 3) what knowledge gaps exist in understanding the effects of plastic within and between biological scales. We also propose potential solutions to address this growing crisis, with an emphasis on One Health perspectives that consider the oneness of animals, humans, and the environment.

KEYWORDS
microplastic toxicity, marine plastic, ecosystem health and pollution, human health, nanoplastic (NP)

Plastic is ubiquitous and interacts with all aspects of the biosphere

Plastics are ubiquitous in our society. Demand for plastic has skyrocketed since the 1950s due its inexpensive, strong, durable, and lightweight properties (Thompson et al., 2009). As a result, plastic pollution is now found all across the planet, including along coastlines (Kwon et al., 2014; Courtene-Jones et al., 2021), in the open ocean (Eriksen et al., 2013; Cózar et al., 2014), the deep sea (Bergmann et al., 2017; Barrett et al., 2020), soils (Fuller and Gautam, 2016), and the atmosphere (González-Pleiter et al., 2021). Current estimates suggest that a minimum of 5.25 trillion plastic particles are present in the world's oceans, a number that is expected to grow (Eriksen et al., 2014). Indeed, the amount of plastic pollution entering the terrestrial and aquatic environment is predicted to grow by an additional 710 million metric tons between 2016 and 2040, even if immediate action is taken to reduce waste (Lau et al., 2020). These plastics are degraded by biotic and abiotic processes in the environment, such as bacterial activity, UV light, temperature, and abrasion, resulting in smaller fragments with altered surface properties. These smaller plastics, classified as microplastics (<5 mm) and nanoplastics (<1 μm), are the most prevalent type of solid waste, especially in the aquatic environment (Jambeck et al., 2015; Gigault et al., 2018). Additionally, both types of small plastics (referred to as micro- and nanoplastics) can be found in commercial and industrial items.

The ubiquity of plastics in the biosphere has made interactions with animals and humans inevitable. Vast numbers of marine species are impacted by plastics (Gall and Thompson, 2015). Microplastics are found in fish, clams, mussels, oysters, and crabs destined for human consumption (Van Cauwenberghe and Janssen, 2014; Li et al., 2015; Rochman et al., 2015; Karami et al., 2017; Su et al., 2018; Waite et al., 2018), as well as table and sea salt (Yang et al., 2015; Zarus et al., 2021), seaweed (Baini et al., 2017), honey (Liebezeit and Liebezeit, 2013; Liebezeit and Liebezeit, 2015), tea (Hernandez et al., 2019), beer (Kosuth et al., 2018), and tap and bottled water (Kosuth et al., 2018; Zuccarello et al., 2019; Kankanige and Babel, 2020). Microplastics have also been documented in the human body, (e.g., in lung tissues (Amato-Lourenço et al., 2021), stool (Schwabl et al., 2019; Ibrahim et al., 2021), blood (Leslie et al., 2022), and even placentas (Ragusa et al., 2021).

There is perhaps no other single anthropogenic contaminant that has had such a wide spectrum of direct exposure ranging across all levels of biology. Plastics disrupt homeostasis at the individual organismal level *via* ingestion of plastic debris (Gall and Thompson, 2015). Plastic pollution can also disrupt ecosystem functioning by changing and damaging habitats (Aloy et al., 2011; Carson et al., 2011; Richards and Beger, 2011) and altering the balance of species across ecosystems (Barnes and Milner, 2005; Goldstein et al., 2012). Such changes, in turn, inevitably have unknown effects upon health. Mitigating plastic impacts on the health of people, animals, and ecosystems requires an approach that transcends traditional species-level risk assessments. One such framework is the concept of One Health (Figure 1). One Health recognizes the interconnectedness of people, animals, and plants, and how their individual health is itself dependent on the health of their shared environment (One Health, 2021). The One Health perspective calls for a multi-sectoral, transdisciplinary, and collaborative approach to solving health issues at the local, national, and global levels (One Health, 2022). While the origins of One Health research stem from the study of zoonotic diseases, this framework provides a transdisciplinary lens to (i) examine the imminent threat to human, animal, and ecosystem health imposed by plastic pollution, (ii) elucidate socio-economic ramifications of plastic pollution and (iii) implement mitigation strategies interlining with the public and private sectors.

To establish the need for an integrated assessment, here, we focus on routes of exposure and the health threats at the cellular, individual organismal, population, and ecosystem levels to highlight plastic pollution impacts across layers of biological organization. The goals of this review are to i) summarize our understanding of how plastic affects layers of biological organization, ii) provide rationale for the use of a One Health paradigm to understand and investigate plastic's consequences on health, and iii) illuminate gaps in existing knowledge and research on the impacts of plastics within the One Health paradigm.

Routes of exposures

Humans and other organisms encounter plastics in a variety of ways, including ingestion, inhalation, and physical contact with plastics and plastic additive chemicals (Cox et al., 2020; World Health Organization, 2022). Humans in the United States are estimated to consume between 39,000 to 52,000 microplastic particles per year from food and beverages alone (Cox et al., 2020) or an average of 0.1-5g of microplastics weekly (Senathirajah et al., 2021). Plastic ingestion is also well documented in other species, including zooplankton (Desforges et al., 2015), fish (Barboza et al., 2020), turtles (Duncan et al., 2019), seabirds (Wilcox et al., 2015), and marine mammals (Nelms et al., 2019).

In addition to ingestion, humans and other terrestrial organisms can also inhale plastics. Micro- and nanoplastics (MNPs) and plastic fibers are released into the atmosphere *via* the washing of synthetic textiles, rubber tires, dried sludge, agriculture, and city and household dust (Wright and Kelly, 2017; Karbalaei et al., 2018; World Health Organization, 2022). MNPs can even be generated through simple tasks, such as

FIGURE 1
Plastic impacts every facet of the One Health paradigm. One Health views animal, human, and environmental health as a single, interconnected entity, with impacts on one sphere affecting all others, both directly and indirectly. Plastic pollution has multiple potential effects on every aspect of global health.

opening and cutting plastic packaging and containers (Sobhani et al., 2020). While the fate of inhaled MNPs and their subsequent uptake in lung tissue is currently unknown (Amato-Lourenço et al., 2021), airborne exposures can occur both indoors, *via* household items and clothing, as well as outdoors from particulate matter (Kasirajan and Ngouajio, 2012; Wright and Kelly, 2017; Catarino et al., 2018). Occupational exposure, exposure to medical devices, and contact exposure to items such as personal care products and plastic toys also contribute to human exposures (Karbalaei et al., 2018; Zarus et al., 2021).

Exposure to plastics is inexorably associated with exposure to plastic additives—compounds added to plastic to improve the functionality of the polymers (Hahladakis et al., 2018; Wiesinger et al., 2021). Additives include plasticizers, flame retardants, heat and light stabilizers, antioxidants, lubricants, pigments, antistatic agents, slip agents, biocides, and thermal stabilizers (Groh et al., 2019). While these additives are helpful to enhance the performance of plastics, there is great potential for additives to contaminate soil, air, water, and food (Hahladakis et al., 2018), with poorly-understood consequences to the environment and to health.

In addition to the chemicals intentionally added, plastics can carry environmental pollutants and microbes. Collected plastic litter has been associated with diverse bacterial species, including human pathogens, suggesting that plastic may lead to transmission of infectious diseases and may contribute to antimicrobial resistance (Rasool et al., 2021). Plastics accumulate persistent organic pollutants and heavy metals (Thompson et al., 2009; Rochman et al., 2014), though more work is needed to understand if these "Trojan horse" or "vector" effects of adsorption are physiologically relevant (Koelmans et al., 2016). In addition to plastic polymers, we must also consider the potential exposure to a variety of chemicals and microbes, when evaluating impacts of plastics on health.

Cross-species comparisons of cellular and organismal effects of plastics

Effects of plastics on animal health

The wide ranging effects of plastic have been assessed multiple organ impacts have been assessed across taxa, including in fish, phytoplankton, zooplankton, and bivalves (Figure 2). Due to their small size, MNPs have the potential to affect organisms on a cellular level (Prinz and Korez, 2020; Banerjee and Shelver, 2021). For example, in fish, MNPs lead to formation of reactive oxygen species (ROS) and increased oxidative stress, inducing cellular damage in liver, blood cells, gills, digestive tract, and brain (Pitt et al., 2018b; Hu and Palić, 2020; Buwono et al., 2022; Capó et al., 2022; Hoyo-Alvarez et al., 2022; Rangasamy et al., 2022). In fish, MNPs induced mitochondrial stress, altered hormonal regulation of energy

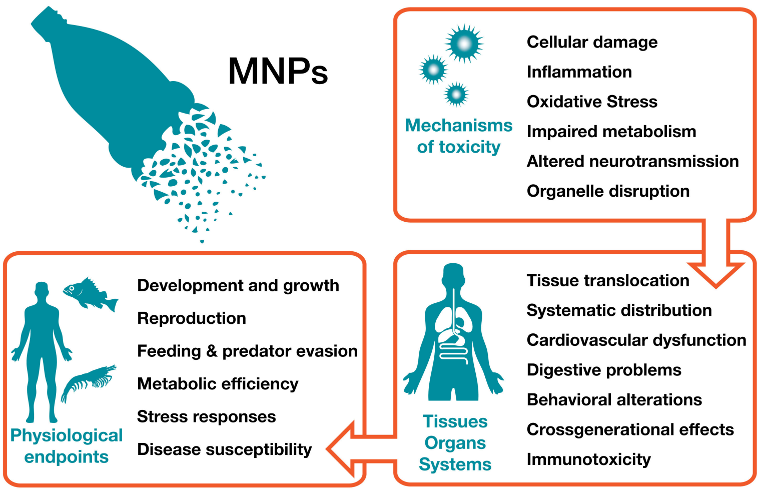

FIGURE 2
The impacts of plastic across all levels of biological organization. Micro- and nanoplastics (MNPs) affect molecular and cellular responses, tissue and organ systems, and physiological/behavioral responses in multiple species. Adapted from Trevisan et al., 2022.

metabolism, and catabolic and anabolic processes, which can limit the ability and flexibility of the organism to respond to future stresses (Brun et al., 2019; Trevisan et al., 2019; Trevisan et al., 2020; Wang et al., 2022). Such alterations affect animal fitness, reproduction, and success (Dreier et al., 2019).

In algae, MNPs can adsorb to cell walls (Nam et al., 2022) and can increase the formation of ROS, reduce cell viability, modify the activity of antioxidant enzymes, and promote lipid peroxidation (Das et al., 2022). These cellular changes are linked to plastic impacts on organisms' growth rates and energy demands. For example, nanoplastics may impact freshwater algae development rates (Huang et al., 2019) and metabolism, chlorophyll-a concentrations (Zhang et al., 2018), and maximal quantum yield of photosynthetic system II *(*Das et al., 2022*)*, although direct effects of plastics are not always evident (Seoane et al., 2019).

MNP exposure also affects growth, reproduction, and fitness of many invertebrates. For example, MNP exposure studies in copepods [e.g., *Calanus finmarchicus* (Cole et al., 2019), *Daphnia magna* (An et al., 2021), and *Artemia parthenogenetica*)] (Wang et al., 2019), in clams [*Corbicula fluminea* (Oliveira et al., 2018)], and mussels [*Mytilus galloprovincialis* (Avio et al., 2015; Abidli et al., 2021)] show effects on mitochondrial gene expression, prey preference, lipid content, molting, feeding rates, filter feeding, survival, growth, and reproduction. In mussels (*Mytilus edulis)*, high-density polyethylene exposure resulted in the accumulation of microplastics in the digestive gland, inflammatory reactions, and lysosomal membrane damage (von Moos et al., 2012). On the other hand, oysters exposed to polystyrene microplastics had a 3% higher algal consumption rate and an 11% higher absorption efficiency of organic matter from ingested food rates (Sussarellu et al., 2016), possibly induced as a compensation for the higher energy demand caused by the detected digestive interference of microplastics. Sampling of gametes from oysters (*Crassostrea gigas*) showed that exposure to 2 µm and 6 µm polystyrene particles led to a 38% drop in oocyte counts and a 23% decrease in the mobility rate of spermatozoa. The offspring produced by artificial fertilization using gametes from exposed parents had a 20% reduction in D-larval yield, an 18% reduction in larval size at 17 days post-fertilization, and a 6-day delay in the time necessary to complete metamorphosis (Sussarellu et al., 2016). These results demonstrate that small plastic particles can affect the health of bivalves at the subcellular and physiological levels.

The intestinal microbiota of vertebrates is critical for health, and disturbance to the microbiota leads to increased risk of disease; however, few studies have investigated the impact of plastic exposure on the gut microbiome. One study exposed male zebrafish to polystyrene microplastics and observed greater mucus levels and significant changes to the species richness and diversity of microbiota in the polystyrene microplastic-exposed zebrafish (Jin et al., 2018). In another study, adult zebrafish (*Danio rerio*) co-exposed to titanium dioxide nanoparticles and the plasticizer bisphenol A (BPA) shifted the intestinal microbial community (Chen et al., 2018).

Exposure to MNPs can cause disruption in the immune and antioxidant systems, as well as the nervous and reproductive systems. For example, mussels exposed to a combination of 2 and 6 µm polystyrene microplastics exhibited disturbance of cellular homeostasis in hemocytes, infiltration of these cells into digestive system tissues, and changes in the activity or gene expression of antioxidant enzymes in gills and digestive glands (Paul-Pont et al., 2016). Sheepshead minnows (*Cyprinodon variegatus*) exposed to irregularly-shaped microplastics led to upregulation of Cxcr5 and Tnfsf13b, both of which are involved in B cell development (Choi et al., 2018). Other studies have demonstrated increased inflammation in fish when fed irregularly-shaped microplastics (Jiang et al., 2016; Tao et al., 2016). In contrast, exposure to PVC microplastics in gilthead seabream (*Sparus aurata* L.) did not alter humoral or cellular immunity, but produced cellular and oxidative stress. These results agree with altered albumin, total proteins and globulin levels observed in juvenile *Clarias gariepinus* serum after virgin microplastic ingestion (Karami et al., 2016).

At the level of the nervous system, exposure of MNPs have also been to affect fish behavior, including reduced swim speed and erratic swimming (Barboza et al., 2018); reduced locomotor activity (Chen et al., 2017); reduced predator avoidance behavior and dysregulated circadian rhythm locomotion (Sarasamma et al., 2020); increased shoal formation and feeding time and less exploration (Mattsson et al., 2017); and reduced predatory performance (Carlos de Sá et al., 2015; Wen et al., 2018). Alterations to locomotory behavior (Bergami et al., 2016) and burrowing kinetics (Silva et al., 2020) have been observed in brine shrimp larvae and polychaeteas upon exposure to nanoplastics.

Ingested MNPs at the lower micron range (<5 µm) can cross the gastrointestinal barrier, reaching the blood and potentially moving to other body compartments (Roch et al., 2020). Very small MNPs can also cross other biological barriers, including the egg chorion (usually particles smaller than a few hundred nm) and the blood brain barrier (particles smaller than a few dozen µm) (Guerrera et al., 2021). This potential for translocation across tissue barriers poses an additional threat to multicellular organisms, as multiple physiological systems could potentially be affected by the plastic particles. Early developmental stages can be particularly susceptible to the translocation of plastics to different organs, as many of these biological barriers are not fully developed, thereby facilitating the distribution of plastic to multiple organs (Pitt et al., 2018a).

Another source of concern, particularly in fish and other marine organisms, is the transfer of plastics through the food web and between generations. MNPs can interact with phytoplankton and zooplankton, which can then be consumed by small fish and passed up the food chain (Benson et al., 2022). Dietary exposure of fish to MNPs can reduce growth rate, cause liver damage, impair swimming performance, and create behavioral abnormalities (da Costa Araújo et al., 2020; Kim et al., 2022). Recent research has also revealed that the translocation of plastics to the gonads of fish can result in the cross-generational transfer of these particles to the offspring, as well as developmental and physiological damage (Pitt et al., 2018b; Zhao et al., 2021). Because most plastic particles are hydrophobic, oocytes may be important targets for the bioaccumulation of MNPs due to their larger size and higher lipid content, suggesting that female fish may be important vectors for the cross-generational transfer of plastics (Pitt et al., 2018b). The interaction of plastic particles with blood proteins, such as vitelogenin, which has already been found with polystyrene nanoplastics, can promote the transportation of plastics to the female gonads and oocytes (Rossi et al., 2014), a topic that requires further investigation.

It is clear from these studies that plastics induce substantial effects on the biology and fitness of these keystone species. Crustacean zooplankton, such as copepods, daphnids, and brine shrimp, play a key role in community structure and act as a critical connection in the trophic web between primary producers and secondary consumers. Bivalves are primary consumers at the base of the food chain that also offer habitat, can improve the diversity and complexity of coastal ecosystems, link the benthic and pelagic systems through their filter-feeding activity, and are an essential nutrient source for other species. Fish are an important food source globally, and play a large role in the ocean food web. Microalgae are vital to the productivity of aquatic environments and play a crucial role in community structure. Plastic exposure could alter the health and abundance of this critically important group of species. While the ecological repercussions of such changes to coastal ecosystems still need to be determined, the ubiquity and volume of plastics and their numerous negative impacts across species call for an urgent need to better understand these consequences and how to combat them.

Effects of plastics on humans

While it is evident that humans have regular exposure to plastics and their byproducts, the impact of these exposures on human health is not currently well understood. Research to date suggests that the potential health effects of exposure to plastics include respiratory irritation, dyspnea, decreased lung capacity, coughing, obesity, increased phlegm production, cardiovascular disease, asthma, and cancer (Wright and Kelly, 2017; Karbalaei et al., 2018; World Health Organization, 2022). It has also been postulated that MNPs may cause inflammation, immune dysfunction, neurotoxicity, neoplasia, and changes in metabolism (Wang et al., 2020; Banerjee and Shelver, 2021; Coffin et al., 2022; World Health Organization, 2022). Furthermore, as observed in fish, human ingestion of microplastics has the potential to impact gut health. Exposure to microplastics can cause inflammation in the gut and destruction of the gut epithelium, which can lead to intestinal leakage and could pose a significant health threat (Huang et al., 2021). This inflammation is thought to be driven by an increase in oxidative stress in intestinal epithelial cells. Additionally, microplastics can reduce the mucus layer in the intestines, which serves as an important chemical barrier in the gut (Huang et al., 2021). Studies have also shown that microplastics affect the microbiota in the gut, which can destabilize the intestinal microenvironment (Yong et al., 2020; Huang et al., 2021).

Much of the research that has explored the health impacts of plastics and plastic additives in humans has focused on the effects of BPA and phthalates. BPA and phthalates are known endocrine disrupting chemicals, and therefore affect development and reproduction. In men, this can manifest as declined reproductive capacity or increased risk of testicular and prostate cancer, whereas in women this can manifest as increased risk for endometriosis, reproductive related cancers, and impaired ovarian function and menstrual cycling (Meeker et al., 2009; Kim and Kim, 2020). Exposure to endocrine disrupting chemicals *in utero* may contribute to diseases of the testis, prostate, kidney, immune system, and cause tumors (Basak et al., 2020). Additionally, exposure to phthalates is positively correlated with shorter gestational age at delivery and worse *in vitro* fertilization outcomes (Latini et al., 2003; Machtinger and Orvieto, 2014; Basak et al., 2020). BPA levels in blood have also been shown to be associated with impaired thyroid functioning (Kwon et al., 2020).

BPA and phthalates may also have neurological impacts by inducing changes in the neuroendocrine system and inflammatory signaling (Solleiro-Villavicencio et al., 2020; Nadeem et al., 2021). For example, BPA can pass through the blood-brain barrier, and BPA exposure is linked with neuropsychological dysfunction, neurobehavioral disorders, and neurodegenerative disease (Wang H. et al., 2019). Exposure to BPA and phthalates is also associated with alterations to the cardiovascular system and metabolism, with studies showing a positive relationship between BPA and phthalates and cardiovascular disease, type 2 diabetes, and increased blood pressure (Lang et al., 2008; Gong et al., 2013; Haq et al., 2020; Mariana and Cairrao, 2020). BPA has also been shown to have epigenetic impacts, such as affecting DNA methylation in first trimester trophoblast cells, sperm cells, prostate carcinoma cells, and neuroblastoma cells (Manikkam et al., 2013; Senyildiz et al., 2017; Basak et al., 2018; Fatma Karaman et al., 2019). It has also been demonstrated that BPA can cause epigenetic alterations that impact cardiac development and metabolic dysfunction (Lombó et al., 2015; Junge et al., 2018). Many of the above studies examined correlations between BPA and phthalate concentrations in humans and the increased risk of certain health impacts, which highlights the potential health effects of exposure to environmentally-relevant doses of these chemicals.

While the vast majority of research on the health impacts of plastics has focused on BPA and phthalates, recent studies have identified more than 10,000 substances related to the manufacture of plastics, including over 2,400 substances that are identified as substances of potential concern (Hahladakis et al., 2018; Groh et al., 2019; Wiesinger et al., 2021). Clearly, the current research has focused on only a small fraction of the additives to which we are likely exposed on a regular basis, demonstrating a clear dearth of knowledge surrounding the full health risks posed by plastics. When these studies expand beyond just a few chemicals, clear exposures are identified. For example, a study that tested estrogenic and androgenic activity in the saliva from children exposed to 18 toys found nine of the 18 toys to have estrogenic effects (Kirchnawy et al., 2020). Of the nine toys that induced an estrogenic response, seven could not be explained by analysis for 41 known endocrine disrupting chemicals, suggesting that other unknown plastic additives existed in these toys with potential to threaten human health.

Furthermore, the ability for plastic additives to leach out of plastic remains a matter of continued debate. Several studies have examined the leachability of certain additives from items such as plastic water bottles, kitchen utensils, and plastic water pipes with mixed results. While some studies have found estrogenic activity in drinking water resulting from plastic bottles and pipes (Wagner and Oehlmann, 2011; Liu et al., 2017), others have determined that the levels of leached additives are below those that would pose a threat to human health (Corea-Téllez et al., 2008; Aneck-Hahn et al., 2018; Wang C. et al., 2019). However, these studies fail to consider the cumulative exposure that an individual may have across sources and over time. When added together, the total exposure to these chemicals may very well exceed the acceptable thresholds; however, current research has yet to quantify such cumulative exposures. The effect of simultaneous co-exposures to these chemicals on human health is also poorly understood, despite the fact that human exposures to complex mixtures of compounds are well documented (Meeker et al., 2009). Furthermore, these studies do not account for the possibility for increased leaching over time, since factors such as UV exposure, mechanical abrasion, hydrolysis, and oxidation cause plastics to break down and release chemicals (Walker et al., 2021). With plastic production and use steadily on the rise, human exposure to plastic will continue to increase. Further, efforts towards waste reduction are driving growth in the reuse of plastic materials, which may also increase health risks due to potential increased chemical leaching (Muncke et al., 2020).

There is also evidence that the impacts of plastic on human health are not readily reversible, given that exposure to plastic additives may continue even after removal of plastics from one's environment. For example, BPA was detected in 23 out of 29 urinary samples from workers in a hazardous waste incinerator, despite the implementation of BPA regulations after a certain time (González et al., 2019). Additionally, an intervention study that removed all sources of plastics from a family's household failed to lead to a clear reduction of phthalate metabolites in urine in all family members even after two months (Hutter et al., 2016). It has also been shown that in office spaces where phthalate-containing materials or sources have been removed, phthalates were still present in dust in non-negligible concentrations (Hutter et al., 2006). This underscores how widespread plastics and plastic additives are in our environment and how difficult it is to avoid such exposures, even with local mitigation or rigorous avoidance strategies.

A recent report released by the World Health Organization highlights the urgent need for improved research on the health effects of MNPs, as research to date is "incomplete and insufficient for an assessment of human risk" (World Health Organization, 2022). While research on the health impacts of plastic is lagging woefully behind human consumption of plastic products, it is clear that plastics have the potential to affect human health in multiple ways. The physical properties of plastics have the potential to damage organs, such as the gastrointestinal and respiratory systems, and chemical exposures from these plastics can have systemic effects, ranging from cellular effects on oxidative stress and apoptosis, to impacts on reproduction, development, metabolism, and even intergenerational effects through epigenetic modifications. As a result, there is an "overwhelming consensus" that measures should be taken to mitigate exposure to MNPs (World Health Organization, 2022).

Disparities exist in causes and consequences of plastic exposure

As with many societal challenges, the impacts of plastic pollution are not distributed evenly across populations. Since the late 1980s, high-income countries have been the primary exporters of plastic pollution, accounting for 87% of all exports (Brooks et al., 2018). Six of the top 20 plastic polluters are high-income countries (United States, Japan, Kuwait, Oman, Argentina, and Italy) (Law et al., 2020) These exports are primarily to lower-income countries in Asia and the Pacific (Brooks et al., 2018). The waste-management infrastructure in the countries receiving these exports cannot handle the excess burden of the exports, which contributes to the disproportional impacts of plastic pollution in these countries (Ncube et al., 2021). The excess burden of plastic waste in specific communities is further compounded by housing shortages and unemployment, both of which can lead to circumstances where humans are prompted to deliberately stay in these areas to better adapt to the more urgent challenges of poverty. For example, the Smokey Mountain in the Philippines, an unregulated dumpsite no less than 20 meters high, housed 30,000 homeless or scavenging Filipino families for 40 years before it was closed in the 1990s (Galarpe, 2015)

Plastic pollution exacerbates the climate-instigated downturn of agriculture and fishery industries that serve as the primary economic activities for certain societies. For example, approximately 10% of the world's population relies heavily on marine environments for their diet and livelihood, with the vast majority (95%) from developing nations (Food and Agriculture Organization, 2014; Taylor et al., 2019). Low-lying Pacific islands with limited arable land bear the brunt of the plastic crisis. Tuvalu, for instance, clings to "blue economy" policies contingent on the use of marine resources to keep their economy and people afloat (International Organization for Migration and International Labour Organization, 2021). These circumstances make the island nation among the hardest hit by plastic accumulation in marine environments and the climate effects of plastic production and incineration. The disproportionate impact of plastic waste on specific communities should be interrogated through a holistic exploration of geo-economic, environmental, structural, and socio-political underpinnings.

Ecosystem-wide effects of plastic

Ecosystem health, function, and services are critically linked with human physical health as well as societal, cultural, and economic well-being (Summers et al., 2012). The various consequences of plastic across all levels of biological organization from cells to populations portend a grim future with respect to the constitution of the natural world, inclusive of humans, and can be exemplified by sentinel species. Among these sentinel species, many marine apex predators, such as marine mammals, have long life spans, amplify trophic information across multiple spatiotemporal scales, and share food resources of commercial and subsistence importance to humans, making them efficacious harbingers of negative impacts to both individual- and population-level animal and human well-being (Bossart, 2011; Hazen et al., 2019). Trophic transfer of microplastic particles to marine mammals from contaminated prey who have consumed microplastics is thought to be the primary route of microplastic exposure for both filter and raptorial predators (Zantis et al., 2022). The direct link between humans and marine mammals is self-evident: as top predators with shared resources, exposure to microplastics in humans *via* consumption is concerning. However, a larger question of indirect consequences looms: does plastic pollution threaten whole ecosystem collapse?

Whether or not plastic threatens the functionality of whole ecosystems is poorly studied (Bucci et al., 2020); however, the potential downstream consequences of plastic to marine mammals and the ecosystems they inhabit are not difficult to imagine, particularly when contextualized through a framework of population consequences of disturbance (Ocean Studies Board et al., 2017; Bucci et al., 2020). Interaction with macroplastic, such as ingestion or entanglement, can lead to physiological and behavioral changes that induce acute or lethal consequences impacting vital rates and subsequently population dynamics (Ocean Studies Board et al., 2017). Similarly, both micro and macroplastics may have chronic, sublethal impacts on individual health, which may also lead to alterations in vital rates (Ocean Studies Board et al., 2017). As instrumental players in nutrient cycling (Roman et al., 2016), the reduction of a whale population, for example, may result in a catastrophic depletion of energy at lower trophic levels that rely on whale excrement and carcasses. This disruption to energy availability at the lower trophic levels could potentially reverberate up each trophic level, including those with cultural, subsistence, and commercial importance to humans, resulting in whole ecosystem remodeling or collapse. Indeed, marine mammals are of great cultural and subsistence importance to indigenous communities (Huntington et al., 2016). For most of the contemporary global human population, marine mammals serve as clear sentinels for a variety of environmental and ecological threats (Bossart, 2011; Hazen et al., 2019). But for some native peoples who consume them, the meat from contaminated marine mammals may have direct consequences to users' health. Ingestion of plastic by whales, seals, sea lions, and polar bears is well documented and may either translocate to, or leach toxic substances into, consumable tissues (Law, 2017; Zantis et al., 2021). Plastic consumed by marine mammals therefore threatens a critical life line, and a way of life, for several indigenous communities world-wide.

Of course, many factors influence the proper functioning of an ecosystem, and processes like emigration/immigration, prey-switching, shifts in species assemblages and niche partitioning among others may all affect the ultimate ecosystem-level consequence of disturbances resulting from plastic exposure. In addition, ecosystems contend with many anthropogenic stressors apart from plastic. Consequently, the interactions between exposure to plastic and climate change, habitat loss/degradation, exploitation, etc. need to be explored, and safeguarding regular and proper functioning of ecosystems from plastic pollution is critical to optimal human, organism, and environmental vitality.

Solutions, adaptations, and future research efforts

As human demand for plastic continues, new solutions will be needed that span the entirety of societal structure, including novel technological innovations to degrade or recycle plastic, campaigns directed at consumer behavior, and implementation of bold policies at all levels of government. These solutions must be implemented across the entire lifecycle of plastic, from reducing the amount of new plastic entering the environment to removing existing plastic pollution. Technological innovations that are underway for clean-up and remediation efforts include a variety of plastic capture approaches. These tools are summarized in "The Inventory," a summary of 52 inventions, such as ocean plastic skimmers, beach cleaning robots, and river and ocean debris filters, that are focused on preventing plastic leakage or collecting marine plastics (Schmaltz et al., 2020). Although these technologies are a necessary component of our efforts to mitigate plastic pollution, their scalability and effectiveness to date does not match the enormity of the plastic pollution problem.

Another novel approach to prevent plastic pollution is the utilization of plastic-degrading bacteria as a mechanism to create a "circular economy of plastic". As plastic has increased in the environment over the past century, microorganisms have evolved enzymes to degrade plastic [reviewed in (Sheth et al., 2019)]. While there may be hundreds of bacterial strains that have evolved plastic-degrading properties, none have been able to do so rapidly; however, further refinement of these naturally-evolved enzymes has led to increasingly-efficient microbially-mediated plastic bioremediation systems (Tournier et al., 2020; Lu et al., 2022). In addition to these substantial improvements in bacterially-mediated degradation of plastic, it will be important to process plastic waste into forms that are readily and fully biodegradable, such as through amorphization of micronization.

Concomitant with the development of new technologies, governments around the world are increasingly using policy, laws, and ordinances to target the plastic pollution issue. Policies can target plastic pollution in a variety of ways through the implementation of regulatory, economic, and educational instruments. A recent review of plastic policies around the world found that international policies primarily focus on plans and future actions, while national and subnational policies most frequently use plastic bans to achieve a reduction in plastic pollution (Diana et al., 2022). Despite this increasing trend, substantial gaps still remain across the policy space, including the types of plastic targeted by these policies. For example, within national policies throughout the world, macroplastics were the most common plastic type targeted, followed by plastic bags (Diana et al., 2022), while only 3 of the 147 national policies to date solely target microplastics. Furthermore, only 5% of national policies have effectiveness studies in the peer-reviewed literature, highlighting the need for more evidenced-based policy development in the future (Diana et al., 2022). Finally, notably lacking from global policy is a binding global treaty targeting plastic pollution (Karasik et al., 2020). Despite an increasing trend of policy implementation to combat plastic waste, progress has been stymied by the COVID-19 pandemic, which prompted a pause in many policies around the world due to safety concerns regarding reusable materials (Karasik et al., 2020). Existing policy limitations, compounded by COVID-19 impacts, call for improved and coordinated policy efforts globally.

To help guide global policy efforts, a planetary boundaries approach has been proposed to first define the limits of waste production that ensure that Earth remains a "safe operating space" for humanity (Folke et al., 2021). To date, planetary boundaries have been defined for climate change, genetic diversity, land-system change, freshwater use, biochemical flows (phosphorus and nitrogen), ocean acidification, and the depletion of stratospheric ozone depletion (Steffen et al., 2015).

However, experts have not yet defined planetary boundaries for plastics or other novel entities. Quantifying the planetary boundary for plastic pollution can help society to understand whether or not plastic pollution is driving large-scale and irreversible harm to the planet and identify measures to prevent exceeding the boundary. By changing ecosystems, generating greenhouse gasses, and impacting the health of people and animals, it remains unclear whether plastic pollution could reach levels that would render the planet inhospitable. Recent efforts have sought to characterize the dangerous pathways that plastic could lead to such irreversible impacts in order to better understand the cumulative and planetary impacts of plastic pollution (Diana et al., 2022). These efforts are the first step towards defining a limit for plastic pollution, which can then facilitate the development of global policy to keep society within the identified boundary.

Finally, in addition to improved technologies and policies that target plastic pollution, increased research on the impacts of plastic are also needed. A recent review of studies examining impacts of plastic pollution highlighted several important gaps in research to date (Bucci et al., 2020). Observational or manipulative field experiments have largely focused on macroplastics (97%), while manipulative laboratory experiments have largely focused on microplastics (96%). Of the experiments that researched microplastics, the majority used polyethylene and polystyrene, and only a few investigated other polymer types such as PVC, PET, polypropylene, and others. Finally, 76% of all studies focused only on the marine environment, whereas relatively little research has been conducted on freshwater and terrestrial ecosystems. Understanding the effects of different plastic types, different sizes and shapes of plastics, as well as the effects in different ecosystems is critical to gaining a complete understanding of the health impacts of plastic pollution globally.

Conclusions

Mounting evidence suggests that plastic can impact multiple layers of biological organization, from molecular and cellular to organismal and population levels. These impacts are wide-ranging, inducing alterations to inflammation and oxidative stress, metabolic function, neurologic function, behavior, reproduction and development, and the microbiome. These effects are mediated both by the physical impacts of ingested or absorbed plastic particles and by the chemicals and microbes present in or on the plastics.

Despite the growing body of research on the impacts of plastics on global human, animal, plant, and overall ecosystem health, many questions remain. For one, more systematic and comprehensive studies are needed to account for the widespread differences in polymer type, plastic particle size, and additive mixtures. Additionally, there is a notable lack of research that integrates cell, organismal, population- and ecosystem-level impacts of plastic pollution, and little is understood about the cumulative exposure to plastics and additives over time across these levels of biology. Furthermore, the pace of global policy response and the adoption of plastic-reducing technologies is lagging substantially behind the rate of plastic consumption and production. A One Health approach can help address these knowledge gaps by providing a framework in which to integrate across biological scales, promote transdisciplinary partnerships, and engage stakeholders from diverse perspectives in an effort to mitigate and prevent the accelerating global plastic pollution crisis for the protection of all life on Earth.

Author contributions

MM, RT, PR, GM, JS, NJ, WE and AH each wrote sections of the manuscript. JS, NJ and WE helped supervise the project. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abidli, S., Pinheiro, M., Lahbib, Y., Neuparth, T., Santos, M. M., and Trigui El Menif, N. (2021). Effects of environmentally relevant levels of polyethylene microplastic on mytilus galloprovincialis (Mollusca: Bivalvia): filtration rate and oxidative stress. *Environ. Sci. pollut. Res.* 28, 26643–26652. doi: 10.1007/s11356-021-12506-8

Aloy, A. B., Vallejo, B. M., and Juinio-Meñez, M. A. (2011). Increased plastic litter cover affects the foraging activity of the sandy intertidal gastropod nassarius pullus. *Mar. pollut. Bull.* 62, 1772–1779. C.OMMAJ.R.X.X.X. doi: 10.1016/j.marpolbul.2011.05.021

Amato-Lourenço, L. F., Carvalho-Oliveira, R., Júnior, G. R., Dos Santos Galvão, L., Ando, R. A., and Mauad, T. (2021). Presence of airborne microplastics in human lung tissue. *J. Hazard. Mater.* 416, 126124. doi: 10.1016/j.jhazmat.2021.126124

Aneck-Hahn, N. H., Van Zijl, M. C., Swart, P., Truebody, B., Genthe, B., Charmier, J., et al. (2018). Estrogenic activity, selected plasticizers and potential health risks associated with bottled water in south Africa. *J. Water Health* 16, 253–262. doi: 10.2166/wh.2018.043

An, D., Na, J., Song, J., and Jung, J. (2021). Size-dependent chronic toxicity of fragmented polyethylene microplastics to daphnia magna. *Chemosphere* 271, 129591. doi: 10.1016/j.chemosphere.2021.129591

Avio, C. G., Gorbi, S., Milan, M., Benedetti, M., Fattorini, D., d'Errico, G., et al. (2015). Pollutants bioavailability and toxicological risk from microplastics to marine mussels. *Environ. pollut.* 198, 211–222. doi: 10.1016/j.envpol.2014.12.021

Baini, M., Martellini, T., Cincinelli, A., Campani, T., Minutoli, R., Panti, C., et al. (2017). First detection of seven phthalate esters (PAEs) as plastic tracers in superficial neustonic/planktonic samples and cetacean blubber. *Anal. Methods* 9, 1512–1520. doi: 10.1039/C6AY02674E

Banerjee, A., and Shelver, W. L. (2021). Micro- and nanoplastic induced cellular toxicity in mammals: A review. *Sci. Total Environ.* 755, 142518. doi: 10.1016/j.scitotenv.2020.142518

Barboza, L. G. A., Lopes, C., Oliveira, P., Bessa, F., Otero, V., Henriques, B., et al. (2020). Microplastics in wild fish from north East Atlantic ocean and its potential for causing neurotoxic effects, lipid oxidative damage, and human health risks associated with ingestion exposure. *Sci. Total Environ.* 717, 134625. doi: 10.1016/j.scitotenv.2019.134625

Barboza, L. G. A., Vieira, L. R., and Guilhermino, L. (2018). Single and combined effects of microplastics and mercury on juveniles of the European seabass (Dicentrarchus labrax): Changes in behavioural responses and reduction of swimming velocity and resistance time. *Environ. pollut.* 236, 1014–1019. doi: 10.1016/j.envpol.2017.12.082

Barnes, D. K. A., and Milner, P. (2005). Drifting plastic and its consequences for sessile organism dispersal in the Atlantic ocean. *Mar. Biol.* 146, 815–825. doi: 10.1007/s00227-004-1474-8

Barrett, J., Chase, Z., Zhang, J., Holl, M. M. B., Willis, K., Williams, A., et al. (2020). Microplastic pollution in deep-sea sediments from the great Australian bight. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.576170

Basak, S., Das, M. K., and Duttaroy, A. K. (2020). Plastics derived endocrine-disrupting compounds and their effects on early development. *Birth Defects Res.* 112, 1308–1325. doi: 10.1002/bdr2.1741

Basak, S., Srinivas, V., and Duttaroy, A. K. (2018). Bisphenol-a impairs cellular function and alters DNA methylation of stress pathway genes in first trimester trophoblast cells. *Reprod. Toxicol.* 82, 72–79. doi: 10.1016/j.reprotox.2018.10.009

Benson, N. U., Agboola, O. D., Fred-Ahmadu, O. H., De-la-Torre, G. E., Oluwalana, A., and Williams, A. B. (2022). Micro(nano)plastics prevalence, food web interactions, and toxicity assessment in aquatic organisms: A review. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.851281

Bergami, E., Bocci, E., Vannuccini, M. L., Monopoli, M., Salvati, A., Dawson, K. A., et al. (2016). Nano-sized polystyrene affects feeding, behavior and physiology of brine shrimp artemia franciscana larvae. *Ecotoxicol. Environ. Saf.* 123, 18–25. doi: 10.1016/j.ecoenv.2015.09.021

Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M. B., et al. (2017). High quantities of microplastic in Arctic deep-Sea sediments from the HAUSGARTEN observatory. *Environ. Sci. Technol.* 51, 11000–11010. doi: 10.1021/acs.est.7b03331

Bossart, G. D. (2011). Marine mammals as sentinel species for oceans and human health. *Vet. Pathol.* 48, 676–690. doi: 10.1177/0300985810388525

Brooks, A. L., Wang, S., and Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. *Sci. Adv.* 4, eaat0131. doi: 10.1126/sciadv.aat0131

Brun, N. R., van Hage, P., Hunting, E. R., Haramis, A.-P. G., Vink, S. C., Vijver, M. G., et al. (2019). Polystyrene nanoplastics disrupt glucose metabolism and cortisol levels with a possible link to behavioural changes in larval zebrafish. *Commun. Biol.* 2, 382. doi: 10.1038/s42003-019-0629-6

Bucci, K., Tulio, M., and Rochman, C. M. (2020). What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. *Ecol. Appl.* 30, e02044. doi: 10.1002/eap.2044

Buwono, N. R., Risjani, Y., and Soegianto, A. (2022). Oxidative stress responses of microplastic-contaminated gambusia affinis obtained from the brantas river in East Java, Indonesia. *Chemosphere* 293, 133543. doi: 10.1016/j.chemosphere.2022.133543

Capó, X., Alomar, C., Compa, M., Sole, M., Sanahuja, I., Soliz Rojas, D. L., et al. (2022). Quantification of differential tissue biomarker responses to microplastic ingestion and plasticizer bioaccumulation in aquaculture reared sea bream sparus aurata. *Environ. Res.* 211, 113063. doi: 10.1016/j.envres.2022.113063

Carlos de Sá, L., Luís, L. G., and Guilhermino, L. (2015). Effects of microplastics on juveniles of the common goby (Pomatoschistus microps): confusion with prey, reduction of the predatory performance and efficiency, and possible influence of developmental conditions. *Environ. pollut.* 196, 359–362. doi: 10.1016/j.envpol.2014.10.026

Carson, H. S., Colbert, S. L., Kaylor, M. J., and McDermid, K. J. (2011). Small plastic debris changes water movement and heat transfer through beach sediments. *Mar. pollut. Bull.* 62, 1708–1713. doi: 10.1016/j.marpolbul.2011.05.032

Catarino, A. I., Macchia, V., Sanderson, W. G., Thompson, R. C., and Henry, T. B. (2018). Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure *via* household fibres fallout during a meal. *Environ. pollut.* 237, 675–684. doi: 10.1016/j.envpol.2018.02.069

Chen, Q., Gundlach, M., Yang, S., Jiang, J., Velki, M., Yin, D., et al. (2017). Quantitative investigation of the mechanisms of microplastics and nanoplastics toward zebrafish larvae locomotor activity. *Sci. Total Environ.*, 584–585, 1022–1031. doi: 10.1016/j.scitotenv.2017.01.156

Chen, L., Guo, Y., Hu, C., Lam, P. K. S., Lam, J. C. W., and Zhou, B. (2018). Dysbiosis of gut microbiota by chronic coexposure to titanium dioxide nanoparticles and bisphenol a: Implications for host health in zebrafish. *Environ. pollut.* 234, 307–317. doi: 10.1016/j.envpol.2017.11.074

Choi, J. S., Jung, Y.-J., Hong, N.-H., Hong, S. H., and Park, J.-W. (2018). Toxicological effects of irregularly shaped and spherical microplastics in a marine teleost, the sheepshead minnow (Cyprinodon variegatus). *Mar. pollut. Bull.* 129, 231–240. doi: 10.1016/j.marpolbul.2018.02.039

Coffin, S., Bouwmeester, H., Brander, S., Damdimopoulou, P., Gouin, T., Hermabessiere, L., et al. (2022). Development and application of a health-based framework for informing regulatory action in relation to exposure of microplastic particles in California drinking water. *Microplastics Nanoplastics* 2, 12. doi: 10.1186/s43591-022-00030-6

Cole, M., Coppock, R., Lindeque, P. K., Altin, D., Reed, S., Pond, D. W., et al. (2019). Effects of nylon microplastic on feeding, lipid accumulation, and moulting in a coldwater copepod. *Environ. Sci. Technol.* 53, 7075–7082. doi: 10.1021/acs.est.9b01853

Corea-Téllez, K. S., Bustamante-Montes, P., García-Fábila, M., Hernández-Valero, M. A., and Vázquez-Moreno, F. (2008). Estimated risks of water and saliva contamination by phthalate diffusion from plasticized polyvinyl chloride. *J. Environ. Health* 71, 34–9, 45. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5633929/

Courtene-Jones, W., Maddalene, T., James, M. K., Smith, N. S., Youngblood, K., Jambeck, J. R., et al. (2021). Source, sea and sink–a holistic approach to understanding plastic pollution in the southern Caribbean. *Sci. Total Environ.* 797, 149098. doi: 10.1016/j.scitotenv.2021.149098

Cox, K. D., Covernton, G. A., Davies, H. L., Dower, J. F., Juanes, F., and Dudas, S. E. (2020). Correction to human consumption of microplastics. *Environ. Sci. Technol.* 54, 10974. doi: 10.1021/acs.est.0c04032

Cózar, A., Echevarría, F., González-Gordillo, J. I., Irigoien, X., Ubeda, B., Hernández-León, S., et al. (2014). Plastic debris in the open ocean. *Proc. Natl. Acad. Sci. U. S. A.* 111, 10239–10244. doi: 10.1073/pnas.1314705111

da Costa Araújo, A. P., de Andrade Vieira, J. E., and Malafaia, G. (2020). Toxicity and trophic transfer of polyethylene microplastics from poecilia reticulata to danio rerio. *Sci. Total Environ.* 742, 140217. doi: 10.1016/j.scitotenv.2020.140217

Das, S., Thiagarajan, V., Chandrasekaran, N., Ravindran, B., and Mukherjee, A. (2022). Nanoplastics enhance the toxic effects of titanium dioxide nanoparticle in freshwater algae scenedesmus obliquus. *Comp. Biochem. Physiol. C. Toxicol. Pharmacol.* 256, 109305. doi: 10.1016/j.cbpc.2022.109305

Desforges, J.-P. W., Galbraith, M., and Ross, P. S. (2015). Ingestion of microplastics by zooplankton in the northeast pacific ocean. *Arch. Environ. Contam. Toxicol.* 69, 320–330. doi: 10.1007/s00244-015-0172-5

Diana, Z., Vegh, T., Karasik, R., Bering, J., Llano Caldas, J. D., Pickle, A., et al. (2022). The evolving global plastics policy landscape: An inventory and effectiveness review. *Environ. Sci. Policy* 134, 34–45. doi: 10.1016/j.envsci.2022.03.028

Diana, Z. T., Karasik, R., Merril, GB., Morrison, M., Corcoran, KA., Vermeer, D., et al. (2022). A transdisciplinary approach to reducing global plastic pollution. *Frontiers in Marine Science*. doi: 10.3389/fmars.2022.1032381

Dreier, D. A., Mello, D. F., Meyer, J. N., and Martyniuk, C. J. (2019). Linking mitochondrial dysfunction to organismal and population health in the context of environmental pollutants: Progress and considerations for mitochondrial adverse outcome pathways. *Environ. Toxicol. Chem.* 38, 1625–1634. doi: 10.1002/etc.4453

Duncan, E. M., Broderick, A. C., Fuller, W. J., Galloway, T. S., Godfrey, M. H., Hamann, M., et al. (2019). Microplastic ingestion ubiquitous in marine turtles. *Glob. Change Biol.* 25, 744–752. doi: 10.1111/gcb.14519

Eriksen, M., Lebreton, L. C. M., Carson, H. S., Thiel, M., Moore, C. J., Borerro, J. C., et al. (2014). Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at Sea. *PloS One* 9, e111913. doi: 10.1371/journal.pone.0111913

Eriksen, M., Maximenko, N., Thiel, M., Cummins, A., Lattin, G., Wilson, S., et al. (2013). Plastic pollution in the south pacific subtropical gyre. *Mar. pollut. Bull.* 68, 71–76. doi: 10.1016/j.marpolbul.2012.12.021

Fatma Karaman, E., Caglayan, M., Sancar-Bas, S., Ozal-Coskun, C., Arda-Pirincci, P., and Ozden, S. (2019). Global and region-specific post-transcriptional and post-translational modifications of bisphenol a in human prostate cancer cells. *Environ. pollut.* 255, 113318. doi: 10.1016/j.envpol.2019.113318

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., et al. (2021). Our future in the anthropocene biosphere. *Ambio* 50, 834–869. doi: 10.1007/s13280-021-01544-8

Food and Agriculture Organization (2014). *The state of world fisheries and aquaculture 2014: opportunities and challenges* (Rome, Italy: Food & Agriculture Organization of the United Nations (FAO).

Fuller, S., and Gautam, A. (2016). A procedure for measuring microplastics using pressurized fluid extraction. *Environ. Sci. Technol.* 50, 5774–5780. doi: 10.1021/acs.est.6b00816

Galarpe, V. R. K. (2015). Review on the impacts of waste disposal sites in the Philippines. *Sci. Int.* 29(2) , 379–385.

Gall, S. C., and Thompson, R. C. (2015). The impact of debris on marine life. *Mar. pollut. Bull.* 92, 170–179. doi: 10.1016/j.marpolbul.2014.12.041

Gigault, J., Halle, A. T., Baudrimont, M., Pascal, P.-Y., Gauffre, F., Phi, T.-L., et al. (2018). Current opinion: What is a nanoplastic? *Environ. pollut.* 235, 1030–1034. doi: 10.1016/j.envpol.2018.01.024

Goldstein, M. C., Rosenberg, M., and Cheng, L. (2012). Increased oceanic microplastic debris enhances oviposition in an endemic pelagic insect. *Biol. Lett.* 8, 817–820. doi: 10.1098/rsbl.2012.0298

Gong, H., Zhang, X., Cheng, B., Sun, Y., Li, C., Li, T., et al. (2013). Bisphenol a accelerates toxic amyloid formation of human islet amyloid polypeptide: a possible link between bisphenol a exposure and type 2 diabetes. *PloS One* 8, e54198. doi: 10.1371/journal.pone.0054198

González, N., Cunha, S. C., Monteiro, C., Fernandes, J. O., Marquès, M., Domingo, J. L., et al. (2019). Quantification of eight bisphenol analogues in blood and urine samples of workers in a hazardous waste incinerator. *Environ. Res.* 176, 108576. doi: 10.1016/j.envres.2019.108576

González-Pleiter, M., Edo, C., Aguilera, Á., Viúdez-Moreiras, D., Pulido-Reyes, G., González-Toril, E., et al. (2021). Occurrence and transport of microplastics sampled within and above the planetary boundary layer. *Sci. Total Environ.* 761, 143213. doi: 10.1016/j.scitotenv.2020.143213

Groh, K. J., Backhaus, T., Carney-Almroth, B., Geueke, B., Inostroza, P. A., Lennquist, A., et al. (2019). Overview of known plastic packaging-associated chemicals and their hazards. *Sci. Total Environ.* 651, 3253–3268. doi: 10.1016/j.scitotenv.2018.10.015

Guerrera, M. C., Aragona, M., Porcino, C., Fazio, F., Laurà, R., Levanti, M., et al. (2021). Micro and nano plastics distribution in fish as model organisms: Histopathology, blood response and bioaccumulation in different organs. *Appl. Sci.* 11, 5768. doi: 10.3390/app11135768

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., and Purnell, P. (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J. Hazard. Mater.* 344, 179–199. doi: 10.1016/j.jhazmat.2017.10.014

Haq, M. E. U., Akash, M. S. H., Sabir, S., Mahmood, M. H., and Rehman, K. (2020). Human exposure to bisphenol a through dietary sources and development of diabetes mellitus: a cross-sectional study in Pakistani population. *Environ. Sci. pollut. Res. Int.* 27, 26262–26275. doi: 10.1007/s11356-020-09044-0

Hazen, E. L., Abrahms, B., Brodie, S., Carroll, G., Jacox, M. G., Savoca, M. S., et al. (2019). Marine top predators as climate and ecosystem sentinels. *Front. Ecol. Environ.* 17, 565–574. doi: 10.1002/fee.2125

Hernandez, L. M., Xu, E. G., Larsson, H. C. E., Tahara, R., Maisuria, V. B., and Tufenkji, N. (2019). Plastic teabags release billions of microparticles and nanoparticles into tea. *Environ. Sci. Technol.* 53, 12300–12310. doi: 10.1021/acs.est.9b02540

Hoyo-Alvarez, E., Arechavala-Lopez, P., Jiménez-García, M., Solomando, A., Alomar, C., Sureda, A., et al. (2022). Effects of pollutants and microplastics ingestion on oxidative stress and monoaminergic activity of seabream brains. *Aquat. Toxicol.* 242, 106048. doi: 10.1016/j.aquatox.2021.106048

Huang, B., Wei, Z.-B., Yang, L.-Y., Pan, K., and Miao, A.-J. (2019). Combined toxicity of silver nanoparticles with hematite or plastic nanoparticles toward two freshwater algae. *Environ. Sci. Technol.* 53, 3871–3879. doi: 10.1021/acs.est.8b07001

Huang, Z., Weng, Y., Shen, Q., Zhao, Y., and Jin, Y. (2021). Microplastic: A potential threat to human and animal health by interfering with the intestinal barrier function and changing the intestinal microenvironment. *Sci. Total Environ.* 785, 147365. doi: 10.1016/j.scitotenv.2021.147365

Huntington, H. P., Quakenbush, L. T., and Nelson, M. (2016). Effects of changing sea ice on marine mammals and subsistence hunters in northern Alaska from traditional knowledge interviews. *Biol. Lett.* 12, 20160198. doi: 10.1098/rsbl.2016.0198

Hu, M., and Palić, D. (2020). Micro- and nano-plastics activation of oxidative and inflammatory adverse outcome pathways. *Redox Biol.* 37, 101620. doi: 10.1016/j.redox.2020.101620

Hutter, H.-P., Kundi, M., Hohenblum, P., Scharf, S., Shelton, J. F., Piegler, K., et al. (2016). Life without plastic: A family experiment and biomonitoring study. *Environ. Res.* 150, 639–644. doi: 10.1016/j.envres.2016.05.028

Hutter, H.-P., Moshammer, H., Wallner, P., Damberger, B., Tappler, P., and Kundi, M. (2006). Health complaints and annoyances after moving into a new office building: a multidisciplinary approach including analysis of questionnaires, air and house dust samples. *Int. J. Hyg. Environ. Health* 209, 65–68. doi: 10.1016/j.ijheh.2005.08.010

Ibrahim, Y. S., Tuan Anuar, S., Azmi, A. A., Wan Mohd Khalik, W. M. A., Lehata, S., Hamzah, S. R., et al. (2021). Detection of microplastics in human colectomy specimens. *JGH Open* 5, 116–121. doi: 10.1002/jgh3.12457

International Organization for Migration and International Labour Organization (2021). Powering past the pandemic: Bolstering tuvalu's socioeconomic resilience in a covid-19 world. Available at: https://publications.iom.int/books/powering-past-pandemic-bolstering-tuvalus-socioeconomic-resilience-covid-19-world

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Marine pollution. plastic waste inputs from land into the ocean. *Science* 347, 768–771. doi: 10.1126/science.1260352

Jiang, J., Chen, Y., Yu, R., Zhao, X., Wang, Q., and Cai, L. (2016). Pretilachlor has the potential to induce endocrine disruption, oxidative stress, apoptosis and immunotoxicity during zebrafish embryo development. *Environ. Toxicol. Pharmacol.* 42, 125–134. doi: 10.1016/j.etap.2016.01.006

Jin, Y., Xia, J., Pan, Z., Yang, J., Wang, W., and Fu, Z. (2018). Polystyrene microplastics induce microbiota dysbiosis and inflammation in the gut of adult zebrafish. *Environ. pollut.* 235, 322–329. doi: 10.1016/j.envpol.2017.12.088

Junge, K. M., Leppert, B., Jahreis, S., Wissenbach, D. K., Feltens, R., Grützmann, K., et al. (2018). Mediates the impact of prenatal bisphenol a exposure on long-term body weight development. *Clin. Epigenet.* 10, 58. doi: 10.1186/s13148-018-0478-z

Kankanige, D., and Babel, S. (2020). Smaller-sized micro-plastics (MPs) contamination in single-use PET-bottled water in Thailand. *Sci. Total Environ.* 717, 137232. doi: 10.1016/j.scitotenv.2020.137232

Karami, A., Romano, N., Galloway, T., and Hamzah, H. (2016). Virgin microplastics cause toxicity and modulate the impacts of phenanthrene on biomarker responses in African catfish (Clarias gariepinus). *Environmental Research* 151, 58–70. doi: 10.1016/j.envres.2016.07.024

Karami, A., Golieskardi, A., Ho, Y. B., Larat, V., and Salamatinia, B. (2017). Microplastics in eviscerated flesh and excised organs of dried fish. *Sci. Rep.* 7, 1–9. doi: 10.1038/s41598-017-05828-6

Karasik, R., Vegh, T., Diana, Z., Bering, J., Caldas, J., Pickle, A., et al. (2020) *20 years of government responses to the global plastic pollution problem: The plastics policy inventory*. Available at: https://nicholasinstitute.duke.edu/sites/default/files/publications/20-Years-of-Government-Responses-to-the-Global-Plastic-Pollution-Problem-New_1.pdf.

Karbalaei, S., Hanachi, P., Walker, T. R., and Cole, M. (2018). Occurrence, sources, human health impacts and mitigation of microplastic pollution. *Environ. Sci. pollut. Res. Int.* 25, 36046–36063. doi: 10.1007/s11356-018-3508-7

Kasirajan, S., and Ngouajio, M. (2012). Polyethylene and biodegradable mulches for agricultural applications: a review. *Agron. Sustain. Dev.* 32, 501–529. doi: 10.1007/s13593-011-0068-3

Kim, L., Cui, R., Kwak, J. I., and An, Y.-J. (2022). Sub-Acute exposure to nanoplastics *via* two-chain trophic transfer: From brine shrimp artemia franciscana to small yellow croaker larimichthys polyactis. *Mar. pollut. Bull.* 175, 113314. doi: 10.1016/j.marpolbul.2021.113314

Kim, J. H., and Kim, S. H. (2020). Exposure to phthalate esters and the risk of endometriosis. *Dev. Reprod.* 24, 71–78. doi: 10.12717/DR.2020.24.2.71

Kirchnawy, C., Hager, F., Osorio Piniella, V., Jeschko, M., Washüttl, M., Mertl, J., et al. (2020). Potential endocrine disrupting properties of toys for babies and infants. *PloS One* 15, e0231171. doi: 10.1371/journal.pone.0231171

Koelmans, A. A., Bakir, A., Burton, G. A., and Janssen, C. R. (2016). Microplastic as a vector for chemicals in the aquatic environment: Critical review and model-supported reinterpretation of empirical studies. *Environ. Sci. Technol.* 50, 3315–3326. doi: 10.1021/acs.est.5b06069

Kosuth, M., Mason, S. A., and Wattenberg, E. V. (2018). Anthropogenic contamination of tap water, beer, and sea salt. *PloS One* 13, e0194970. doi: 10.1371/journal.pone.0194970

Kwon, B. G., Saido, K., Koizumi, K., Sato, H., Ogawa, N., Chung, S.-Y., et al. (2014). Regional distribution of styrene analogues generated from polystyrene degradation along the coastlines of the north-East pacific ocean and Hawaii. *Environ. pollut.* 188, 45–49. doi: 10.1016/j.envpol.2014.01.019

Kwon, J. A., Shin, B., and Kim, B. (2020). Urinary bisphenol a and thyroid function by BMI in the Korean national environmental health survey (KoNEHS) 2012-2014. *Chemosphere* 240, 124918. doi: 10.1016/j.chemosphere.2019.124918

Lang, I. A., Galloway, T. S., Scarlett, A., Henley, W. E., Depledge, M., Wallace, R. B., et al. (2008). Association of urinary bisphenol a concentration with medical disorders and laboratory abnormalities in adults. *JAMA* 300, 1303–1310. doi: 10.1001/jama.300.11.1303

Latini, G., De Felice, C., Presta, G., Del Vecchio, A., Paris, I., Ruggieri, F., et al. (2003). *In utero* exposure to di-(2-ethylhexyl)phthalate and duration of human pregnancy. *Environ. Health Perspect.* 111, 1783–1785. doi: 10.1289/ehp.6202

Lau, W. W. Y., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., et al. (2020). Evaluating scenarios toward zero plastic pollution. *Science* 369, 1455–1461. doi: 10.1126/science.aba9475

Law, K. L. (2017). Plastics in the marine environment. *Ann. Rev. Mar. Sci.* 9, 205–229. doi: 10.1146/annurev-marine-010816-060409

Law, K. L., Starr, N., Siegler, T. R., Jambeck, J. R., Mallos, N. J., and Leonard, G. H. (2020). The united states' contribution of plastic waste to land and ocean. *Sci. Adv.* 6, eabd0288. doi: 10.1126/sciadv.abd0288

Leslie, H. A., van Velzen, M. J. M., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., and Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environ. Int.* 163, 107199. doi: 10.1016/j.envint.2022.107199

Liebezeit, G., and Liebezeit, E. (2013). Non-pollen particulates in honey and sugar. *Food Addit. Contam. Part A Chem. Anal. Control Expo. Risk Assess.* 30, 2136–2140. doi: 10.1080/19440049.2013.843025

Liebezeit, G., and Liebezeit, E. (2015). Origin of synthetic particles in honeys. *Pol. J. Food Nutr. Sci.* 65, 143–147. doi: 10.1515/pjfns-2015-0025

Liu, Z.-H., Yin, H., and Dang, Z. (2017). Do estrogenic compounds in drinking water migrating from plastic pipe distribution system pose adverse effects to human? an analysis of scientific literature. *Environ. Sci. pollut. Res. Int.* 24, 2126–2134. doi: 10.1007/s11356-016-8032-z

Li, J., Yang, D., Li, L., Jabeen, K., and Shi, H. (2015). Microplastics in commercial bivalves from China. *Environ. pollut.* 207, 190–195. doi: 10.1016/j.envpol.2015.09.018

Lombó, M., Fernández-Díez, C., González-Rojo, S., Navarro, C., Robles, V., and Herráez, M. P. (2015). Transgenerational inheritance of heart disorders caused by paternal bisphenol a exposure. *Environ. pollut.* 206, 667–678. doi: 10.1016/j.envpol.2015.08.016

Lu, H., Diaz, D. J., Czarnecki, N. J., Zhu, C., Kim, W., Shroff, R., et al. (2022). Machine learning-aided engineering of hydrolases for PET depolymerization. *Nature* 604, 662–667. doi: 10.1038/s41586-022-04599-z

Machtinger, R., and Orvieto, R. (2014). Bisphenol a, oocyte maturation, implantation, and IVF outcome: review of animal and human data. *Reprod. Biomed. Online* 29, 404–410. doi: 10.1016/j.rbmo.2014.06.013

Manikkam, M., Tracey, R., Guerrero-Bosagna, C., and Skinner, M. K. (2013). Plastics derived endocrine disruptors (BPA, DEHP and DBP) induce epigenetic transgenerational inheritance of obesity, reproductive disease and sperm epimutations. *PloS One* 8, e55387. doi: 10.1371/journal.pone.0055387

Mariana, M., and Cairrao, E. (2020). Phthalates implications in the cardiovascular system. *J. Cardiovasc. Dev. Dis.* 7. doi: 10.3390/jcdd7030026

Mattsson, K., Johnson, E. V., Malmendal, A., Linse, S., Hansson, L.-A., and Cedervall, T. (2017). Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain. *Sci. Rep.* 7, 11452. doi: 10.1038/s41598-017-10813-0

Meeker, J. D., Sathyanarayana, S., and Swan, S. H. (2009). Phthalates and other additives in plastics: human exposure and associated health outcomes. *Philos. Trans. R. Soc Lond. B Biol. Sci.* 364, 2097–2113. doi: 10.1098/rstb.2008.0268

Muncke, J., Andersson, A.-M., Backhaus, T., Boucher, J. M., Carney Almroth, B., Castillo, A., et al. (2020). Impacts of food contact chemicals on human health: a consensus statement. *Environ. Health* 19, 25. doi: 10.1186/s12940-020-0572-5

Nadeem, A., Ahmad, S. F., Al-Harbi, N. O., Attia, S. M., Bakheet, S. A., Alsanea, S., et al. (2021). Aggravation of autism-like behavior in BTBR T+tf/J mice by environmental pollutant, di-(2-ethylhexyl) phthalate: Role of nuclear factor erythroid 2-related factor 2 and oxidative enzymes in innate immune cells and cerebellum. *Int. Immunopharmacol.* 91, 107323. doi: 10.1016/j.intimp.2020.107323

Nam, S.-H., Lee, J., and An, Y.-J. (2022). Towards understanding the impact of plastics on freshwater and marine microalgae: A review of the mechanisms and toxicity endpoints. *J. Hazard. Mater.* 423, 127174. doi: 10.1016/j.jhazmat.2021.127174

Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., and Beas, I. N. (2021). An overview of plastic waste generation and management in food packaging industries. *Recycl. Today* 6, 12. doi: 10.3390/recycling6010012

Nelms, S. E., Barnett, J., Brownlow, A., Davison, N. J., Deaville, R., Galloway, T. S., et al. (2019). Microplastics in marine mammals stranded around the British coast: ubiquitous but transitory? *Sci. Rep.* 9, 1075. doi: 10.1038/s41598-018-37428-3

Ocean Studies Board, Division on Earth and Life Studies, National Academies of Sciences Engineering and Medicine and Committee On The Assessment Of The Cumulative Effects Of Anthropogenic Stressors On Marine Mammals (2017). *Approaches to understanding the cumulative effects of stressors on marine mammals* (Washington, D.C., DC: National Academies Press).

Oliveira, P., Barboza, L. G. A., Branco, V., Figueiredo, N., Carvalho, C., and Guilhermino, L. (2018). Effects of microplastics and mercury in the freshwater bivalve corbicula fluminea (Müller 1774): Filtration rate, biochemical biomarkers and mercury bioconcentration. *Ecotoxicol. Environ. Saf.* 164, 155–163. doi: 10.1016/j.ecoenv.2018.07.062

One Health (2021) *OIE - world organisation for animal health*. Available at: https://www.oie.int/en/what-we-do/global-initiatives/one-health/ (Accessed May 13, 2022).

One Health (2022). Available at: https://www.cdc.gov/onehealth/index.html (Accessed May 13, 2022).

Paul-Pont, I., Lacroix, C., González Fernández, C., Hégaret, H., Lambert, C., Le Goïc, N., et al. (2016). Exposure of marine mussels mytilus spp. to polystyrene microplastics: Toxicity and influence on fluoranthene bioaccumulation. *Environ. pollut.* 216, 724–737. doi: 10.1016/j.envpol.2016.06.039

Pitt, J. A., Kozal, J. S., Jayasundara, N., Massarsky, A., Trevisan, R., Geitner, N., et al. (2018a). Uptake, tissue distribution, and toxicity of polystyrene nanoparticles in developing zebrafish (Danio rerio). *Aquat. Toxicol.* 194, 185–194. doi: 10.1016/j.aquatox.2017.11.017

Pitt, J. A., Trevisan, R., Massarsky, A., Kozal, J. S., Levin, E. D., and Di Giulio, R. T. (2018b). Maternal transfer of nanoplastics to offspring in zebrafish (Danio rerio): A case study with nanopolystyrene. *Sci. Total Environ.* 643, 324–334. doi: 10.1016/j.scitotenv.2018.06.186

Prinz, N., and Korez, Š. (2020). "Understanding how microplastics affect marine biota on the cellular level is important for assessing ecosystem function: A review," in *YOUMARES 9 - the oceans: Our research, our future* (Cham: Springer International Publishing), 101–120.

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., et al. (2021). Plasticenta: First evidence of microplastics in human placenta. *Environ. Int.* 146, 106274. doi: 10.1016/j.envint.2020.106274

Rangasamy, B., Malafaia, G., and Maheswaran, R. (2022). Evaluation of antioxidant response and Na-K-ATPase activity in zebrafish exposed to polyethylene microplastics: Shedding light on a physiological adaptation. *J. Hazard. Mater.* 426, 127789. doi: 10.1016/j.jhazmat.2021.127789

Rasool, F. N., Saavedra, M. A., Pamba, S., Perold, V., Mmochi, A. J., Maalim, M., et al. (2021). Isolation and characterization of human pathogenic multidrug resistant bacteria associated with plastic litter collected in Zanzibar. *J. Hazard. Mater.* 405, 124591. doi: 10.1016/j.jhazmat.2020.124591

Richards, Z. T., and Beger, M. (2011). A quantification of the standing stock of macro-debris in Majuro lagoon and its effect on hard coral communities. *Mar. pollut. Bull.* 62, 1693–1701. doi: 10.1016/j.marpolbul.2011.06.003

Roch, S., Friedrich, C., and Brinker, A. (2020). Uptake routes of microplastics in fishes: practical and theoretical approaches to test existing theories. *Sci. Rep.* 10, 3896. doi: 10.1038/s41598-020-60630-1

Rochman, C. M., Hentschel, B. T., and Teh, S. J. (2014). Long-term sorption of metals is similar among plastic types: implications for plastic debris in aquatic environments. *PloS One* 9, e85433. doi: 10.1371/journal.pone.0085433

Rochman, C. M., Tahir, A., Williams, S. L., Baxa, D. V., Lam, R., Miller, J. T., et al. (2015). Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Sci. Rep.* 5, 14340. doi: 10.1038/srep14340

Roman, J., Nevins, J., Altabet, M., Koopman, H., and McCarthy, J. (2016). Endangered right whales enhance primary productivity in the bay of fundy. *PloS One* 11, e0156553. doi: 10.1371/journal.pone.0156553

Rossi, G., Barnoud, J., and Monticelli, L. (2014). Polystyrene nanoparticles perturb lipid membranes. *J. Phys. Chem. Lett.* 5, 241–246. doi: 10.1021/jz402234c

Sarasamma, S., Audira, G., Siregar, P., Malhotra, N., Lai, Y.-H., Liang, S.-T., et al. (2020). Nanoplastics cause neurobehavioral impairments, reproductive and oxidative damages, and biomarker responses in zebrafish: Throwing up alarms of wide spread health risk of exposure. *Int. J. Mol. Sci.* 21, 1410. doi: 10.3390/ijms21041410

Schmaltz, E., Melvin, E. C., Diana, Z., Gunady, E. F., Rittschof, D., Somarelli, J. A., et al. (2020). Plastic pollution solutions: emerging technologies to prevent and collectmarineplastic pollution. *Environ. Int.* 144, 106067. doi: 10.1016/j.envint.2020.106067

Schwabl, P., Köppel, S., Königshofer, P., Bucsics, T., Trauner, M., Reiberger, T., et al. (2019). Detection of various microplastics in human stool: A prospective case series. *Ann. Intern. Med.* 171, 453–457. doi: 10.7326/M19-0618

Senathirajah, K., Attwood, S., Bhagwat, G., Carbery, M., Wilson, S., and Palanisami, T. (2021). Estimation of the mass of microplastics ingested - a pivotal first step towards human health risk assessment. *J. Hazard. Mater.* 404, 124004. doi: 10.1016/j.jhazmat.2020.124004

Senyildiz, M., Karaman, E. F., Bas, S. S., Pirincci, P. A., and Ozden, S. (2017). Effects of BPA on global DNA methylation and global histone 3 lysine modifications in SH-SY5Y cells: An epigenetic mechanism linking the regulation of chromatin modifiying genes. *Toxicol. In Vitro* 44, 313–321. doi: 10.1016/j.tiv.2017.07.028

Seoane, M., González-Fernández, C., Soudant, P., Huvet, A., Esperanza, M., Cid, Á., et al. (2019). Polystyrene microbeads modulate the energy metabolism of the marine diatom chaetoceros neogracile. *Environ. pollut.* 251, 363–371. doi: 10.1016/j.envpol.2019.04.142

Sheth, M. U., Kwartler, S. K., Schmaltz, E. R., Hoskinson, S. M., Martz, E. J., Dunphy-Daly, M. M., et al. (2019). Bioengineering a future free of marine plastic waste. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00624

Silva, M. S. S., Oliveira, M., Valente, P., Figueira, E., Martins, M., and Pires, A. (2020). Behavior and biochemical responses of the polychaeta hediste diversicolor to polystyrene nanoplastics. *Sci. Total Environ.* 707, 134434. doi: 10.1016/j.scitotenv.2019.134434

Sobhani, Z., Lei, Y., Tang, Y., Wu, L., Zhang, X., Naidu, R., et al. (2020). Microplastics generated when opening plastic packaging. *Sci. Rep.* 10, 1–7. doi: 10.1038/s41598-020-61146-4

Solleiro-Villavicencio, H., Gomez-De León, C. T., Del Río-Araiza, V. H., and Morales-Montor, J. (2020). The detrimental effect of microplastics on critical periods of development in the neuroendocrine system. *Birth Defects Res.* 112, 1326–1340. doi: 10.1002/bdr2.1776

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., et al. (2015). Sustainability. planetary boundaries: guiding human development on a changing planet. *Science* 347, 1259855. doi: 10.1126/science.1259855

Su, L., Cai, H., Kolandhasamy, P., Wu, C., Rochman, C. M., and Shi, H. (2018). Using the Asian clam as an indicator of microplastic pollution in freshwater ecosystems. *Environ. pollut.* 234, 347–355. doi: 10.1016/j.envpol.2017.11.075

Summers, J. K., Smith, L. M., Case, J. L., and Linthurst, R. A. (2012). A review of the elements of human well-being with an emphasis on the contribution of ecosystem services. *Ambio* 41, 327–340. doi: 10.1007/s13280-012-0256-7

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M. E. J., et al. (2016). Oyster reproduction is affected by exposure to polystyrene microplastics. *Proc. Natl. Acad. Sci. U. S. A.* 113, 2430–2435. doi: 10.1073/pnas.1519019113

Tao, S., Zhang, Y., Yuan, C., Gao, J., Wu, F., and Wang, Z. (2016). Oxidative stress and immunotoxic effects of bisphenol a on the larvae of rare minnow gobiocypris rarus. *Ecotoxicol. Environ. Saf.* 124, 377–385. doi: 10.1016/j.ecoenv.2015.11.014

Taylor, S. F. W., Roberts, M. J., Milligan, B., and Ncwadi, R. (2019). Measurement and implications of marine food security in the Western Indian ocean: an impending crisis? *Food Secur.* 11, 1395–1415. doi: 10.1007/s12571-019-00971-6

Thompson, R. C., Moore, C. J., vom Saal, F. S., and Swan, S. H. (2009). Plastics, the environment and human health: current consensus and future trends. *Philos. Trans. R. Soc Lond. B Biol. Sci.* 364, 2153–2166. doi: 10.1098/rstb.2009.0053

Tournier, V., Topham, C. M., Gilles, A., David, B., Folgoas, C., Moya-Leclair, E., et al. (2020). An engineered PET depolymerase to break down and recycle plastic bottles. *Nature* 580, 216–219. doi: 10.1038/s41586-020-2149-4

Trevisan, R., Ranasinghe, P., Jayasundara, N., and Di Giulio, R. T. (2022). Nanoplastics in aquatic environments: Impacts on aquatic species and interactions with environmental factors and pollutants. *Toxics* 10, 326. doi: 10.3390/toxics10060326

Trevisan, R., Uzochukwu, D., and Di Giulio, R. T. (2020). PAH sorption to nanoplastics and the trojan horse effect as drivers of mitochondrial toxicity and PAH localization in zebrafish. *Front. Environ. Sci. Eng. China* 8. doi: 10.3389/fenvs.2020.00078

Trevisan, R., Voy, C., Chen, S., and Di Giulio, R. T. (2019). Nanoplastics decrease the toxicity of a complex PAH mixture but impair mitochondrial energy production in developing zebrafish. *Environ. Sci. Technol.* 53, 8405–8415. doi: 10.1021/acs.est.9b02003

Van Cauwenberghe, L., and Janssen, C. R. (2014). Microplastics in bivalves cultured for human consumption. *Environ. pollut.* 193, 65–70. doi: 10.1016/j.envpol.2014.06.010

von Moos, N., Burkhardt-Holm, P., and Köhler, A. (2012). Uptake and effects of microplastics on cells and tissue of the blue mussel mytilus edulis l. after an experimental exposure. *Environ. Sci. Technol.* 46, 11327–11335. doi: 10.1021/es302332w

Wagner, M., and Oehlmann, J. (2011). Endocrine disruptors in bottled mineral water: estrogenic activity in the e-screen. *J. Steroid Biochem. Mol. Biol.* 127, 128–135. doi: 10.1016/j.jsbmb.2010.10.007

Waite, H. R., Donnelly, M. J., and Walters, L. J. (2018). Quantity and types of microplastics in the organic tissues of the eastern oyster crassostrea virginica and Atlantic mud crab panopeus herbstii from a Florida estuary. *Mar. pollut. Bull.* 129, 179–185. doi: 10.1016/j.marpolbul.2018.02.026

Walker, I., Montaño, M. D., Lankone, R. S., Fairbrother, D. H., and Ferguson, P. L. (2021). Influence of CNT loading and environmental stressors on leaching of polymer-associated chemicals from epoxy and polycarbonate nanocomposites. *Environ. Chem.* 18, 131. doi: 10.1071/EN21043

Wang, Q., Bai, J., Ning, B., Fan, L., Sun, T., Fang, Y., et al. (2020). Effects of bisphenol a and nanoscale and microscale polystyrene plastic exposure on particle uptake and toxicity in human caco-2 cells. *Chemosphere* 254, 126788. doi: 10.1016/j.chemosphere.2020.126788

Wang, C., Gao, W., Liang, Y., Jiang, Y., Wang, Y., Zhang, Q., et al. (2019). Migration of chlorinated paraffins from plastic food packaging into food simulants: Concentrations and differences in congener profiles. *Chemosphere* 225, 557–564. doi: 10.1016/j.chemosphere.2019.03.039

Wang, C., Hou, M., Shang, K., Wang, H., and Wang, J. (2022). Microplastics (Polystyrene) exposure induces metabolic changes in the liver of rare minnow (). *Molecules* 27, 584. doi: 10.3390/molecules27030584

Wang, H., Zhao, P., Huang, Q., Chi, Y., Dong, S., and Fan, J. (2019). Bisphenol-a induces neurodegeneration through disturbance of intracellular calcium homeostasis in human embryonic stem cells-derived cortical neurons. *Chemosphere* 229, 618–630.

Wang, Y., Mao, Z., Zhang, M., Ding, G., Sun, J., and Du, M. (2019c). The uptake and elimination of polystyrene microplastics by the brine shrimp, Artemia parthenogenetica, and its impact on its feeding behavior and intestinal histology. *Chemosphere* 234, 123–131. doi: 10.1016/j.chemosphere.2019.05.267

Wen, B., Zhang, N., Jin, S.-R., Chen, Z.-Z., Gao, J.-Z., Liu, Y., et al. (2018). Microplastics have a more profound impact than elevated temperatures on the predatory performance, digestion and energy metabolism of an Amazonian cichlid. *Aquat. Toxicol.* 195, 67–76. doi: 10.1016/j.aquatox.2017.12.010

Wiesinger, H., Wang, Z., and Hellweg, S. (2021). Deep dive into plastic monomers, additives, and processing aids. *Environ. Sci. Technol.* 55, 9339–9351. doi: 10.1021/acs.est.1c00976

Wilcox, C., Van Sebille, E., and Hardesty, B. D. (2015). Threat of plastic pollution to seabirds is global, pervasive, and increasing. *Proc. Natl. Acad. Sci. U. S. A.* 112, 11899–11904. doi: 10.1073/pnas.1502108112

World Health Organization (2022) *Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health*. Available at: https://www.who.int/publications/i/item/9789240054608.

Wright, S. L., and Kelly, F. J. (2017). Plastic and human health: A micro issue? *Environ. Sci. Technol.* 51, 6634–6647. doi: 10.1021/acs.est.7b00423

Yang, D., Shi, H., Li, L., Li, J., Jabeen, K., and Kolandhasamy, P. (2015). Microplastic pollution in table salts from China. *Environ. Sci. Technol.* 49, 13622–13627. doi: 10.1021/acs.est.5b03163

Yong, C. Q. Y., Valiyaveettil, S., and Tang, B. L. (2020). Toxicity of microplastics and nanoplastics in mammalian systems. *Int. J. Environ. Res. Public Health* 17, 1509. doi: 10.3390/ijerph17051509

Zantis, L. J., Bosker, T., Lawler, F., Nelms, S. E., O'Rorke, R., Constantine, R., et al. (2022). Assessing microplastic exposure of large marine filter-feeders. *Sci. Total Environ.* 818, 151815. doi: 10.1016/j.scitotenv.2021.151815

Zantis, L. J., Carroll, E. L., Nelms, S. E., and Bosker, T. (2021). Marine mammals and microplastics: A systematic review and call for standardisation. *Environ. pollut.* 269, 116142. doi: 10.1016/j.envpol.2020.116142

Zarus, G. M., Muianga, C., Hunter, C. M., and Pappas, R. S. (2021). A review of data for quantifying human exposures to micro and nanoplastics and potential health risks. *Sci. Total Environ.* 756, 144010. doi: 10.1016/j.scitotenv.2020.144010

Zhang, Q., Qu, Q., Lu, T., Ke, M., Zhu, Y., Zhang, M., et al. (2018). The combined toxicity effect of nanoplastics and glyphosate on microcystis aeruginosa growth. *Environ. pollut.* 243, 1106–1112. doi: 10.1016/j.envpol.2018.09.073

Zhao, X., Liu, Z., Ren, X., and Duan, X. (2021). Parental transfer of nanopolystyrene-enhanced tris(1,3-dichloro-2-propyl) phosphate induces transgenerational thyroid disruption in zebrafish. *Aquat. Toxicol.* 236, 105871. doi: 10.1016/j.aquatox.2021.105871

Zuccarello, P., Ferrante, M., Cristaldi, A., Copat, C., Grasso, A., Sangregorio, D., et al. (2019). Exposure to microplastics (<10 μm) associated to plastic bottles mineral water consumption: The first quantitative study. *Water Res.* 157, 365–371. doi: 10.1016/j.watres.2019.03.091

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The plastic-scape: Applying seascape ecology to marine plastic pollution

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Marine plastic pollution (MPP) has emerged as a global sustainability challenge with environmental, social, and economic consequences. This has inspired action at every scale of governance—from the local level to international institutions. However, policy and management efforts have been reactive and *ad hoc*, resulting in concerns about their efficacy, cost, and unintended consequences. To adequately address MPP and its global impacts, a systematic, evidence-based approach is needed. Seascape ecology, a subdiscipline of landscape ecology, is an interdisciplinary system science focused on the reciprocal relationship between the patterns and processes that shape seascapes. In this paper, we define the plastic-scape as all the social-ecological systems that interact with plastic (as a product and pollutant), the drivers and pathways of MPP, and the natural and human environments impacted by MPP. We then demonstrate the ways in which principles, methods, tools, and transdisciplinary research approaches from seascape ecology can be applied to better understand the plastic-scape, inform future MPP research and improve management strategies.

KEYWORDS

landscape ecology, plastic, pollution, policy, mitigation, marine, seascape ecology

1 Introduction

Marine plastic pollution (MPP) is an urgent sustainability challenge. In 2016 alone, between 19.3 and 23.4 million metric tons of plastic entered aquatic ecosystems (Borrelle et al., 2020). This pollution has environmental, economic, and social consequences (Beaumont et al., 2019), which have inspired global stakeholder action (Xanthos and Walker, 2017; Schnurr et al., 2018). Still, even if these ambitious actions are achieved, plastic pollution emissions will continue to rise due to increased production (Borrelle et al., 2020). As MPP continues to increase, so will its social, ecological, and economic consequences (Beaumont et al., 2019).

Current management efforts for MPP are often *ad hoc*, without consideration for decision-makers' goals, scale of governance, context of implementation, or systematic coordination across scales and sectors (Excell et al., 2018). Intervention efficacy is rarely evaluated and evaluated interventions report mixed outcomes (Excell et al., 2018). For example, bag regulations are among the most popular policies for plastics across the globe, yet less than half have been evaluated for effectiveness in reducing bag consumption, and 40% of evaluated policies have achieved little to no impact (Excell et al., 2018). In general, the effectiveness of popular interventions—bag bans and levies, deposit refund schemes, and dumping fines—are conditional on the context of implementation, including governance, socio-economic status, and environmental conditions (Lavee, 2010; McIlgorm et al., 2011; Oosterhuis et al., 2014; Excell et al., 2018).

Effectively implemented policies may still fail to reduce MPP. Research has shown that even if the most ambitious global commitments are achieved, annual plastic emissions will continue increase due to increased production driven by global development and population growth (Borrelle et al., 2020). This indicates that the suite of solutions being implemented are largely insufficient for addressing the primary sources and environmental pathways of MPP.

Finally, effective policy must ultimately reduce the social and ecological consequences of MPP, which depend on how MPP interacts with social and ecological communities. Not all ecosystems are equally vulnerable to MPP, and marine regions vary in their social and economical importance (Murphy et al. *in review*; Beaumont et al., 2019; Armoškaitė et al., 2020). As a result, policy effectiveness should not only be measured by MPP reduction, but also by social-ecological outcomes.

Failure to mitigate MPP and its consequences through current efforts has fueled calls for transformative, system-wide change along the entire plastics' life cycle (Borrelle et al., 2020; Raubenheimer and Urho, 2020). This will require action across scales of governance that not only consider policy objectives, but also feasibility, cost, trade-offs, and efficacy for mitigating the social, ecological, and economic consequences of MPP (Tessnow-von Wysocki and Le Billon, 2019; Murphy et al., 2021; Helm et al., 2022). This approach must 1) be transdisciplinary, 2) be multi-scale, 3) be spatially-explicit, and 4) encompass the entire *plastic-scape*—which includes all the governance systems, human actors, and ecological components (i.e., abiotic, and biotic processes) that contribute to patterns of plastic production, use, and pollution, as well as the interactions between MPP and human and natural communities that drive its social and ecological consequences (Figure 1).

Landscape ecology (LE) provides a spatially explicit, multi-scale approach for understanding social-ecological landscapes that is well-suited for MPP research and management (Wu, 2013; Opdam et al., 2018). LE draws on natural and human ecology, geography, history, economics, and wildlife management to understand the relationship between pattern and process in the environment (Risser et al., 1984; Wu, 2013). Historically, European LE focused on human landscapes and solutions-oriented questions, while North American LE aimed to advance quantitative methods for understanding natural systems (Wu and Hobbs, 2002). The integration of these approaches provides theory, principles, methods, and tools for studying complex and spatially explicit environmental challenges (Wu, 2013). Additionally, LE's contributions to sustainability science, environmental management, and conservation demonstrate its value in achieving conservation outcomes (Wu, 2006; Opdam et al., 2018).

More recently, seascape ecology (SE) has emerged (Pittman, 2018). Like LE, it is well-suited to support sustainability science and has informed several marine conservation issues (e.g., habitat restoration, marine planning), but its application to MPP has been limited (Fraschetti et al., 2009; Stamoulis and Friedlander, 2013; Rees et al., 2018).

SE offers a multi-scale approach for understanding and evaluating the *plastic-scape* (Cumming et al., 2017; Opdam et al., 2018). Below, we explore opportunities for applying SE to MPP research and management.

2 The seascape ecology approach

A seascape ecology approach can help address the shortcomings of the current approach by providing a framework that 1) is spatially explicit, to account for context of implementation, 2) is holistic and multi-scale, to ensure that the sum of individual interventions is enough to address this global challenge, and 3) integrates social and ecological outcomes.

The maturation of SE has promoted the emergence of seascape specific principles, tools, and methods to capture the dynamic and three-dimensional structure of the seascape, which is necessary for understanding MPP (Wedding et al., 2011; Kavanaugh et al., 2016; Lepczyk et al., 2021; Swanborn et al., 2022). It has also sparked interest in novel research priorities—seascape connectivity; seascape goods and services; ecosystem-based management; and applications for marine management (Pittman et al., 2021). This has driven novel approaches for evaluating these seascape components, which are important aspects of the *plastic-scape* that have been difficult to quantify (Grober-Dunsmore et al., 2009; Halpern et al., 2010; Barbier and Lee, 2014; Urlich et al., 2022).

Landscape sustainability science, another emerging subdiscipline, aims to understand how landscape structure and elements influence the sustainability of real-world landscapes, including biodiversity, ecological processes, ecosystem services, and human wellbeing (Wu, 2021). To center human dimensions of the landscape, the landscape sustainability science framework

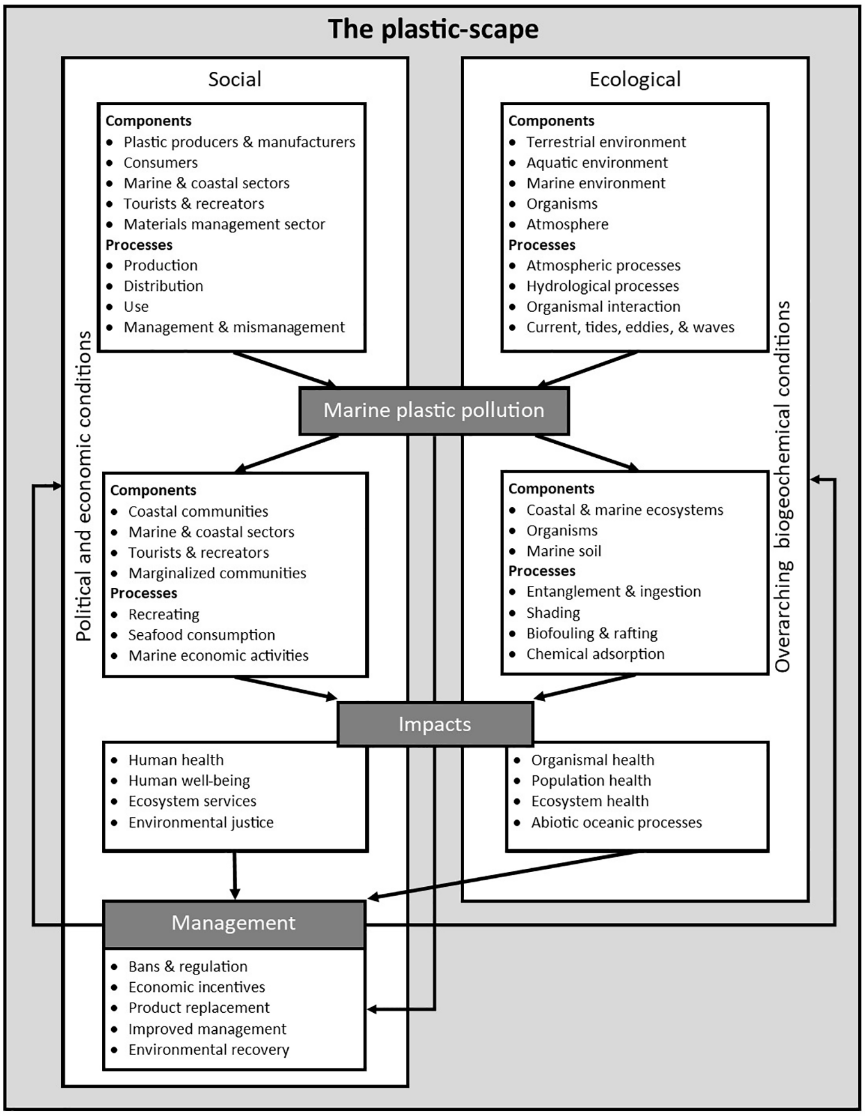

FIGURE 1
A conceptual model of the plastic-scape. The first set of social and ecological components and processes drive the creation and distribution of marine plastic pollution. The second interact with marine plastic pollution to drive the social-and ecological impacts of marine plastic pollution. Finally, marine plastic pollution and its impacts drive management actions that can act along the entire plastic-scape. The social and ecological components of the plastic-scape also interact with and influence each other.

captures a broader set of landscape pattern drivers than traditional LE—socioeconomic, political, technological, natural, and cultural—all of which are important in the *plastic-scape* (Bürgi et al., 2005). Further, landscape sustainability science is inherently transdisciplinary and applied. Therefore, approaches from this field can be used to inform transdisciplinary research and management approaches for the *plastic-scape* (Wu, 2021).

Below, we describe the ways SE principles can inform our understanding of the *plastic-scape*, describe applicable methods and tools for evaluating the *plastic-scape*, and discuss how LE and SE transdisciplinary research approaches can improve research and management.

2.1 Concepts from seascape ecology

2.1.1 Heterogeneity and pattern-process relationships

Heterogeneity is the spatial variation—or patterns—in a seascape, represented as patches or gradients (Wu, 2012;

Pittman, 2018). Composition relates to the number and proportion of patch types, while configuration relates to their spatial arrangement (Gustafson, 1998).

The *plastic-scape* is heterogenous in both its social and ecological dimensions. Patterns in MPP configuration exist, such as gradients throughout the water column and high-density patches in the gyres and coastal zones (Eriksen et al., 2014; Hardesty et al., 2017; Brignac et al., 2019). These patterns are well-represented in the MPP literature; however, the social-ecological components of the plastic-scape also have patterns, making the impacts of MPP on biodiversity, human health, marine ecosystem services, and human well-being heterogenous (Barbier and Lee, 2014; Bucci et al., 2020; Phelan et al., 2020). Heterogeneity in these other dimensions must also be considered to effectively address MPP and its consequences more broadly.

Processes are dynamic features that create and are influenced by seascape patterns (Turner, 1989; Boström et al., 2011; Fu et al., 2011). Seascape connectivity—the movement of living and non-living material from one location to another—is an important component of these pattern-process relationships (Hyndes et al., 2014; Olds et al., 2016; Olds et al., 2018). Most MPP is derived from land-based sources, which makes understanding land-sea connectivity and connectivity between human-dominated and natural ecosystems critical (Napper and Thompson, 2020).

Processes influencing the *plastic-scape* include all five drivers from landscape sustainability science—socioeconomic, political, technological, natural, and cultural (Bürgi et al., 2005). Socioeconomic, technological, cultural, and political processes affect the patterns of plastic production, use, management, and mismanagement in our environment, ultimately shaping the pathways of plastic leakage (Napper and Thompson, 2020; Thushari and Senevirathna, 2020). They also influence patterns of plastic type, shape, and chemical composition in the ocean (Napper and Thompson, 2020; Thushari and Senevirathna, 2020). The human processes driving patterns in the plastic-scape are influenced by the overarching geopolitical and socio-economic context, such as patterns of human population density, wealth, and governance (Jambeck et al., 2015; Borrelle et al., 2020).

Natural processes also drive patterns in the *plastic-scape*. Ecological processes (e.g., rainfall, animal movements) influence patterns of plastic leakage from management sites, such as landfills (Axelsson and van Sebille, 2017; Ballejo et al., 2021). Once in the environment, hydrological processes are one of the primary pathways for transporting terrestrial plastic pollution to the ocean, making watershed patterns important for informing patterns of MPP (Lebreton et al., 2017; Windsor et al., 2019; Correa-Araneda et al., 2022).

Oceanographic processes—currents, tides, and eddies—are the primary processes driving MP transportation and deposition in the ocean (Eriksen et al., 2014; Brignac et al., 2019). Interactions with animals (e.g., ingestion), plants (e.g., entanglement), bacteria (e.g., biofouling), and human activities (e.g., clean-ups) also contribute (Ocean Conservancy, 2016; Kaiser et al., 2017; Jacquin et al., 2019; Ryan, 2020; Sanchez-Vidal et al., 2021). Understanding the relationship between these processes and patterns, and which are most important across contexts, is critical for effective management.

Beyond exploring processes that drive MPP patterns, the *plastic-scape* must also integrate the pattern-process relationships of MPP impacts on human and natural communities. Considering patterns within the human and natural components of the *plastic-scape* can provide insight into the processes that drive patterns of impacts. For instance, overlaying patterns of MPP and human use of seascapes (e.g., tourist beaches or fishing areas), may inform patterns of high MPP impact (Mouat et al., 2010; Leggett et al., 2018; Beaumont et al., 2019). Currently, this is a significant gap in MPP research, which would benefit from place-based, seascape ecology approaches. Ultimately, as the impacts of MPP drive action, these pattern-process relationships should be centered in management approaches.

2.1.2 Scale and hierarchy organization

Scale is the grain (finest resolution) and extent (total area) of a seascape. As scale changes, dominant processes and patterns change (Wu, 2012). To fully understand the *plastic-scape*, processes and patterns must be studied across spatial and temporal scales, and the correct scale for analysis will depend on the patterns or processes of interest (Figure 2).

At the global scale, particular nations have been identified as MPP sources, but at finer scales different leakage patterns emerge, such as high MPP densities near urban centers, rivers, and landfills (Eriksen et al., 2014; Huang et al., 2020). The dominant processes driving national leakage patterns are wealth, governance, and socio-economic status, while infrastructure, municipal management practices, and local hydrology are more important locally (Jambeck et al., 2015; Lebreton et al., 2017; Thushari and Senevirathna, 2020). Spatial and temporal scales are often linked, with change occurring faster at finer scales (Westley et al., 2002). Current-driven accumulation of MPP in oceanographic gyres is a global pattern-process relationship occurring on the time scale of years to decades, while finer scale patterns are driven by smaller and faster oceanographic processes—wave action, eddies, or tides (Eriksen et al., 2014; Brignac et al., 2019).

Hierarchy theory assumes systems can be divided into nested levels, where patterns and processes occurring across scales are part of a single system with cross-scale effects (Kavanaugh et al., 2016; Allen and Starr, 2017).

Patterns and processes that emerge at different temporal and spatial scales of the plastic-scape influence each other. For example, global oceanographic processes are the dominant processes driving patterns of MPP associated with the gyres. However, these currents also contribute to local heterogeneity,

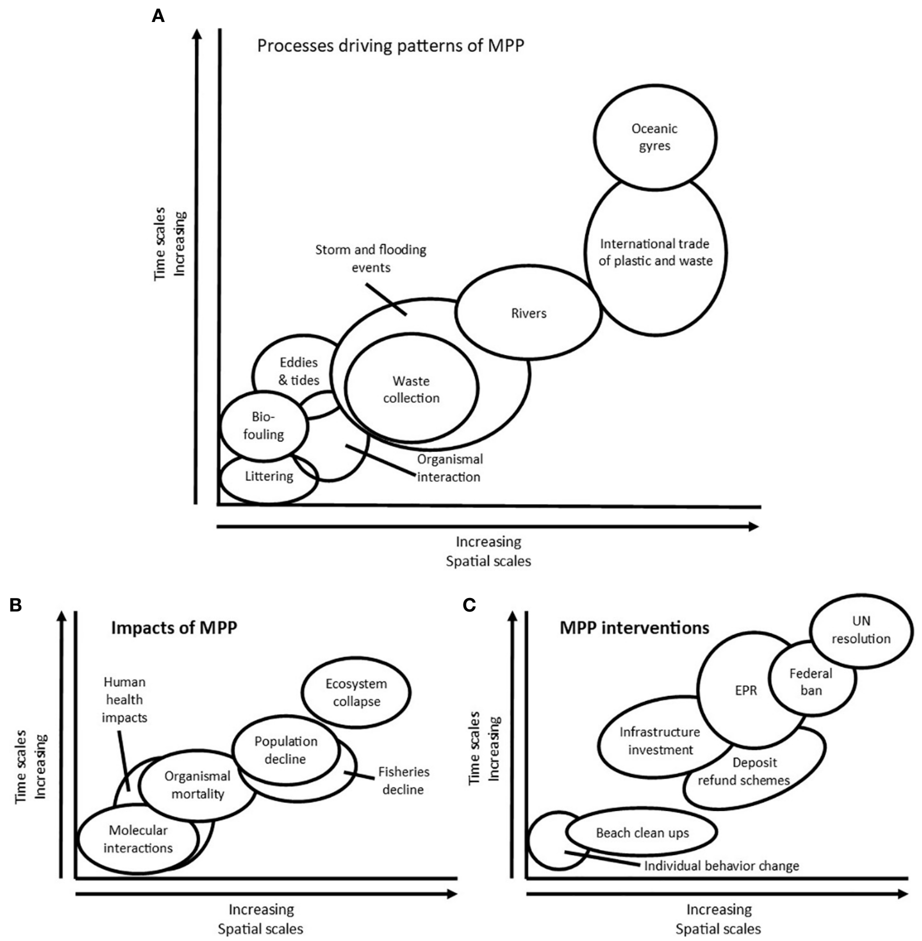

FIGURE 2
Time-space diagrams showcasing the multi-scale nature of the plastic-scape. **(A)** Provides examples of anthropogenic and natural processes that drive the spatial arrangement of marine plastic pollution. **(B)** Provides examples of the social-ecological impacts of plastic pollution. **(C)** Provides examples of marine plastic pollution management strategies.

such as the variation in MPP density between windward and leeward coasts (Brignac et al., 2019). Another cross-scale impact is the influence of national governance and socio-economic status on local plastic waste management strategies. National governance and wealth influence the resources, technology, and funding available to implement local waste management, ultimately changing local leakage rates (Helm et al., 2022).

Hierarchy theory can also be implemented to understand management across scales. Policies introduced at one scale of governance will influence others. For example, China's National Sword Policy, which regulates the import of recyclables, affected U.S. municipalities by decreasing the demand for plastic waste, ultimately driving local action (Murphy et al., 2020; Vedantam et al., 2022). Therefore, hierarchy theory provides an approach for understanding the *plastic-scape* as a whole and understanding the influence of interventions across levels of governance.

2.2 Methods and tools

SE provides tools, metrics, and methods that can be applied to the *plastic-scape* (Wedding et al., 2011; Costa et al., 2018). Additionally, it provides an ecological framework, technical skills, and best practices for applying them (Grober-Dunsmore et al., 2009; Lepczyk et al., 2021; Cumming et al., 2022).

Seascape ecologists employ a breadth of imaging tools—satellites and aerial photography, drones, boat-based sensors (e.g., LIDAR), autonomous vehicles, underwater imaging, benthic mapping, and semi-automated image classification—that can be used to map and monitor plastics (Costa et al., 2018; D'Urban Jackson et al., 2020). However, their limited use has focused on characterizing MPP transport and deposition (Lebreton et al., 2017; Salgado-Hernanz et al., 2021). MPP researchers have already called for the broader application of these methods, in the form of the integrated marine debris observing system, to develop global MPP maps for long-term monitoring and management (Maximenko et al., 2019).

SE also provides metrics to quantify characteristics of the *plastic-scape*. Spatial pattern metrics are applied to maps to quantify, characterize, and interpret patterns and pattern-process relationships (Boström et al., 2011; Wedding et al., 2011; Pittman et al., 2021). These metrics can be applied to the *plastic-scape* to quantify and interpret the distribution of MPP, the configuration of its social-ecological consequences, and the effects of management on these patterns.

Finally, SE provides modelling approaches. Network models, predictive spatial models, neutral seascape models and dynamic models have been applied to better understand marine conservation issues, characterize complex connectivity patterns at management appropriate scales, and simulate management outcomes under various scenarios (Pittman et al., 2007; Engelhard et al., 2017; Costa et al., 2018; Stamoulis et al., 2018; Treml and Kool, 2018; Wedding et al., 2019). We have seen the value of modeling MPP to understand patterns of MPP leakage (Lebreton et al., 2017; Borrelle et al., 2020). The application of SE models will improve the evaluation of interventions, provide spatially explicit outputs, and allow for multi-scale models.

2.3 Transdisciplinary research for management

SE transdisciplinary approaches can inform more effective MPP research and management (Pittman et al., 2021; Wu, 2021). First, research agendas should be co-produced. In SE, practitioners are being included in discussions about future research agendas, with their priorities deemed equally important to academics (Pittman et al., 2021). Though differences between these two groups remain, areas of agreement provide clear opportunities for collaboration (Cvitanovic et al., 2016; Dey et al., 2020). Setting a co-produced research agenda presents an opportunity for aligning the goals of the diverse group of stakeholders addressing MPP.

SE also provides methods for transdisciplinary research, including management specific metrics, predictive models to inform decision making, monitoring approaches, and tools to evaluate management outcomes (Nassauer and Opdam, 2008; Pressey and Bottrill, 2009; Olds et al., 2016; Pittman, 2018). The benefits of these approaches are exemplified by their rapid adoption in biodiversity conservation, restoration, and sustainable development (Choi et al., 2008; Opdam et al., 2018; Balbar and Metaxas, 2019).

3 Future research

Generally, an SE approach should be applied to answer spatially explicit, place-based questions about patterns in the *plastic-scape*, and the processes that drive them, with a focus on informing management. Since MPP is primarily land-based, characterizing connectivity between terrestrial and marine systems is critical. Hydrological models have already been applied to identify MPP leakage patterns and particular rivers as management priorities (Lebreton et al., 2017; Windsor et al., 2019; Correa-Araneda et al., 2022). Future research could explore different scales and processes to identify other contributors to leakage patterns.

Researchers should also explore how seascape configuration influences MPP pathways and patterns. For example, certain habitats act as plastic sinks (Martin et al., 2020; Sanchez-Vidal et al., 2021). Research on the relationship between seascape configuration and MPP deposition can be used to predict MPP patterns and inform management priorities.

Future work could also employ social sensing—the characterization of human components of the *plastic-scape* (Liu et al., 2015). Integration of human activity and social data into MPP maps and models could provide more insight into anthropogenic pathways of MPP leakage and the efficacy of different management efforts.

Finally, research to inform and evaluate management should be prioritized. For example, researchers can employ predictive spatial models to compare outcomes associated with various intervention strategies and inform a multi-scale management plan that integrates action across levels of governance. SE approaches could also provide baselines, allowing researchers to better monitor changes in *plastic-scape* patterns to evaluate management efficacy (Maximenko et al., 2019).

4 Limitations

Using the tools of SE, researchers can better understand the *plastic-scape*; however, this approach has limitations. The primary limitation is technological. To date, remote sensing has only been used to quantify surficial MPP (Goddijn-Murphy and Williamson, 2019). Additionally, satellite data typically has a resolution of >1 meter, which is too coarse to detect most MPP. Though alternatives exist, they can be expensive (e.g., aerial imaging and high spectral sensors), inconsistent (e.g., thermal infrared sensing), or range limited (e.g., drones) (Goddijn-Murphy and Williamson, 2019; Salgado-Hernanz et al., 2021). However, as technology improves and data collection becomes easier, the value of employing an SE approach will continue to increase.

Second, land-based pollution is not a research priority in SE (Pittman et al., 2021). Further, plastic pollution is a non-point source pollutant with a complex life cycle largely driven by human activity (Napper and Thompson, 2020). Identifying the appropriate scope and scale of analyses and actions may prove challenging. MPP also represents a breadth of pollutants that have different patterns, processes, and social-ecological consequences as they degrade, making MPP less predictable than other pollutants (Eriksen et al., 2014; Luo et al., 2022).

Finally, more research is needed on integrating human dimensions (e.g., ecosystem services) into SE models (Barbier and Lee, 2014; Pittman et al., 2021). Still, LE and SE continuously adapt to better address applied research questions. Therefore, as SE is further applied to MPP research and management, many of these limitations could be addressed.

5 Conclusion

The *plastic-scape* includes all the human (i.e., governance systems and actors) and ecological components (i.e., abiotic, and biotic processes) of the system that contribute to patterns of plastic production, use, and pollution, as well as the interactions between MPP and human and natural communities that drive its social and ecological consequences. Failures to effectively mitigate MPP and its consequences are exacerbated by the complexity of this system and the *ad hoc*, reactive nature of many management efforts. SE provides a novel approach for researching the *plastic-scape* informing effective management.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

EM: Conceptualization, led writing. BP: writing and editing. LG: writing and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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References

Allen, T. F. H., and Starr, T. B. (2017). *Hierarchy: Perspectives for ecological complexity* (Chicago: University of Chicago Press). doi: 10.7208/9780226489711

Armoškaitė, A., Puriņa, I., Aigars, J., Strāķe, S., Pakalniete, K., Frederiksen, P., et al. (2020). Establishing the links between marine ecosystem components, functions and services: An ecosystem service assessment tool. *Ocean. Coast. Manag.* 193, 105229. doi: 10.1016/j.ocecoaman.2020.105229

Axelsson, C., and van Sebille, E. (2017). Prevention through policy: Urban macroplastic leakages to the marine environment during extreme rainfall events. *Mar. Poll. Bull.* 124 (1), 211–227. doi: 10.1016/j.marpolbul.2017.07.024

Balbar, A. C., and Metaxas, A. (2019). The current application of ecological connectivity in the design of marine protected areas. *Glob. Ecol. Conserv.* 17, e00569. doi: 10.1016/j.gecco.2019.e00569

Ballejo, F., Plaza, P., Speziale, K. L., Lambertucci, A. P., and Lambertucci, S. A. (2021). Plastic ingestion and dispersion by vultures may produce plastic islands in natural areas. *Sci. Tot. Envir.* 755, 142421. doi: 10.1016/j.scitotenv.2020.142421

Barbier, E. B., and Lee, K. D. (2014). Economics of the marine seascape. *Int. Rev. Envir. Res. Econ.* 7 (1), 35–65. doi: 10.1561/101.00000056

Beaumont, N. J., Aanesen, M., Austen, M. C., Börger, T., Clark, J. R., Cole, M., et al. (2019). Global ecological, social and economic impacts of marine plastic. *Mar. Poll. Bull.* 142, 189–195. doi: 10.1016/j.marpolbul.2019.03.022

Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., et al. (2020). Global plastic waste generation exceeds efforts to mitigate plastic pollution. *Sci.* 369 (6510), 1515–1518. doi: 10.1126/science.aba3656

Boström, C., Pittman, S. J., Simenstad, C., and Kneib, R. T. (2011). Seascape ecology of coastal biogenic habitats: Advances, gaps, and challenges. *Mar. Eco. Pro. Ser.* 427, 191–217. doi: 10.3354/meps09051

Brignac, K. C., Jung, M. R., King, C., Royer, S. J., Blickley, L., Lamson, M. R., et al. (2019). Marine debris polymers on main Hawaiian island beaches, sea surface, and seafloor. *Enviro. Sci. Tech.* 53 (21), 12218–12226. doi: 10.1021/acs.est.9b03561

Bucci, K., Tulio, M., and Rochman, C. M. (2020). What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. *Ecol. App.* 30 (2), e02044. doi: 10.1002/eap.2044

Bürgi, M., Hersperger, A. M., and Schneeberger, N. (2005). Driving forces of landscape change - current and new directions. *Land. Ecol.* 19, 857–868. doi: 10.1007/s10980-005-0245-3

Choi, Y. D., Temperton, V. M., Allen, E. B., Grootjans, A. P., Halassy, M., Hobbs, R. J., et al. (2008). Ecological restoration for future sustainability in a changing environment. *Ecosci.* 15 (1), 53–64. doi: 10.2980/1195-6860(2008)15[53:ERFFSI]2.0.CO;2

Correa-Araneda, F., Pérez, J., Tonin, A. M., Esse, C., Boyero, L., Díaz, M. E., et al. (2022). Microplastic concentration, distribution and dynamics along one of the largest Mediterranean-climate rivers: A whole watershed approach. *Enviro. Res.* 209, 112808. doi: 10.1016/j.envres.2022.112808

Costa, B., Walker, B. K., and Dijkstra, J. A. (2018). "Mapping and quantifying seascape patterns," in *Seascape ecology*. Ed. S. Pittman (Hoboken, NJ: John Wiley & Sons), 27–56.

Cumming, G. S., Morrison, T. H., and Hughes, T. P. (2017). New directions for understanding the spatial resilience of social–ecological systems. *Eco.* 20, 649–664. doi: 10.1007/s10021-016-0089-5

Cumming, G. S., Magris, R. A., and Maciejewski, K. (2022). Quantifying cross-scale patch contributions to spatial connectivity. *Land. Eco.* 37(9), 2255–2272. doi: 10.1007/s10980-022-01497-7

Cvitanovic, C., McDonald, J., and Hobday, A. J. (2016). From science to action: principles for undertaking environmental research that enables knowledge exchange and evidence-based decision-making. *J. Environ. Manage.* 183, 864–874. doi: 10.1016/j.jenvman.2016.09.038

Dey, C. J., Rego, A. I., Midwood, J. D., and Koops, M. A. (2020). A review and meta-analysis of collaborative research prioritization studies in ecology, biodiversity conservation and environmental science. *Proc. R. Soc Bio.* 287, 20200012. doi: 10.1098/rspb.2020.0012

D'Urban Jackson, T., Williams, G. J., Walker-Springett, G., and Davies, A. J. (2020). Three-dimensional digital mapping of ecosystems: A new era in spatial ecology. *Pro. R. Soc Bio.* 287 (1920), 20192383. doi: 10.1098/rspb.2019.2383

Engelhard, S. L., Huijbers, C. M., Stewart-Koster, B., Olds, A. D., Schlacher, T. A., and Connolly, R. M. (2017). Prioritising seascape connectivity in conservation using network analysis. *J. App. Ecol.* 54 (4), 1130–1141. doi: 10.1111/1365-2664.12824

Eriksen, M., Lebreton, L. C., Carson, H. S., Thiel, M., Moore, C. J., Borerro, J. C., et al. (2014). Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PloS One* 9 (12), e111913. doi: 10.1371/journal.pone.0111913

Excell, C., Salcedo-La Viña, C., Worker, J., and Moses, E. (2018). *Legal limits on single-use plastics and microplastics: A global review of national laws and regulations* (Nairobi, Kenya: UNEP and WRI).

Fraschetti, S., D'Ambrosio, P., Micheli, F., Pizzolante, F., Bussotti, S., and Terlizzi, A. (2009). Design of marine protected areas in a human-dominated seascape. *Mar. Ecol. Prog. Ser.* 375, 13–24. doi: 10.3354/meps07781

Fu, B., Liang, D., and Lu, N. (2011). Landscape ecology: Coupling of pattern, process, and scale. *Chin. Geo. Sci.* 21 (4), 385–391. doi: 10.1007/s11769-011-0480-2

Goddijn-Murphy, L., and Williamson, B. (2019). On thermal infrared remote sensing of plastic pollution in natural waters. *Rem. Sens.* 11 (18), 2159. doi: 10.3390/rs11182159

Grober-Dunsmore, R., Pittman, S. J., Caldow, C., Kendall, M. S., and Frazer, T. K. (2009). "A landscape ecology approach for the study of ecological connectivity across tropical marine seascapes," in *Ecological connectivity among tropical coastal ecosystems* (Dordrecht: Springer), 493–530. doi: 10.1007/978-90-481-2406-0_14

Gustafson, E. J. (1998). Quantifying landscape spatial pattern: What is the state of the art? *Eco.* 1 (2), 143–156. doi: 10.1007/s100219900011

Halpern, B. S., Lester, S. E., and McLeod, K. L. (2010). Placing marine protected areas onto the ecosystem-based management seascape. *Proc. Nat. Acad. Sci.* 107 (43), 18312–18317. doi: 10.1073/pnas.0908503107

Hardesty, B. D., Harari, J., Isobe, A., Lebreton, L., Maximenko, N., Potemra, J., et al. (2017). Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment. *Fron. Mar. Sci.* 4. doi: 10.3389/fmars.2017.00030

Helm, L. T., Murphy, E. L., McGivern, A., and Borrelle, S. B. (2022). Impacts of plastic waste management strategies. *Enviro. Rev., (ja)*. doi: 10.1139/er-2021-0117

Huang, Y., Tian, M., Jin, F., Chen, M., Liu, Z., He, S., et al. (2020). Coupled effects of urbanization level and dam on microplastics in surface waters in a coastal watershed of southeast China. *Mar. Poll. Bull.* 154, 111089. doi: 10.1016/j.marpolbul.2020.111089

Hyndes, G. A., Nagelkerken, I., McLeod, R. J., Connolly, R. M., Lavery, P. S., and Vanderklift, M. A. (2014). Mechanisms and ecological role of carbon transfer within coastal seascapes. *Bio. Rev.* 89 (1), 232–254. doi: 10.1111/brv.12055

Jacquin, J., Cheng, J., Odobel, C., Pandin, C., Conan, P., Pujo-Pay, M., et al. (2019). Microbial ecotoxicology of marine plastic debris: A review on colonization and biodegradation by the "Plastisphere". *Front. Micro.* 10. doi: 10.3389/fmicb.2019.00865

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Sci.* 347 (6223), 768–771. doi: 10.1126/science.1260352

Kaiser, D., Kowalski, N., and Waniek, J. J. (2017). Effects of biofouling on the sinking behavior of microplastics. *Env. Res. Lett.* 12 (12), 124003. doi: 10.1088/1748-9326/aa8e8b

Kavanaugh, M. T., Oliver, M. J., Chavez, F. P., Letelier, R. M., Muller-Karger, F. E., and Doney, S. C. (2016). Seascapes as a new vernacular for pelagic ocean monitoring, management and conservation. *ICES J. Mar. Sci.* 73 (7), 1839–1850. doi: 10.1093/icesjms/fsw086

Lavee, D. (2010). A cost-benefit analysis of a deposit-refund program for beverage containers in Israel. *Waste. Manag.* 30(2), 338–345. doi: 10.1016/j.wasman.2009.09.026

Lebreton, L., van der Zwet, J., Damsteeg, J. W., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nat. Commun.* 8 (1), 1–10. doi: 10.1038/ncomms15611

Leggett, C. G., Scherer, N., Haab, T. C., Bailey, R., Landrum, J. P., and Domanski, A. (2018). Assessing the economic benefits of reductions in marine debris at southern California beaches: a random utility travel cost model. *Mar. Res. Econ.* 33 (2), 133–153. doi: 10.1086/697152

Lepczyk, C. A., Wedding, L. M., Asner, G. P., Pittman, S. J., Goulden, T., Linderman, M. A., et al. (2021). Advancing landscape and seascape ecology from a 2D to a 3D science. *BioS.* 71 (6), 596–608. doi: 10.1093/biosci/biab001

Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., et al. (2015). Systems integration for global sustainability. *Sci.* 347 (6225), 1258832. doi: 10.1126/science.1258832

Luo, H., Liu, C., He, D., Xu, J., Sun, J., Li, J., et al. (2022). Environmental behaviors of microplastics in aquatic systems: A systematic review on degradation, adsorption, toxicity and biofilm under aging conditions. *J. Haz. Mat.* 423, 126915. doi: 10.1016/j.jhazmat.2021.126915

Martin, C., Baalkhuyur, F., Valluzzi, L., Saderne, V., Cusack, M., Almahasheer, H., et al. (2020). Exponential increase of plastic burial in mangrove sediments as a major plastic sink. *Sci. Adv.* 6 (44), eaaz5593. doi: 10.1126/sciadv.aaz5593

Maximenko, N., Corradi, P., Law, K. L., Van Sebille, E., Garaba, S. P., Lampitt, R. S., et al. (2019). Toward the integrated marine debris observing system. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00447

McIlgorm, A., Campbell, H. F., and Rule, M. J. (2011). The economic cost and control of marine debris damage in the Asia-Pacific region. *Ocean Coast. Manag.* 54(9), 643–651. doi: 10.1016/j.ocecoaman.2011.05.007

Mouat, J., Lozano, R. L., and Bateson, H. (2010) *Economic impacts of marine litter. KIMO international*. Available at: https://www.kimointernational.org/wp/wp-content/uploads/2017/09/KIMO_Economic-Impacts-of-Marine-Litter.pdf.

Murphy, E. L., Bernard, M. L., Helm, L., Hill, I., and Tuñas-Corzón, Á. (2020). Policy recommendations to reinvigorate recycling in Arizona. *J. Sci. Pol. Gov.* 17. doi: 10.38126/JSPG170115

Murphy, E. L., Bernard, M., Iacona, G., Borrelle, S. B., Barnes, M., McGivern, A., et al. (2021). A decision framework for estimating the cost of marine plastic pollution interventions. *Con. Bio.* 36 (2), e13827. doi: 10.1111/cobi.13827

Murphy, E. L., Fredette-Roman, C., Rochman, C., Gerber, L. R., and Polidoro, B. (in review). Assessing the relative vulnerability of marine biodiversity to macroplastics. *Front. Eco. Enviro.*

Napper, I. E., and Thompson, R. C. (2020). Plastic debris in the marine environment: history and future challenges. *Glob. Chall.* 4 (6), 1900081. doi: 10.1002/gch2.201900081

Nassauer, J., and Opdam, P. (2008). Design in science: Extending the landscape ecology paradigm. *Land. Ecol.* 23, 633–644. doi: 10.1007/s10980-008-9226-7

Ocean Conservancy (2016) *30th anniversary international coastal cleanup*. Available at: https://oceanconservancy.org/wp-content/uploads/2017/04/2016-Ocean-Conservancy-ICC-Report.pdf.

Olds, A. D., Connolly, R. M., Pitt, K. A., Pittman, S. J., Maxwell, P. S., Huijbers, C. M., et al. (2016). Quantifying the conservation value of seascape connectivity: A global synthesis. *Glob. Ecol. Biog.* 25 (1), 3–15. doi: 10.1111/geb.12388

Olds, A. D., Nagelkerken, I., Huijbers, C. M., Gilby, B. L., Pittman, S. J., and Schlacher, T. A. (2018). "Connectivity in coastal seascapes," in *Seascape ecology*. Ed. S. Pittman (Hoboken, NJ: John Wiley & Sons), 261–292.

Oosterhuis, F., Papyrakis, E., and Boteler, B. (2014). Economic instruments and marine litter control. *Ocean .Coast. Manag.* 102, 47–54. doi: 10.1016/j.ocecoaman.2014.08.005

Opdam, P., Luque, S., Nassauer, J., Verburg, P. H., and Wu, J. (2018). How can landscape ecology contribute to sustainability science? *Land. Ecol.* 33 (1), 1–7. doi: 10.1007/s10980-018-0610-7

Phelan, A., Ross, H., Setianto, N. A., Fielding, K., and Pradipta, L. (2020). Ocean plastic crisis–mental models of plastic pollution from remote Indonesian coastal communities. *PloS One* 15 (7), e0236149. doi: 10.1371/journal.pone.0236149

Pittman, S. J. (2018). *Seascape ecology* (Hoboken, NJ: John Wiley & Sons).

Pittman, S. J., Christensen, J. D., Caldow, C., Menza, C., and Monaco, M. E. (2007). Predictive mapping of fish species richness across shallow-water seascapes in the Caribbean. *Ecol. Mod.* 204 (1-2), 9–21. doi: 10.1016/j.ecolmodel.2006.12.017

Pittman, S. J., Yates, K. L., Bouchet, P. J., Alvarez-Berastegui, D., Andréfouët, S., Bell, S. S., et al. (2021). Seascape ecology: identifying research priorities for an emerging ocean sustainability science. *Mar. Ecol. Pro. Ser.* 663, 1–29. doi: 10.3354/meps13661

Pressey, R. L., and Bottrill, M. C. (2009). Approaches to landscape-and seascape-scale conservation planning: convergence, contrasts and challenges. *Oryx* 43 (4), 464–475. doi: 10.1017/S0030605309990500

Raubenheimer, K., and Urho, N. (2020). *Possible elements of a new global agreement to prevent plastic pollution* (Copenhagen, Denmark: Nordic Council of Ministers).

Rees, M. J., Knott, N. A., and Davis, A. R. (2018). Habitat and seascape patterns drive spatial variability in temperate fish assemblages: Implications for marine protected areas. *Mar. Ecol. Pro. Ser.* 607, 171–186. doi: 10.3354/meps12790

Risser, P. G., Karr, J. R., and Forman, R. T. T. (1984) *Landscape ecology: directions and approaches*. Available at: https://www.ideals.illinois.edu/handle/2142/111627.

Ryan, P. G. (2020). Using photographs to record plastic in seabird nests. *Mar. Poll. Bull.* 156, 111262. doi: 10.1016/j.marpolbul.2020.111262

Salgado-Hernanz, P. M., Bauzà, J., Alomar, C., Compa, M., Romero, L., and Deudero, S. (2021). Assessment of marine litter through remote sensing: recent approaches and future goals. *Mar. Poll. Bull.* 168, 112347. doi: 10.1016/j.marpolbul.2021.112347

Sanchez-Vidal, A., Canals, M., de Haan, W. P., Romero, J., and Veny, M. (2021). Seagrasses provide a novel ecosystem service by trapping marine plastics. *Sci. Rep.* 11 (1), 1–7. doi: 10.1038/s41598-020-79370-3

Schnurr, R. E., Alboiu, V., Chaudhary, M., Corbett, R. A., Quanz, M. E., Sankar, K., et al. (2018). Reducing marine pollution from single-use plastics (SUPs): A review. *Mar. Poll. Bull.* 137, 157–171. doi: 10.1016/j.marpolbul.2018.10.001

Stamoulis, K. A., Delevaux, J. M., Williams, I. D., Poti, M., Lecky, J., Costa, B., et al. (2018). Seascape models reveal places to focus coastal fisheries management. *Ecol. App.s* 28 (4), 910–925. doi: 10.1002/eap.1696

Stamoulis, K. A., and Friedlander, A. M. (2013). A seascape approach to investigating fish spillover across a marine protected area boundary in hawai ‘i. *Fish. Res.* 144, 2–14. doi: 10.1016/j.fishres.2012.09.016

Swanborn, D. J., Huvenne, V. A., Pittman, S. J., and Woodall, L. C. (2022). Bringing seascape ecology to the deep seabed: A review and framework for its application. *Lim. Ocean.* 67 (1), 66–88. doi: 10.1002/lno.11976

Tessnow-von Wysocki, I., and Le Billon, P. (2019). Plastics at sea: Treaty design for a global solution to marine plastic pollution. *Enviro. Sci. Pol.* 100, 94–104. doi: 10.1016/j.envsci.2019.06.005

Thushari, G. G. N., and Senevirathna, J. D. M. (2020). Plastic pollution in the marine environment. *Heli.* 6 (8), e04709. doi: 10.1016/j.heliyon.2020.e04709

Treml, E. A., and Kool, J. (2018). “Networks for quantifying and analysing seascape connectivity,” in *Seascape ecology*. Ed. S. Pittman (Hoboken, NJ: John Wiley & Sons), 293–318.

Turner, M. G. (1989). Landscape ecology: The effect of pattern on process. *Ann. Rev. Ecol. Syst.* 20 (1), 171–197. doi: 10.1146/annurev.es.20.110189.001131

Urlich, S. C., White, F. R., and Rennie, H. G. (2022). Characterising the regulatory seascape in aotearoa new Zealand: Bridging local, regional and national scales for marine ecosystem-based management. *Oc. Coast. Man.* 224, 106193. doi: 10.1016/j.ocecoaman.2022.106193

Vedantam, A., Suresh, N. C., Ajmal, K., and Shelly, M. (2022). Impact of china’s national sword policy on the US landfill and plastics recycling industry. *Sust.* 14 (4), 2456. doi: 10.3390/su14042456

Wedding, L. M., Jorgensen, S., Lepczyk, C. A., and Friedlander, A. M. (2019). Remote sensing of three-dimensional coral reef structure enhances predictive modeling of fish assemblages. *Rem. Sens. Ecol. Cons.* 5 (2), 150–159. doi: 10.1002/rse2.115

Wedding, L. M., Lepczyk, C. A., Pittman, S. J., Friedlander, A. M., and Jorgensen, S. (2011). Quantifying seascape structure: Extending terrestrial spatial pattern metrics to the marine realm. *Mar. Ecol. Pro. Ser.* 427, 219–232. doi: 10.3354/meps09119

Westley, F., Carpenter, S. R., Brock, W. A., Holling, C. S., and Gunderson, L. H. (2002). “Why systems of people and nature are not just social and ecological systems,” in *Panarchy: Understanding transformations in human and natural systems*. Eds. L. H. Gunderson and C. S. Holling (Washington, DC: Island Press), 103–120.

Windsor, F. M., Durance, I., Horton, A. A., Thompson, R. C., Tyler, C. R., and Ormerod, S. J. (2019). A catchment-scale perspective of plastic pollution. *Glob. Cha. Bio.* 25 (4), 1207–1221. doi: 10.1111/gcb.14572

Wu, J. J. (2006). Landscape ecology, cross-disciplinarity, and sustainability science. *Land. Ecol.* 21 (1), 1–4. doi: 10.1007/s10980-006-7195-2

Wu, J. (2012). “Landscape ecology,” in *Encyclopedia of theoretical ecology*. Eds. A. Hastings and L. Gross (Berkeley, CA: University of California Press), 392–396.

Wu, J. (2013). Key concepts and research topics in landscape ecology revisited: 30 years after the allerton park workshop. *Land. Ecol.* 28 (1), 1–11. doi: 10.1007/s10980-012-9836-y

Wu, J. (2021). Landscape sustainability science (II): Core questions and key approaches. *Land. Ecol.* 36 (8), 2453–2485. doi: 10.1007/s10980-021-01245-3

Wu, J., and Hobbs, R. (2002). Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. *Land. Ecol.* 17 (4), 355–365. doi: 10.1023/A:1020561630963

Xanthos, D., and Walker, T. R. (2017). International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): A review. *Mar. Poll. Bull.* 118 (1-2), 17–26. doi: 10.1016/j.marpolbul.2017.02.048

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China's regulatory respond to plastic pollution: Trends and trajectories

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Despite China having an international reputation as one of the largest contributors to plastic pollution in the world's oceans, research analyzing China's regulatory approach to governing plastic has been limited and fragmented, and as such, little is known about trends and trajectories dominating China's plastic policy landscape. In this paper, we seek to address this gap in the literature through the construction and analysis of a complete inventory of China plastic-related policies from 1 January 2000 to 30 June 2021. Utilizing NVIVO (a qualitative analysis software), our analysis of 231 Chinese plastic policy documents shows that China's serious and concentrated effort to governing plastics really took off in the year 2016. From 2016, China saw a rapid increase in the attention paid to plastic pollution in the regulatory realm. In 2000, there were only four plastic-pertinent policies, but by the first half of 2021, this number has grown to 41, representing an increase of 925%. In this period, China has also significantly transformed its approach to governing plastics; not only has the goal and purpose of regulating plastic increased in complexity, but the type of plastics targeted and the different aspects of the plastic value chain included in various policies have become increasingly comprehensive over time. Concurrently, the deployment of different types of regulatory instruments utilized for the purpose of governing plastics in China has become much more diversified, with a major focus on prohibitive bans and information campaigns currently dominating Chinese plastic policy instruments. Economic policy instruments, on the other hand, especially economic incentives, have only recently been gaining popularity. Finally, today, most government agencies have published policies that are relevant to the regulation of plastic pollution control and prevention in China. Despite the massive increase in plastic pertinent policies in China, the predominant focus is still on back-end policy, with little regulatory attention on the upstream part of the plastic lifecycle (i.e., prodigious production of plastics). China's fairly recent plastic policy awakening should be understood in light of China's focus on the circular economy, the county's ramping up of regulatory focus, and fiscal investment in solid waste management and pertinent infrastructure. Towards the end of the paper, we point to some possible trajectories for the China plastic policy landscape, highlighting the synergies between reducing plastic production, consumption, and waste treatment and China's carbon neutrality ambition, as well as predicting a stronger policy focus and emphasis on plastic cleanup efforts.

KEYWORDS

China, plastic, policy instrument, plastic policy, plastic pollution management, regulatory framework and governance, policy design, policy trend analysis

1 Introduction

China is now the world's largest plastic producer. In 2021 alone, China produced 80.1 million tons of plastic (NBS, 2022), and whereas estimates vary[1] with regard to China's impact of plastic pollution on the world's oceans, it is clear that China plays an important role in addressing the global plastic pollution challenge. Despite earning an international reputation as one of the biggest contributors to global plastic pollution (Chen et al., 2019), China has undertaken serious efforts in the last two decades to address plastic pollution through, among others, ramping up and strengthening its regulatory frameworks with an ambition to significantly reduce leakage of plastic into the environment (Wang and Li, 2021). Some of these policies, such as China's ban on imports of plastic waste in 2017[2], are well-known to the international community for their remarkable impacts on global plastic trade flow (Brooks et al., 2018; Wang et al., 2019), but many of the plastic-related regulations and policies that have been developed on subnational levels in China in recent years are less well known. The Chinese legal and policy ecosystem is complex, and it is not within the scope of this paper to detail the structure of this system in detail. However, to support the reader in fully understanding the analysis presented in this paper, it is pivotal to explain some of the central features of how Chinese laws and policies are enacted and amended. It is the National People's Congress (NPC)[3] and its Standing Committee[4] that exercise the legislative power of the Chinese state. They enact and amend basic laws governing criminal offenses, civil affairs, state organs, and other matters (Gasper, 1982; Backer, 2012; Zhang, 2017). The NPC Standing Committee enacts and amends laws when the NPC is not in session, as long as such enactments or amendments are not in contradiction to the basic principles of such laws (Yan, 2013). The State Council formulates administrative regulations in accordance with the Constitution and laws and, upon

1 For example, Jambeck et al. (2015) estimated that 76% of all of China's waste had been mismanaged in the year 2010, which resulted in over 8 million tons of mismanaged plastic every year, of which between 1 and 3 million tons of plastic has been estimated to be released into the global oceans from China. In a paper published in 2020, Law et al. (2020) put China's mismanagement rate at 25% (for the year 2016) and the annual mismanaged plastic in China at about 1 million tons. In 2020, Li et al. calculated the mismanaged waste percentage for Chinese cities to range between 1% and 3.9% in 2017, whereas the estimated proportion was 12.8% and 27% for towns and rural townships, respectively. Li et al. therefore concluded that the annual mismanaged waste entering ocean from China to be between 0.257 and 0.353 million tons (in 2020).

2 In July, *Notice of the General Office of the State Council on Issuing the Implementation Plan for Prohibiting the Entry of Foreign Garbage and Advancing the Reform of the Solid Waste Import Administration System* (official English translation, "禁止洋垃圾入境推进固体废物进口管理制度改革实施方案" in Chinese) was approved and issued by the state council, which would stop the import of 24 kinds of solid waste from foreign countries, including plastics, textiles, paper products, etc.

3 The NPC is the highest organ of State power in China. It is composed of NPC deputies who are elected from 35 electoral units according to the law. These units include people's congresses of provinces, autonomous regions, municipalities directly under the central government, the servicemen's congress of the People's Liberation Army, the deputy election council of the Hong Kong Special Administrative Region, the deputy election council of the Macao Special Administrative Region, and the Taiwan compatriots' consultation election council. Each congress is elected for a term of 5 years.

4 The NPC Standing Committee is composed of a chairperson, several vice-chairpersons, the secretary general, and other members. They are all elected by the NPC from its deputies for a 5-year term, the same as the NPC term. The NPC Standing Committee normally meets once every 2 months. It may hold interim meetings when there is a special need. The NPC Standing Committee is responsible to the NPC and reports on its activities to it. The NPC has the power to alter or annul inappropriate decisions made by the Standing Committee and to remove its members from office.

authorization by the NPC, enacts provisional rules and regulations on economic system reform and opening–up policy (Yi-chong and Weller, 2016). Below the national government are local governments at the provincial, prefectural, county, township, and village levels. Here, the legal and policymaking infrastructure resembles that of the national level, with the local parties, governments, and people's congresses playing analogous roles (Xia, 1997). Subnational laws and policies can be developed by relevant state organs given that they are not in violation of related national-level policies (Li, 2010; Zhong, 2003). In addition, it should be noted that China retains many features of a command economy. One of the most prominent is the government's reliance on 5-year plans[5] and pertinent action plans to guide policymaking and measure the effectiveness of implementation (Hu, 2013).

In the last two decades, there have been several developments pertaining to China's approach to governing plastic within this complex ecosystem of state organs issuing laws and policies. Yet today, the Chinese landscape of plastic-related policies and regulatory developments remains uncharted territory. This might be due to the fact that research investigating China's plastic policies remains at an early stage. A handful of studies portray policies focusing on plastic packaging (Wei and Dong, 2008), disposable foam plastic tableware (Dong, 2009), the import of plastic waste, the ban on nondegradable single-use plastic straws (Xu et al., 2021), and tax policy for plastic pollution control (Xu et al., 2021). Certain studies go more in-depth in the analysis of a specific plastic policy; for example, Wei and Dong (2008) provide an analysis of plastic-related policies and pertinent developments with regard to the implementation of a quality safety licensing system for plastic packaging for food. Some studies have attempted to assess the effectiveness of various plastic bans or restriction orders, pointing to certain deficiencies in the policy design that led to ineffective implementation of such bans (at the early stages of the plastic bans in the mid-2000s) (Wang et al., 2019). One study, which investigated the usage of plastic bags in China after 2020 (Wang and Li, 2021), discovered several unintended impacts of the pricing policy and pointed to several gaps and loopholes in the design and the implementation of plastic-banning-related policies. One group of researchers assessing China's plastic bag policy (O'Loughlin, 2010) has highlighted that a plastic bag recycling program and the mainstream uptake within the general public of using environmentally friendly products is still underdeveloped in China. Other studies have found that policies banning plastic bags have led to a 49% reduction in the use of new plastic bags (He, 2012). However, the study finds that the regulatory effects of such plastic bag-banning policies differ broadly among consumer groups, regions, and shopping occasions. A study looking into promoting plastic pollution control through tax policy (GPTS, 2021) discovered that China's current laws and regulations related to plastic pollution governance are mostly administrative directives and that fiscal and tax policies have not yet become an important tool to restrict the production and use of plastic products. Jiang et al. (2020) have focused on assessing plastic stocks and flows in China from 1978 to 2017 and argues that material and waste management policies have been found to have a positive impact on improving recycling on a generic level, and although plastic policies *per se* was not an explicit focus of this particular study, it can be deduced that such polices have also had a positive impact on plastic waste management (Li, 2020).

Our current knowledge about China's approach to regulating plastics is therefore informed only by studies that take a narrow focus on examining policies targeting specific plastic products. Studies which comprehensively analyze the trends and trajectories of Chinese plastic policies on a national and subnational level are virtually nonexistent. This paper seeks to address some of the current gaps in the literature and subsequent general understanding of China's approach to regulating plastics through a regulatory and policy framework by asking and answering the following research questions:

1. What regulatory approach has China adopted to address plastic pollution since the year 2000? Which policies, regulating which type of plastic and at which stage of the plastic value chain, have been issued at what levels (national, provincial, city) by which agencies since the year 2000?
2. Which types of regulatory instruments have Chinese policymakers utilized to regulate which types of plastics since the year 2000? Which entities are targeted in such policies?
3. What trends and trajectories can be derived from the analysis of Chinese plastic-pertinent policies since the year 2000?

In this paper, we present a comprehensive mapping and analysis of 231 Chinese policy documents pertaining to the whole value chain of plastic production, consumption, and waste management. Based on NVIVO and textual analysis, this paper provides a comprehensive and in-depth analysis of various trends and trajectories pertaining to China's approach to managing plastics over the last 20 years. In the next section, we will introduce the methodology upon which the analysis presented in this paper is based. In the following section, we will present the main findings and analysis of the study. This will be followed by a discussion section and a concluding section.

5 The Five-Year Plan, full name: the "Outline of the Five-Year Plan for National Economic and Social Development of the People's Republic of China," is an important part of China's national economic plan. It is mainly created to set goals and directions for the long-term development of the national economy, culture, environment, etc.

2 Methodology and conceptual framework

This study draws on previous research conducted by Diana et al. (2022) and Karasik et al. (2020) mapping the global regulatory landscape of plastic policies and nation-state approaches to governing plastic.

In order to identify and characterize the public policy instruments various government agencies (such as the Ministry of Ecology and Environment and their subnational counterparties) have used to regulate plastic pollution in China, and in order to answer the research questions stated above, we undertook several analytical steps to screen the relevant policies, while concurrently building a conceptual framework for analysis of the regulatory documents included in the study. The study was guided by two overarching steps, each with several subcomponents:

1. The construction of a noncomprehensive China Plastics Policy Inventory through a screening process; and
2. Analysis of the content of the policy documents in the inventory to identify and characterize trends and trajectories of the identified policy instruments.

In the following section, we explain these steps. More detailed information about the methodology can be found in the appendices labeled "Detailed description of data cleaning" and "Complete codebook."

2.1 The construction of a noncomprehensive inventory of Chinese plastic policies

As with the methodological approach taken by Diana et al. (2022) and Karasik et al. (2020) in their study on the global plastics policy inventory and effectiveness review[6], we started this research process with the compilation of original Chinese public policy documents, defined here as official documents that include public-facing laws, statutes, ordinances, and management plans written and adopted by government entities, demonstrating an intent to reduce plastic pollution at various stages of the life cycle of plastics. We did not include other government documents such as judicial interpretation, monitoring reports, typical cases of trials[7], replies to administrative permit applications[8], or research papers. Given that, at the time of conducting this research, there was no (publicly available) comprehensive database of Chinese policies addressing plastic pollution, we had to start from scratch with the creation of a Chinese plastic policy inventory (hereinafter referred to as "the Inventory"). Only policies issued by mainland China government agencies have been included in the Inventory and the study.

The researchers utilized PKULaw (https://pkulaw.com) to search for relevant regulatory documents. PKULaw is considered to be one of the most comprehensive, professional, and authoritative law and policy databases in China, including nearly comprehensive coverage of laws and regulations from modern China (1949–present) promulgated by Chinese central and local governments.[9] In order to build the Inventory, we confined the search for documents to be included based on a list of keywords. As a complementary to the work undertaken by Karasik et al. (2020) and Diana et al. (2022) on the global plastic policy landscape, we used a new set of keywords as used by these scholars in their relevant scholarly work. For the purpose of this study, we added four new keywords in the search including plasticizer, polyethylene terephthalate[10], polyester, and fiber, as shown in Table 1. These keywords were added based on consultations with several relevant Chinese scholars and practitioners. The search was conducted using Chinese, the official written language in China, in order to capture as many details as possible in the original language (as only a limited number of policies were available in English).

Once we had decided on the list of keywords, we started to search for the relevant law and policy documents. In order to assure the most comprehensive results, we searched all the keywords independently *via* full-text search in the PKULaw database, rather than conducting searches with combined texts (e.g., plastic AND tire). The first screening result yielded approximately 20,000 policy documents, which were included in the original pool of policy

6 Chinese policies are included in the global inventory developed by Diana et al. (2022) and Karasik et al. (2020) but are limited to national-level policies, which have been issued also in English (in addition to Chinese). This study does not capture the complexities of the Chinese regulatory landscape.

7 Different levels of courts in China irregularly publish several cases of trials on the same subjects (such as damaging environmental resources, judicial protection of intellectual property rights, protection of juveniles, etc.), which are typical and have a strong demonstration significance, as a collective file.

8 Different levels of the Chinese government publish some replies to administrative permit applications for multiple issues, such as the constructional detailed planning of the land reconstruction project of a factory, renaming a branch of a state bank, etc.

9 The PKULaw database also includes secondary legal information such as white papers, law journal articles, legal news, and more, but these materials were not utilized for the purpose of this study.

10 Plastics are sometimes abbreviated in English, e.g., PET, PP, and PVC. In China, both Chinese full-names and English abbreviations may be used based on different contexts. In Chinese policies, such specific types of plastic are not usually listed, rather the generic term 'plastic' is utilized, with specific types of plastics or polymers referred to in policy appendices.

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TABLE 1 Keywords used to search for relevant public policy documents.

English	Chinese
Cigarette waste, marine debris, marine litter, microplastic, microfiber, nurdle, nylon, plastic, polyethylene, polymethyl methacrylate, polypropylene, polystyrene, polyvinyl chloride, shopping bag, styrofoam, synthetic disposable, tire, tyre, beach clean-up, coast clean-up, river clean-up, recyclate, polymer, bioplastic, oxodegradable, **plasticizer, polyethylene terephthalate, polyester, fiber**	烟蒂, 海洋废弃物, 海洋垃圾, 微塑料, 微纤维, 树脂颗粒, 尼龙, 塑料, 聚乙烯, 聚甲基丙烯酸甲酯, 聚丙烯, 聚苯乙烯, 聚氯乙烯, 购物袋, 泡沫塑料, 一次性用品, 轮胎, 车胎, 净滩, 河流清理, 可回收, 聚合物, 生物塑料, 可降解, **增塑剂, 聚对苯二甲酸乙酯, 涤纶, 纤维**

documents entering the screening process. We then embarked on a screening process following the steps outlined below, and in the end, we decided on a total number of 231 policy documents, which were included, full text, in the Inventory utilized for the purpose of the study (see Supplementary Material "China plastics policy inventory" for more details). The process of going from the original result of 20,000 policy documents, which included one of the keywords listed above, to the selection of the 231 core policy documents analyzed in this study is described in more detail in Figure 1.

For more details on the whole process of screening the policy documents, please see the Supplementary Material "Detailed description of data cleaning."

We acknowledge that there are methodological caveats in our study which may well bias our interpretation of the plastic-related policies of China. First, this study only accounts for regulatory documents in the period between 1 January 2000 and 30 June 2021. Policies issued before or after this time period are not accounted for. We are confident that this does influence our results, given the limited focus on plastic within the Chinese policy domain prior to the year

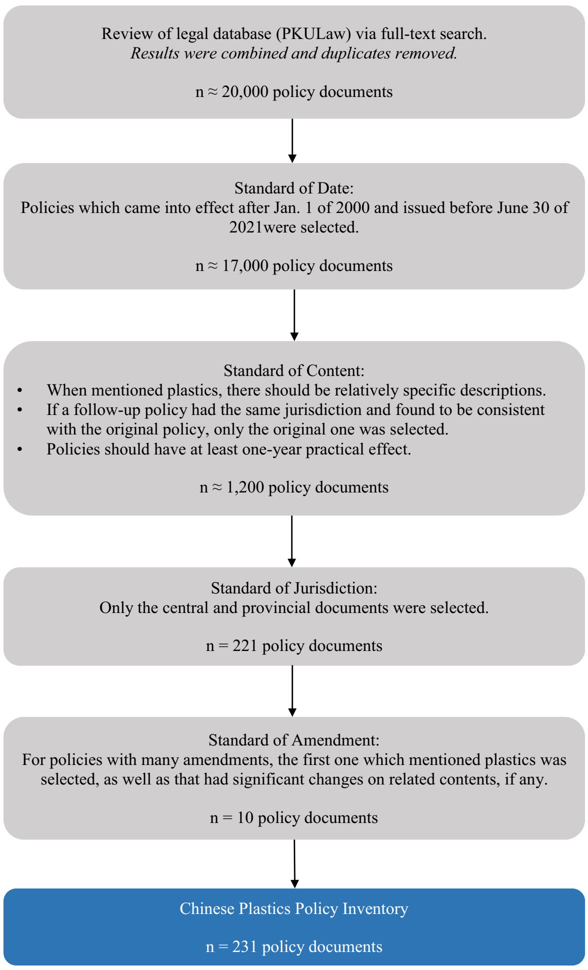

FIGURE 1
Brief summary of steps to construct a Chinese plastic policy inventory.

2000. Some relevant policies have been implemented in the period between the analysis of the Inventory and the writing of this paper. For instance, *a Notice by the National Development and Reform Commission and the Ministry of Ecology and Environment for the "14th Five-Year Plan" Action Plan for Plastic Pollution Control* issued on 8 September 2021, *Notice by the State Council of the Action Plan for Carbon Dioxide Peaking Before 2030* issued on 24 October 2021, and *Notice by the General Office of the State Council for New Pollutant Control Action Plan* issued on 4 May 2022. Although these policies and action plans are not included in the Inventory, we refer to them in our discussion section towards the latter part of the paper. Second, as the Inventory utilized for the purpose of the analysis in this paper includes both national-level and subnational-level policies, the manner in which subnational-level policies are oftentimes a response to the issuance of a national-level policy might have some impacts on the trends and trajectories derived from the analysis. For example, after the policy document *Opinions on Further Strengthening the Control of Plastic Pollution*[11] was issued by the National Development and Reform Commission and Ministry of Ecology and Environment in January 2020, 19 provinces and province-level cities subsequently issued similar policies later in the same year. As a result, when several subnational policies are released on the same topic, it is possible that there might be some inaccuracies in our analysis of pertinent trends and trajectories due to duplicated or variant policies. Moreover, our study does not address questions related to the effect or impact of the enacted laws and policies. Whereas we acknowledge that laws and policies on paper do not necessarily lead to changes on the ground, it is not within the scope of this study to examine the policy effectiveness of China's approach to regulating plastics.

2.2 From law and policy inventory to analysis

After law and policy documents were used to compile the Inventory, a methodology for analyzing these documents was devised. A codebook, drawing on the approach utilized by Diana et al. (2022) and Karasik et al. (2020), was adopted for the purpose of this study, which contains four "attribute" types (including "jurisdiction," "policy efficacy," "effective date," and "the main purpose of policy") and four sets of "nodes" (including "plastic targeted," "stage of the plastic life cycle targeted," "types of policy instrument," and "publishing agency"). Details pertaining to the codebook can be found in "Complete codebook" and will not be introduced in detail here. We used NVIVO—a qualitative analysis software—for textual analysis of the documents included in the Inventory. All 231 policy documents were input into NVIVO in full text in Mandarin. The coding and analysis were also conducted in Mandarin to ensure the most accurate analytical results. The results presented in the following section were subsequently translated back into English.

3 Results

3.1 The development of Chinese plastic policies: From calm waters in the early 2000s to a tidal wave of policies starting from 2016

In the early 2000s and before that, China was still at an initial stage with regard to the governance of plastic pollution. From 2000 to 2007 (effective dates of the policies), there were only 13 policies adopted that referenced plastic issues, most of which only mentioned plastics in a very generic manner, and which were included in other environmentally relevant regulatory frameworks, for example, the *Atmospheric Pollution Prevention and Control Law, Marine Environment Protection Law*, and *Regulations on Environmental Protection*. China's more explicit focus on regulating the consumption and use of plastic started in 2007 with very specific and targeted bans on certain plastic products namely a *Notice from the general office of the State Council on restricting the production, sale, and use of plastic shopping bags*[12]. A couple of months later (1 June 2008), the production, sale, and use of plastic bags with a thickness of less than 0.025 mm were banned in China. At the same time, a fee[13] for purchasing shopping bags was introduced. Specific provisions were made in the following years, on the production, sales, and use of plastic bags in order to take effective measures from the source, urging enterprises to produce durable and easy-to-recycle plastic shopping bags, while guiding and encouraging the general public to use plastic bags rationally, with the overarching goal of building a resource-saving and environment-friendly society.[14] However, the impact of

11 Translated by authors, "关于进一步加强塑料污染治理的意见" in Chinese. This policy was announced in January, 2020 by the Chinese National Development and Reform Commission and the Ministry of Ecology and Environment.

12 Translated by authors, "国务院办公厅关于限制生产销售使用塑料购物袋的通知" in Chinese.

13 The price of paid plastic bags is between 0.1 and 0.3 CNY.

14 Typical examples include the *Announcement on the inclusion of ultra-thin plastic shopping bags in the list of eliminated industries* (translated by authors, "国 家发展和改革委员会公告2008年第33号——关于将超薄塑料购物袋列入淘汰类产业目录的公告" in Chinese, effective in 2008), *Administrative Measures for the Paid Use of Plastic Bags at Commodity Retailing Places* (official English translation, "商品零售场所塑料购物袋有偿使用管理办法" in Chinese, effective in 2008), and *Notice on Deepening the Implementation of Restrictions on Production, Sales, and Use of Plastic Shopping Bags* (translated by authors, "国家发展和改革委员会、教育部、工业和信息化部等关于深化限制生产销售使用塑料购物袋实施工作的通知" in Chinese, effective in 2013).

these bans was limited, and for about 10 years, the focus on plastic pollution prevention and mitigation in China was put in the shadow of China's war on air pollution and the very early stages of solid waste management, which developed slowly until around 2019 (Guo et al., 2021).

The year 2016 marked a watershed movement in the development of Chinese plastic policies. This tidal wave of plastic-related policies most likely occurred as a response to the 13th Five-Year Plan (2016–2020), which laid the foundation for an unprecedented high level of ambition with regard to improving China's ecological and environmental quality by 2020 (Wan et al., 2022). As exemplified in one of the key policies issued during this period, the *Circular of the State Council on Printing and Distributing the 13th Five-Year Plan for the Protection of Ecological Environment*:

> "The overall objective is to improve the environmental quality by 2020. This includes specified targets of promoting green life and production, advancing low-carbon development, notably bringing down the total discharge of major pollutants, effectively controlling environmental risks, reversing biodiversity loss, striving for a more stable ecosystem, building ecological- security shields, achieving significant strides in modernizing national environmental governance system and capacity, and of bringing ecological civilization more aligned with the goal of achieving a moderately prosperous society in all aspects."[15]

To meet these targets, a number of policies have been issued in the domains of air, water, and soil pollution and their prevention, energy efficiency, etc. Concurrently, and for the first time, the number of new national-level policies addressing plastic issues promulgated within a single year reached 15, as illustrated in Figure 2A.

2020 is another critical year in China's plastic regulation history, marking the beginning of a new stage and approach concentrating explicitly on the governance of specific plastic types such as disposable plastic products, express packaging, and fertilizer packages, as well as specific stages of the plastic life cycle, including the use, collection, recycling, and reuse of various plastics. The policy document *Opinions on Further Strengthening the Control of Plastic Pollution*[16], well-known as the new "plastic ban,"[17] could be considered to be one of the most important policies issued in 2020. Many provinces and province-level cities subsequently issued similar policies later in that year, and a record high of 39 plastic policies were issued in 2020.

In the first half of the year 2021, when the 14th Five-Year Plan started, the total number of newly issued policies pertaining to plastic remained high, with 41 in total. A comparison between the 13th and the 14th Five-Year Plan shows that many more provinces and province-level cities mentioned plastics in their 14th Five-Year Plan, from 0 to 13. Overall, the total number of related policies has increased from 4 in 2000 (1-year data) to 231 by June 2021 (20.5-year data), which represents an increase of 5,675%. Central and provincial policies over the past two decades increased respectively from 3 to 97 and from 1 to 134 (Figure 2B).

3.2 Regulating plastics in China: From a single-issue ban on plastic bags to a comprehensive regulatory system governing the whole life cycle of plastics

3.2.1 The purpose of plastic policies is increasingly complex

One of the characteristics we utilized when analyzing the 231 policy documents in our Inventory was the "main purpose of the policy." This attribute of the policies has been applied in the process of identifying the goal of the different plastic policies issued by various Chinese authorities. Based on the analysis of our Inventory, we identified five overarching policy/legal goals and 12 relevant subgoals. For each policy, we have only accounted for one subgoal, as such subgoals relate to the "main" purpose of the legal document or policy. For more details about examples and the complete classification, please see the Supplementary Material "Complete codebook."

Among all the identified major goals, "plastics management and treatment," "comprehensive plan or regulation," and "specific ecosystem conservation" account for the top three, with a proportion of 36.8%, 26.4%, and 20.8%, respectively. Narrowing down the level of policies' goals, "ban or limit plastics (mainly bags and macroplastics)" is the most popular subpurpose among the policies issued (20.8%), followed by "development of ecological civilization (specific)" (18.2%) and "water protection (ocean, river, lake, and wetland)" (12.1%) (Figure 3).

15 *Circular of the State Council on Printing and Distributing the 13th Five-Year Plan for the Protection of Ecological Environment* (official English translation, "国务院关于印发'十三五' 生态环境保护规划的通知" in Chinese) issued in 2016.

16 Translated by authors, "关于进一步加强塑料污染治理的意见" in Chinese. It was announced in January, 2020 by the Chinese National Development and Reform Commission and Ministry of Ecology and Environment.

17 The old "plastic ban" generally refers to *Notice of the General Office of State Council on Restricting the Production, Sale and Use of Plastic Shopping Bags* (translated by authors, "国务院办公厅关于限制生产销售使用塑料购物袋的通知" in Chinese) issued in 2007, which first proposed that ultra-thin plastic bags would be banned nationwide and plastic bags would be paid for use. It should be pointed out that the name plastic ban here, whether the old or new, was given by the masses and is commonly used in unofficial scenarios such as media reports, daily chats, etc.

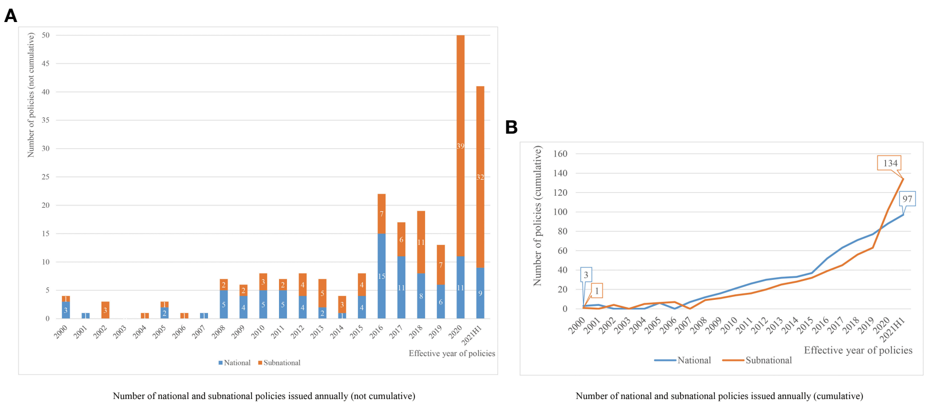

FIGURE 2
Trends in the number of Chinese plastic-pertinent policies. **(A)** Number of national and subnational policies issued annually (not cumulative). **(B)** Number of national and subnational policies issued annually (cumulative).

Considering the main goals of national policies only, policies issued on "plastics management and treatment" and "economic transformation and development" increased in fluctuation in the analyzed time period (Figure 4).

When taking subpurposes into account for all the policies, it is evident that a number of new purposes emerged around the year 2010, including "energy saving and emission reduction" (2008), "industrial or investment structure adjustment" (2009), "source collection and recycling" (2009), "body health" (2010), "deepening reform and opening-up (multiple aspects)" (2013), and "green transformation" (2013)[18], which has increased the diversity of policy types (Figure 5).

After 2016, the first watershed year for Chinese plastic-pertinent policies, the subpurposes of policies mainly concentrated on the following four issues: "ban or limit plastics (mainly bags and macroplastics)," "development of ecological civilization (specific)," "waters protection (ocean, river, lake, and wetland)," and "deepening reform and opening-up (multiple aspects)." They correspond to concrete plastics, macroscopic planning, ecological conservation, and economic development, respectively.

18 Most of the subpurposes are self-explanatory, whereas we may need to specify two here: "body health" means "to protect human health, usually including policies about the safety of food and drinking water, as well as control of smoking," and "industrial or investment structure adjustment" means "to accelerate structural adjustment and promote industrial upgrading." For the whole definition of all the subpurposes, please see the "Complete codebook."

3.2.2 The plastic types targeted are increasingly becoming more complex

During 2000–2021, macroplastics and general waste (referred to as the category "all (general)" in the codebook) were the most frequently referenced plastic types targeted in Chinese policies, both occurring in over half of the 231 policies in our Inventory, followed by agricultural mulch (44.2%), bags (31.6%), and pesticide packages[19] (19.5%) as shown in (Figure 6), indicating a stronger focus on challenges pertaining to managing plastic waste in the agricultural sector and in rural areas in the later years.

As shown in Figure 7, microplastics, agricultural mulch, and pesticide packages are policy targets that have increased rapidly as items of interest for Chinese policymakers, among which microplastics is a fairly new plastic issue to be regulated in China. "Microplastics" first occurred in three government documents in 2016; two responded to the Notification of the

19 Farmers are a large part of the Chinese population, and plastic pollution in the agricultural sector remains a challenge in the Chinese context. As such, many policies have been designed to address "issues concerning agriculture, countryside, and farmers." In plastic-pertinent policies, in particular, "agricultural mulch" and "pesticide packages" are mentioned frequently. Given the extensive utilization of such plastic products, it makes logical sense to single these plastic items out as separate categories to be regulated. In China, pesticide packages can be hard plastic bottles (containing liquid or solid pesticides) or large and thick plastic bags (containing solid pesticides or fertilizers). Current Chinese policies do not distinguish pesticide packages in a comprehensive and overarching consistent manner, but they are treated somewhat differently in different policies.

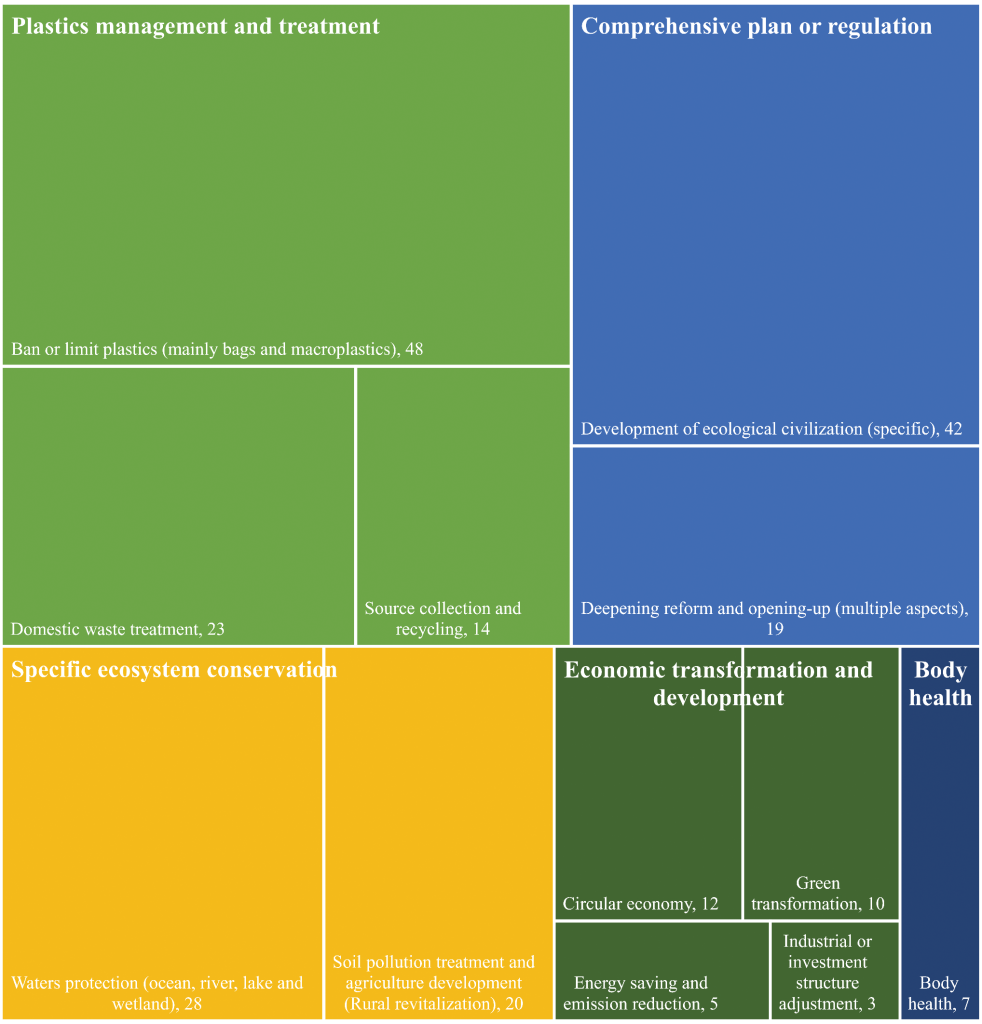

FIGURE 3
Number of policies issued on five major goals and 12 sub-purposes.

Marine Industry Standard System Revision, and one was related to the Notice of a disease research project application.[20] However, these notifications do not fall under the scope of documents included in this study, and as a result, the first detection we found for microplastics in our Inventory occurred in 2017. From 2017 to the first half of 2021, the number of policies referencing microplastics increased from 1 (2017) to a total of 29 (30 June 2021), most of which are provincial-level policies issued in 2020.

From the top to the bottom in Figure 8, the absolute quantity of policies corresponding to each exact subpurpose goes from

20 The first two are *Notice of the State Oceanic Administration on Organizing the Application for the Project Establishment of the 2016 Marine National Standard and Industry Standard Formulation and Revision Plan* (translated by authors, "国家海洋局关于组织申报2016年度海洋国家标准和行业标准制修订计划项目立项的通知" in Chinese) and *Notice of the State Oceanic Administration on the issuance of 49 marine industry standard formulation and revision plans including the 2016 "Technical Regulations for Monitoring and Early Warning of Marine Resources and Environment Carrying Capacity"* (translated by authors, "国家海洋局关于下达2016年度《海洋资源环境承载能力监测预警技术规程》等49项海洋行业标准制修订计划项目的通知" in Chinese), and the latter is *Notice of the Ministry of Science and Technology on Issuing the 2016 Project Application Guidelines for the National Key Research and Development Program - 2016 Annual Project Application Guidelines for Key Projects such as Major Chronic Non-communicable Disease Prevention and Control Research* (translated by authors, "科技部关于发布国家重点研发计划重大慢性非传染性疾病防控研究等重点专项2016年度项目申报指南的通知" in Chinese).

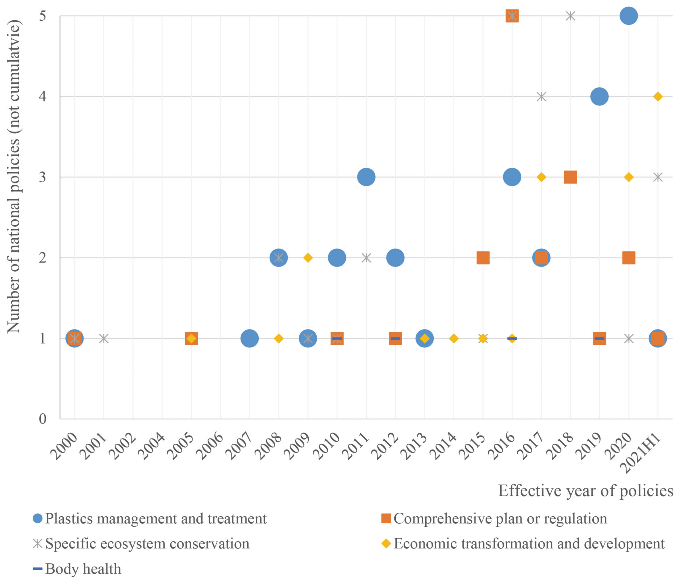

FIGURE 4
Number of national policies issued on five major goals annually (not cumulative).

high to low[21]. This chart indicates a strong correlation between the plastic targeted and the policies' subpurposes: policies on plastic ban or limit are relatively specific to plastic types such as bags, macroplastics, microplastics, agricultural mulch, and pesticide packages, accounting for over 90% of all the policies on "ban or limit plastics." General waste was most frequently mentioned in policies where the objective of the policy was to manage domestic waste (45.5%); marine sources, as a category of plastic analyzed in our study, play an important role (30.4%) in policies issued with the goal of protecting water, as do agricultural mulch and pesticide packages (74.2%) for policies issued in relation to "soil pollution treatment and agricultural development." An emphasis on agricultural plastic types by "circular economy" policies is also clear; agricultural mulch and pesticide packages account for 1/3 of all mentioned plastic targeted, which indicates the importance of agricultural issues within the Chinese circular economy.

3.2.3 The stages of the plastic value chain targeted are increasingly becoming more complex

China's plastic-pertinent policies have mainly focused on the following stages of the plastic life cycle: "collection" occurred in 72.7% of the policies, followed by "recycling" in 61.9%, "use" in 55.8%, "production" in 42.0%, "sales" in 39.4%, "disposal" in 34.6%, etc. (Figure 9).

Looking at the trend of stages of the plastic life cycle targeted from the temporal perspective (Figure 10), the proportion of front-end phases (including production, import, and selling) showed a fluctuating downward trend in recent years, whereas that of back-end phases (including collection, recycling, and reuse) has experienced exactly the opposite development, with an increase in policies issued for the purpose of managing plastic waste.

When taking five major goals of policies into consideration, as shown in Figure 11[22], the stage of disposal was mentioned most frequently (20.2%) in policies issued on "specific ecosystem conservation," compared to the same stage in other policies. Moreover, policies on economic transformation and development focus more on plastics' reuse than others, with a percentage of 15.5%.

3.3 Chinese authorities utilize all the tools in the regulatory instrument toolbox to regulate plastics

In our analysis of the regulatory approaches utilized by Chinese policymakers, we investigated three overarching types of policy

21 For reference, since one policy that has only one subpurpose may mention multiple plastic targeted in the content, the total number of each bar in this figure might be higher than that of policies on the subpurpose itself.

22 For reference, as one policy that has only one major goal may mention multiple stages of the plastic life cycle targeted, the total number of each column in this figure might be higher than that of policies on the main goal itself.

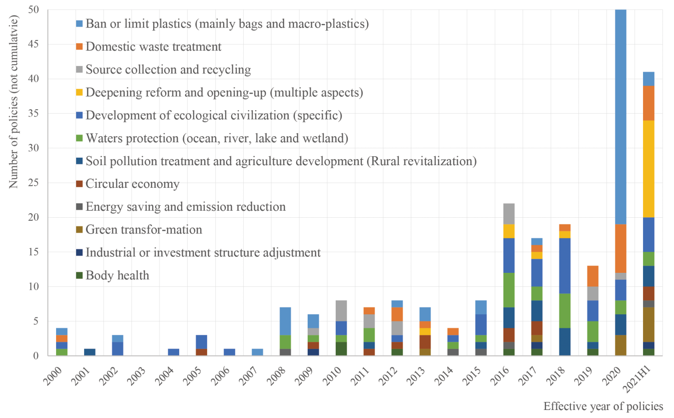

FIGURE 5
Number of policies issued on 12 sub-purposes annually (not cumulative).

instruments: regulation, economic tools, and information. Among the 231 policies in the Inventory, 98.3% mentioned the use of at least one type of policy instrument. In total, 95.7% have used regulation as a policy tool; information has been utilized in 74.0% of the policies; and economic instruments have been incorporated in 45.0% of the policies in the Inventory.

As shown in Figure 12A, among the 221 policies utilizing regulation as a policy instrument, "responsible handling of plastic" is the most used instrument (77.4%) to achieve affirmative regulation, while "limit plastic" is the most frequently utilized for the purpose of prohibitive regulation (48.9%). For 104 policies with economic instruments, 83.7% referred to incentives[23], while 41.3% utilized disincentives, including fees, tax, levy, and duty. Such economic disincentives can be applied under several circumstances in pertinent Chinese plastic policies. For example, a fee can be added to the use of plastic bags a fee can be charged for waste disposal for urban residents, a higher tax rate for the heavier-polluted industry, and a fee for irresponsible handling of plastics. Out of the 171 policies utilizing information tools as a policy instrument, 80.7% focused on environmental education or outreach to the public[24], 69.0% of them focused on the utilization of research data collection to promote sustainable waste management[25], and 33.9% of them mentioned the usage of labels, placards, or notices with pertinent environmental information.

When looking at these instruments over time (Figure 12B), we can see a similar tendency among all instruments except the "Economic - Disincentive"; from 2018 to 2021, the number of policies using this policy tool has kept increasing, from 1 to 13 (not cumulative). This indicates that Chinese policymakers have decided to ramp up efforts to regulate plastics through stronger economic disincentives.

Among the study's policy instruments, we noticed three interesting trends. First, "Non-government investment (encouragement)" as a category of policy instrument first

23 Here are some typical examples for different economic incentives: "Cash or token for return": In the *Procedures of Shanghai Municipality on the Administration of Renewable Resource Recovery* (official English translation, "上海市再生资源回收管理办法" in Chinese), city and county authorities should guide relevant enterprises to launch trade-in and bonus-point activities to promote recycling resources. "Subsidy": In the *Regulations of Guangdong Province on the Management of Urban and Rural Domestic Waste* (translated by authors, "广东省城乡生活垃圾管理条例" in Chinese), the waste disposal treatment fee can be raised with governmental subsidies. "Tax break": In the *Regulations of Hainan Special Economic Zone on Prohibiting Disposable Non-degradable Plastic Products* (translated by authors, "海南经济特区禁止一次性不可降解塑料制品规定" in Chinese), a tax break can be applied to companies that produce substitutes for disposable nondegradable plastic products and recycle disposable plastic products.

24 Many Chinese policies involve public participation in the form of public education and outreach. For example, in the *Law of the People's Republic of China on the Prevention and Control of Environment Pollution Caused by Solid Wastes* (official English translation, "中华人民共和国固体废物污染环境防治法" in Chinese), it is suggested that national authorities educate the public to participate in solid waste pollution prevention and guide consumers to use green packages.

25 A typical example of research data collection is in the *Law of the People's Republic of China on the Prevention and Control of Environment Pollution Caused by Solid Wastes* (official English translation, "中华人民共和国固体废物污染环境防治法" in Chinese), in which waste disposal treatment entities are required to monitor and publish the real-time pollution data.

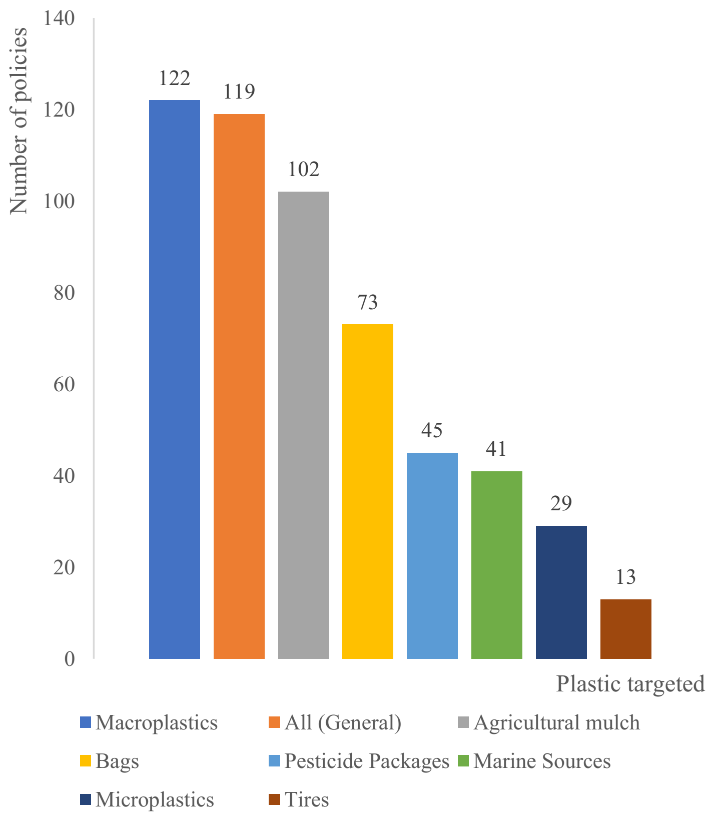

FIGURE 6
Number of policies that contained different plastic types.

occurred in *Measures for Comprehensive Utilization of Renewable Resources in Gansu Province*[26] issued in 2010, encouraging units and individuals to invest in the construction of renewable resource utilization projects with high technology content and advanced technology, representing Chinese government's will to involve more actors in the overarching plastic governance process. Second, "Cash or Token for Return" as a policy instrument was first utilized in *Opinions of the General Office of the State Council on Establishing a Complete and Advanced Recycling System for Waste and Used Commodities*[27] issued in 2011. This policy document is the first document we have identified which focuses on the establishment of automatic paid recycling machines as one of several flexible and diverse recycling methods, along with deposit recycling and trade-in, which indicates the emergence of a new incentive-type policymakers used to reduce (plastic) waste. Third, the instrument "post-leakage plastic capture," as a policy instrument, was not used before 2012 when it first appeared in the *Notice of the State Oceanic Administration on Printing and Distributing the National Island Protection Plan*,[28] which is the first policy document that mentions carrying out marine litter clean-up. This instrument increased rapidly after the year 2018. From 2012 to the first half year of 2021, the number of policies that used "post-leakage plastic capture" as an affirmative regulation tool increased from 1 to 39 (cumulative).

3.4 A complex system of government agencies involved in governing plastics

In order to examine and capture trends and trajectories pertaining to the state agencies involved in the issuance of plastic

26 Translated by authors, "甘肃省再生资源回收综合利用办法" in Chinese.

27 Official English translation, "国务院办公厅关于建立完整的先进的废旧商品回收体系的意见" in Chinese.

28 Translated by authors, "国家海洋局关于印发全国海岛保护规划的通知" in Chinese.

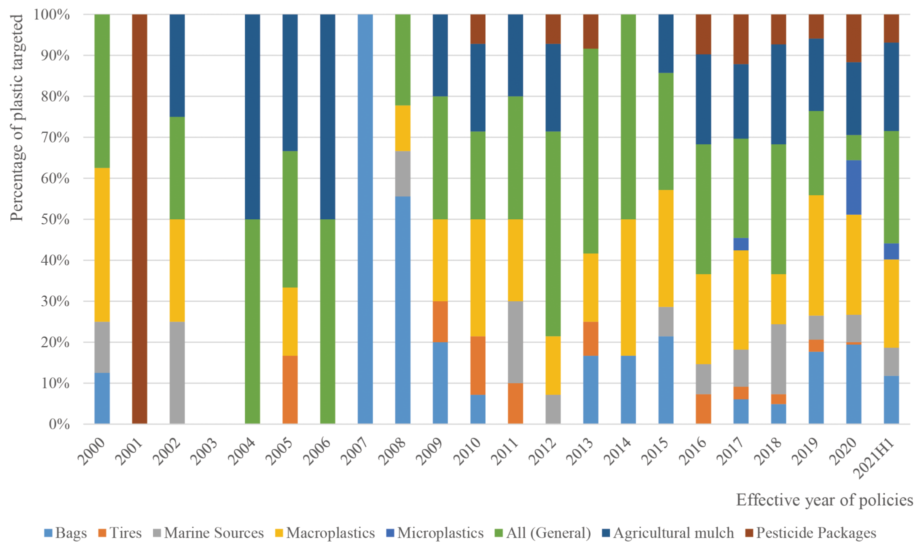

FIGURE 7
Proportion of plastic targeted contained in Chinese plastic-pertinent policies annually.

policies, we classify Chinese policymakers into five types: "Party-masses body," "People's Congress," "Governmental body," "Deliberation and Coordination Agencies (Temporary Small Groups)," and "Social organizations with a governmental background." There are 1 to 24 subagencies under each type. For the full classification, please see the "Complete codebook."

In China, a policy document may be published by more than one agency. Among all the 375 publishing agencies of the 231 policies, governmental bodies appeared most frequently with a percentage of 75.5 (Figure 13A). Thereinto, the top five are "Central and Provincial Government" (n = 72), "Development and Reform Commission" (n = 45), "Ecology and Environment (previously Environmental Protection)" (n = 42), "Commerce" (n = 21), and "Agriculture and Rural Affairs (previously Agriculture, Agriculture Commission)" (n = 16).

As shown in Figure 13B, from 2000 to the first half of 2021, the number of policies published by the People's Congress has increased steadily, while policies published by different governmental agencies have experienced a remarkable growth. Policies following *Opinions on Further Strengthening the Control of Plastic Pollution*[29] in 2020 and the 14th Five-Year Plan in 2021 led to the peak in 2020 and 2021.

29 Translated by authors, "关于进一步加强塑料污染治理的意见" in Chinese. This policy was announced by the Chinese National Development and Reform Commission and the Ministry of Ecology and Environment.

4 Trends, trajectories, and the possible future for China's plastic policy landscape

4.1 China's plastic policy landscape has mushroomed in all aspects in the last decade

Our analysis of 231 plastic-related Chinese policies reveals several clear trends and trajectories, illuminating China's shifting approach to governing plastics in the last two decades. Here, we summarize these trends and trajectories and, based on our analysis, point to some possible future advances in China's plastic regulatory landscape.

China's serious and concentrated effort to govern plastics really took off in the year 2016. Prior to 2016, plastic regulations were relatively scarce and fragmented in a number of different regulatory frameworks. In the time leading up to 2016, a particular focus was put on regulating the usage of various types of plastic bags. Starting with the 13th Five-Year Plan, China saw a rapid increase in the attention paid to plastic pollution in the regulatory realm. This focus has been further strengthened in the 14th Five-Year Plan. From 2000 to the first half of 2021 (effective date), the total number of Chinese plastic-pertinent policies has increased from 4 to 231. In this period, China has also significantly transformed its approach to governing plastics; not only has the goal and purpose of

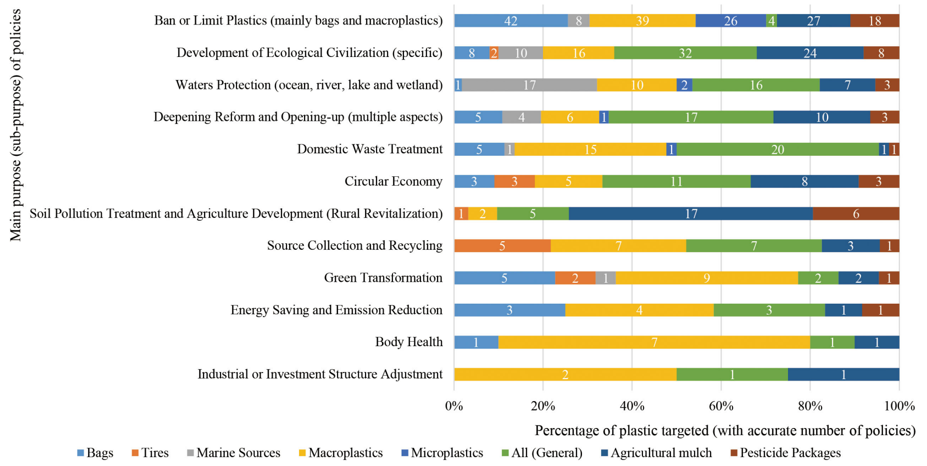

FIGURE 8
Proportion of plastic targeted contained in Chinese plastic-pertinent policies on 12 sub-purposes.

regulating plastic increased in complexity, but the type of plastics targeted and the different aspects of the plastic value chain have also become more comprehensive over time. In a similar fashion, the utilization of different types of regulatory instruments employed for the purpose of governing plastics in China has become much more diversified over time, and finally, today, most government agencies have published policies that are relevant to the regulation of plastic pollution control and prevention in China. Today, governing plastic is certainly not seen as the responsibility of the Chinese environmental authorities alone.

Over two decades of addressing plastic pollution, China has yet to develop a regulatory framework that addresses the upstream parts of the plastic lifecycle, namely the production of plastic products and the involvement of the extractive resources industry and chemical companies in such processes.

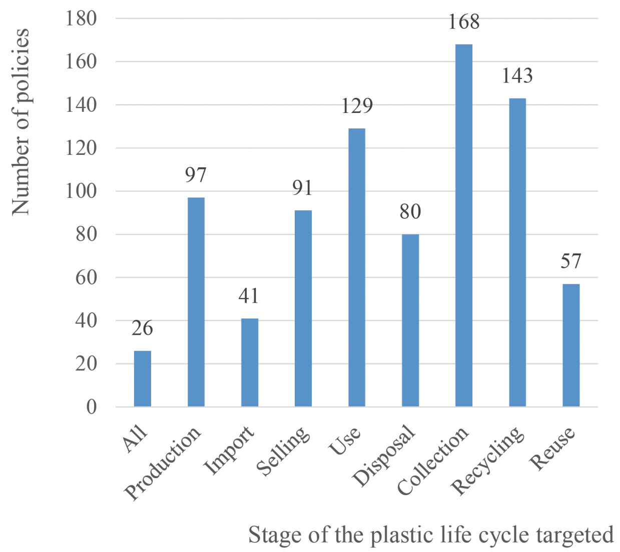

FIGURE 9
Number of policies that contained different stages of the plastic life cycle targeted.

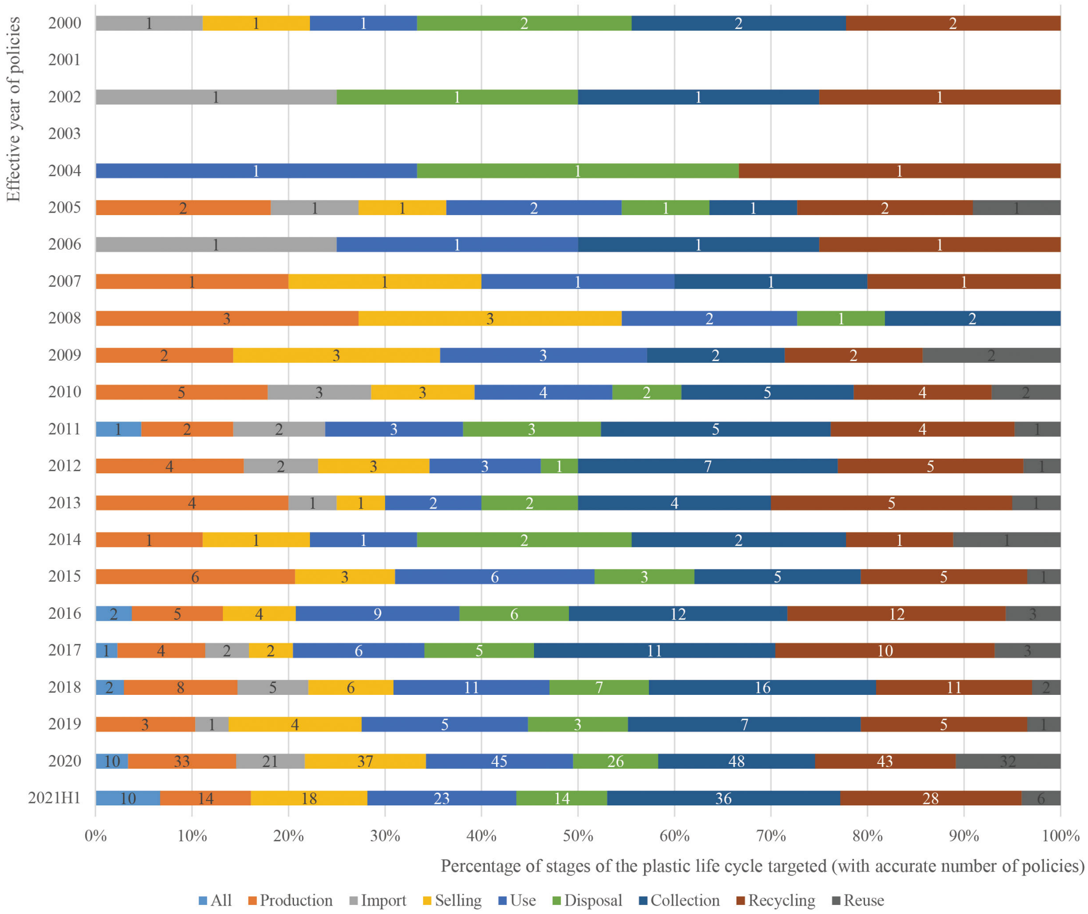

FIGURE 10
Number of policies that contained different stages of the plastic life cycle targeted annually (not cumulative).

Like many other countries in the world, China is focusing its regulatory attention on plastic treatment on the symptoms of the problem (e.g., cleanup, recycling, etc.), not the source (i.e., prodigious production of plastics) (Owens and Conlon, 2021).

China's efforts to address plastic pollution take place within the broader context of tackling solid waste pollution, upgrading city planning, and installing a "circular economy." Long before China started to seriously regulate plastic production, consumption, and waste management, the *Circular Economy Promotion Law of the People's Republic of China* came into force[30]. In line with the basic principles of the circular economy law, China now clearly intends to build a circular plastic value chain, and as such, new plastic pollution restrictions have set up a life-cycle regulatory regime, covering all aspects of production, consumption, and treatment[31].

30 Official English translation, "中华人民共和国循环经济促进法" in Chinese. It was issued on 1 January 2009, and revised on 26 October 2018.

31 Examples include but are not limited to *Opinions of the General Office of the State Council on Establishing a Complete and Advanced Recycling System for Waste and Used Commodities* (official English translation, "国务院办公厅关于建立完整的先进的废旧商品回收体系的意见" in Chinese, effective in 2011), *Provisions on the Administration of Prevention and Control of Environmental Pollution by Processing and Utilization of Waste Plastics* (official English translation, "废塑料加工利用污染防治管理规定" in Chinese, effective in 2012), *Notice of the National Development and Reform Commission, the Ministry of Education, the Ministry of Industry and Information Technology, etc. on deepening the implementation of restrictions on production, sales, and use of plastic shopping bags* (translated by authors, "国家发展和改革委员会、教育部、工业和信息化部等关于深化限制生产销售使用塑料购物袋实施工作的通知" in Chinese, effective in 2013).

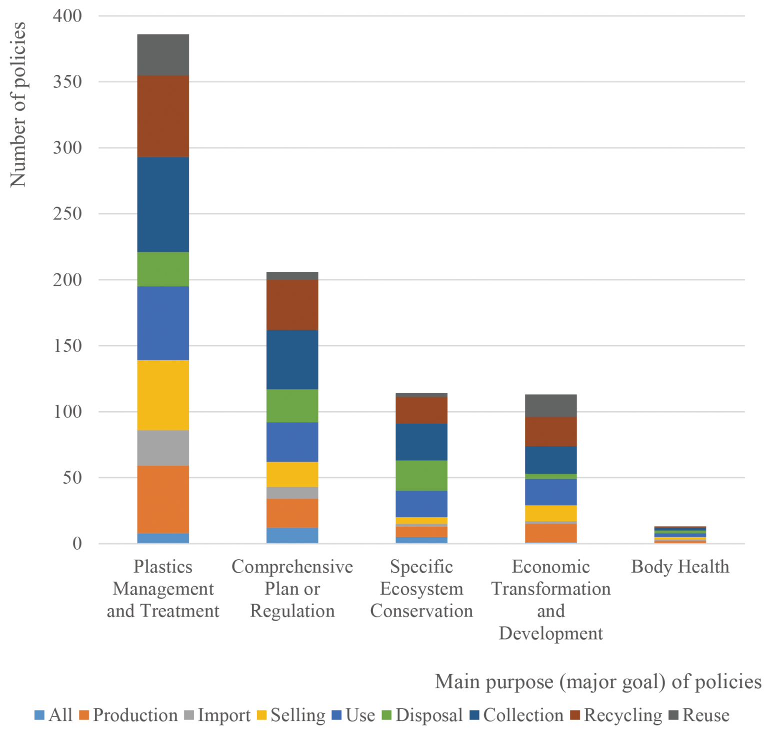

FIGURE 11
Number of policies issued on five major goals that contain different stages of the plastic life cycle targeted.

Alongside the importance of understanding China's approach to plastic pollution governance and management in light of the country's overarching focus on a circular economy, China's efforts to manage plastics should also be analyzed and understood in conjunction with the country's effort to overhaul the solid waste management regulatory framework and infrastructure. The *Law of the People's Republic of China on the Prevention and Control of Environment Pollution Caused by Solid Wastes*[32] (generally referred to as the Solid Waste Law) is the main body of legislation relevant to solid waste governance and pollution control. In December 2004, the Solid Waste Law was amended for the first time since its enactment in 1996, and subsequent amendments were made in 2013, 2015, 2016, and 2020. Plastic was not explicitly referenced prior to the 2020 amendment to this law, despite the fact that collected municipal solid waste consists of estimates varying between 25% plastic (Zhan et al., 2008) and 10%–20% plastic (Zhang et al., 2010), and despite the fact that plastic is one of the fastest growing waste streams in China (Hoornweg and Bhada-Tata, 2012). Moreover, research indicates that the presence of heavy metals (Ba, Zn, Cu, Mn) was high in most plastic waste samples (Xu et al., 2020). Additionally, the detection of exceeded levels of various heavy metals (trespassing the threshold for national drinking water quality), including Mn, Pb, Ni, and Zn, which can be attributed to the release of chemical compounds stemming from plastic waste, has occasionally been found in samples of drinking water (Xu et al., 2020). Thus, researchers suggested that plastic waste should be managed in a controlled manner (Xu et al., 2020). The 2020 amendment of the Solid Waste Law has responded to some of these issues, as the law, for the first time, specifies plastic waste management[33] and control of plastic pollution, and clearly stipulates the pollution prevention and control of agricultural films, packaging materials, and disposable plastic products, while also clarifying the legal responsibility for relevant illegal acts. The 2020 amendment to the Solid Waste Law, therefore, in theory at least, provides a legal guarantee to control plastic pollution.

32 Official English translation, "中华人民共和国固体废物污染环境防治法" in Chinese.

33 Article 69 and 106 strengthened the relevant requirements for the prevention.

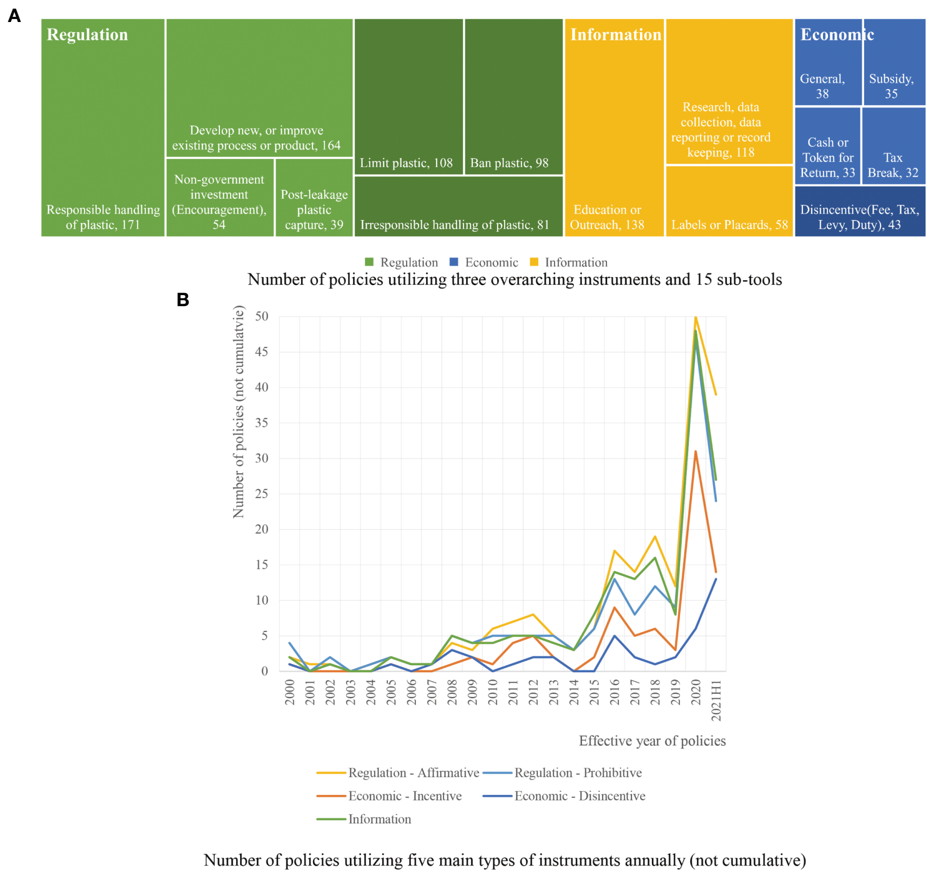

FIGURE 12
Chinese authorities have utilized multiple instruments to regulate plastics. (A) Number of policies utilizing three overarching instruments and 15 subtools. (B) Number of policies utilizing five main types of instruments annually (not cumulative).

4.2 What is next for China's plastic policy developments?

China has already developed a strong regulatory framework to govern various aspects of plastic production, consumption, and waste management. What does the future hold for China's plastic governance? Here, we ponder some possible developments. First, it is likely that China's carbon neutrality ambitions will further strengthen the motivation for various Chinese stakeholders to adopt measures to reduce plastic production, consumption, and (mismanaged) waste.

According to the *Action Plan for Carbon Dioxide Peaking Before 2030*[34], controlling and treating plastic pollution will be an important element in China's road toward carbon neutrality. Recently, researchers and practitioners have been urging us to pay closer attention to the links between plastic and climate, as plastic produces tremendous carbon emissions from the cradle to the grave at every stage (Zheng and Suh, 2019). Given that China's plastic manufacturing operations are largely dependent on fossil fuels, carbon emissions from the production of plastics remain high, and the potential for carbon reduction in this sector is equally elevated. Whereas the direct links between plastics and carbon are not often explicitly expressed in Chinese policy documents, we find plenty of evidence of the implicit relationships. For example, the *Action Plan for Carbon Dioxide Peaking Before 2030* stresses the urgency of peaking carbon in the petrochemical and chemical industries, both of which are closely related to plastic production. The 14th *Five-Year Plan for Green Industrial Development*[35] also mentioned the need to support the development of the plastic recycling industry in

34 Official English translation, "2030年前碳达峰行动方案" in Chinese.

35 **Translated by authors,** "'十四五'工业绿色发展规划" in Chinese.

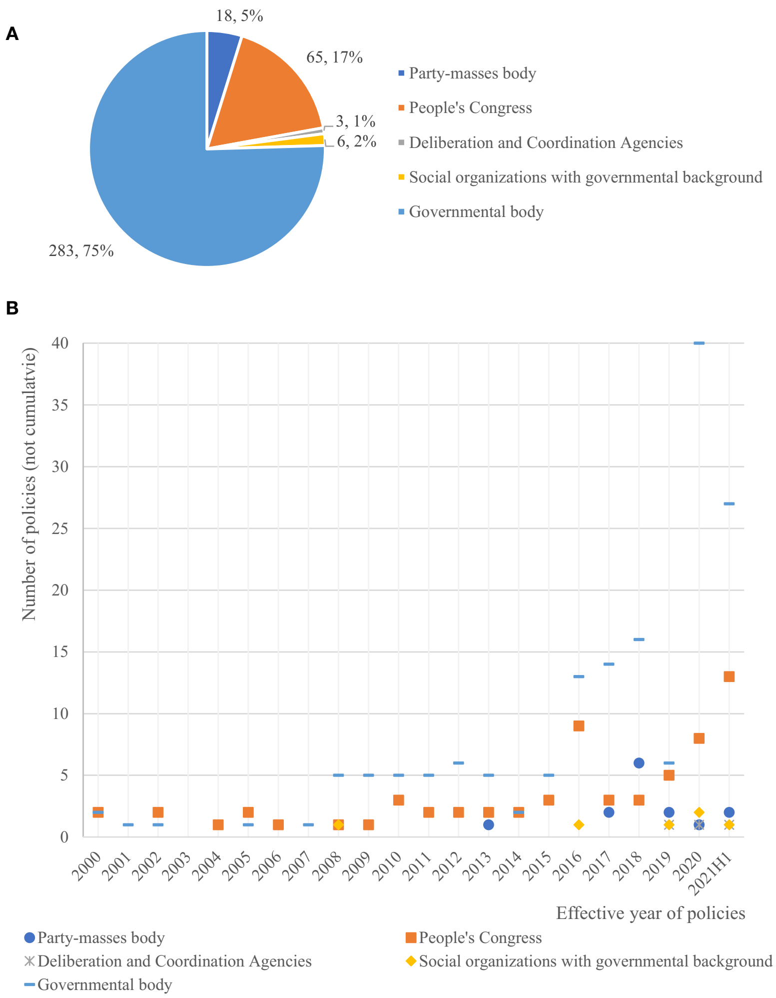

FIGURE 13
A complex system of government agencies involved in plastic governing. **(A)** Number and proportion of policies published by different agency types. **(B)** Number of policies published by different agency types annually (not cumulative).

China. This is important as, at present, much of the discarded plastics in China, especially low-value packaging materials, are mixed with household waste and end up in either landfills or incinerators (Wen et al., 2021). However, currently, other policy developments are not necessarily designed to address these challenges. The latest 14th *Five-Year Plan for Solid Waste Environmental Management of Hunan Province*[36] indicates that the percentage of incineration will increase to 65% in 2025 from the current level of 45%, adding additional carbon footprints as the burning of plastic emits 2.9 kg of CO_2 for every kg of plastic burned. To achieve its ambitious carbon neutrality goal, China must therefore among others, address issues pertaining to treating end-of-life plastic through incinerators.

In the coming years, we will also likely see a focus on cleanups. Several action plans issued by the Chinese central government, such as the *Action Plan for Water Pollution Prevention and Control*[37] issued in 2015, the *Action Plan for Tackling Pollution in Agriculture and Rural Areas*[38] issued in 2018, and the *Action Plan of Bohai Sea comprehensive governance*[39] issued in 2018, have referenced the removal of

36 Translated by authors, "湖南省‘十四五’固体废物环境管理规划" in Chinese.

37 Translated by authors, "水污染防治行动计划" in Chinese.

38 Translated by authors, "农业农村污染治理攻坚战行动计划" in Chinese.

39 Translated by authors, "渤海综合治理攻坚战行动计划" in Chinese.

waste in a generic and marginal manner, with no explicit focus on plastic waste cleanup. This is about to change. In 2020, Fujian province issued the *Action Plan for Further Strengthening the Comprehensive Management of Floating Garbage in the Sea*[40], which, to the best of our knowledge, is the first Chinese policy document explicitly developed for the purpose of comprehensively addressing marine waste cleanups, including, of course, plastic waste in the marine environment. In September 2021, another important policy document, the *"14th Five-Year Plan" Action Plan for Plastic Pollution Control* was issued, which highlights the importance of "vigorously carrying out the cleaning-up of plastic waste in key areas" as one of the three main tasks detailed in this Action Plan.[41] Moreover, this Action Plan also proposes that, by the year 2025, the historical legacy of open-air plastic waste in key water areas, key tourist attractions, and rural areas should be effectively removed. Furthermore, a goal for this Action Plan is to effectively control the leakage of plastic waste into the natural environment by 2025.[42] Alas, it is highly likely that a stronger regulatory focus will be placed on plastic cleanup initiatives in the years to come.

5 Conclusion

Despite earning an international reputation as one of the largest contributors to plastic pollution in the world's oceans, research comprehensively examining the Chinese plastic policy landscape has been scarce, and much of the developments taking place within this policy terrain, particularly at the subnational level, have not been documented. We have sought to address some of the gaps in this field through a comprehensive analysis of an Inventory of the Chinese plastic policy documents. From our analysis, we find that policies explicitly managing and governing plastics are a fairly recent policy phenomenon in China, commencing in 2008. This changed rapidly in the period between 2016 and 2021, when there was an incredible increase in plastic policies. In this period, China has also significantly transformed its approach to governing plastics. Not only has the goal and purpose of regulating plastic increased in complexity, but the type of plastics targeted and the different aspects of the plastic value chain included in various pertinent policies have also become more comprehensive over time. In a similar fashion, the utilization of different types of regulatory instruments utilized for the purpose of governing plastics in China has become much more diversified over time, and finally, today, most government agencies have published policies that are relevant to the regulation of plastic pollution control and prevention in China. Furthermore, we find that a diverse set of regulatory instruments have been utilized by Chinese policymakers in designing policies with the aim of regulating plastics. Our analysis also reflects an increased acknowledgment of the complexities of governing plastics, as such policies have evolved significantly in terms of the type of plastic governed by such policies and the stage of its life cycle targeted, as well as a more diversified utilization of more comprehensive regulatory instruments. Overall, our analysis of these policy documents indicates that plastic pollution has become a growing concern for the Chinese government at both national and subnational levels since early 2000, with a sharp increase since 2016. Today, China has a fairly well-established regulatory framework aimed at reducing plastic pollution through the overarching approach of circular economy, ramping up of solid waste management and infrastructure as well as an overhaul of city planning. However, this China's plastic policy landscape focuses much on the end pipe solution, while a focus on addressing the production of plastics is limited. As a global leader in plastic production, China has a great deal of power in demonstrating effective strategies for solving the plastic problem. However, as long as China is focusing on back-end policies, this could potentially mean that the reduction of plastic production will be very limited. Moreover, this current approach to regulating plastics domestically in China could have implications for China's position in the upcoming global plastic treaty negotiation process.

Whereas this study has provided important new insights pertaining to China's approach to governing plastic, it has also laid the foundation to explore other relevant questions. First, and perhaps the most pressing question related to examining the impact of these policies, China has adopted several regulatory instruments to govern plastic, but how effective are these instruments in preventing and/or controlling plastic pollution? How do different stakeholders respond to these different instruments? Which variable factors can explain and account for the different effects of the regulatory instruments? Some scholarly progress has been made in addressing these questions (Diana et al., 2022; Global Plastic Policy Centre, 2022). However, little is known about effective enforcement and compliance with such policies in China and the variable factors that influence such processes. Our study and the creation of the inventory of China's plastic policies have laid the foundation for future research undertakings seeking to examine the policy effectiveness of

40 Translated by authors, "进一步加强海漂垃圾综合治理行动方案" in Chinese.

41 The other two were "actively promoting the reduction of plastic production and use at source" and "accelerating the promotion of standardized recycling and disposal of plastic waste," which all had targeted policies over the past two decades.

42 *Notice by the National Development and Reform Commission and the Ministry of Ecology and Environment for the "14th Five-Year Plan" Action Plan for Plastic Pollution Control* (translated by authors, "国家发展改革委、生态环境部关于印发'十四五' 塑料污染治理行动方案的通知" in Chinese). The texts of the goal are also translated by authors. This policy is not involved in this study, since we only accounted for policy documents in the period between 1 January 2000 and 30 June 2021.

China's regulatory response to the plastic pollution crisis. As our work has focused on analyzing the trend of policy issuances and the characteristics of these policies, we have not been able to focus on the enforcement and implementation of these policies. How are different state and nonstate actors involved in the processes leading up to the issuance of plastic policies? And what role do they play, once policies and regulations have been issued, in governing plastics in China? Second, whereas our research shows a sharp increase in national- and subnational-level policies published by a variety of different government agencies, we still do not know a lot about what motivates the issuance of plastic-related policies by these different actors. Why have some provinces taken a more proactive role in issuing plastic-related policies? Future research can build on this study when examining the drivers and motivations behind the promulgation of plastic-related policies at subnational levels in China. Third, and on a related note, our research shows that Chinese policymakers have had a strong focus on the utilization of information based on regulatory policy instruments and that there is still a strong emphasis on mandating the implementation of information campaigns and awareness-raising as a means to reduce plastic pollution reduction among the general public. However, we know little about the effect of such information campaigns, as we lack data on the general level of knowledge and awareness among the general public on issues related to plastic production, consumption, and waste management (and the impact and consequences of inadequate plastic waste management). There is also a need to critically examine the rationale behind the policies utilizing information as a regulatory instrument, as we know little about the actual impact on an increased level of awareness and/or knowledge about different problems related to plastic; do information campaigns lead to a higher level of knowledge, and do higher levels of knowledge lead to behavior change?

The process of establishing and analyzing our database of China's plastic policy landscape has provided new insights into China's regulatory approach to addressing plastic pollution. At the same time, we are left with a number of new and burning research questions that urgently need more attention from our collective scholarly community ahead of the global plastic treaty negation process.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

KF: conceptualization, methodology, writing—original draft, writing—review and editing, and funding acquisition. YF: methodology, investigation, writing—original draft, writing—review and editing, data curation, and visualization. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.982546/full#supplementary-material

References

Backer, L. C. (2012). Party, people, government and state: on constitutional values and the legitimacy of the Chinese state-party rule of law system. *BU Int'l LJ* 30, 331. Available at https://ssrn.com/abstract=1977551.

Brooks, A. L., Wang, S., and Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. *Sci. Adv.* 4 (6), eaat0131. doi: 10.1126/sciadv.aat0131

Chen, Y., Cui, Z., Cui, X., Liu, W., Wang, X., Li, X., et al. (2019). Life cycle assessment of end-of-life treatments of waste plastics in China. *Resources Conserv. Recycling* 146, 348–357. doi: 10.1016/j.resconrec.2019.03.011

Diana, Z., Vegh, T., Karasik, R., Bering, J., Caldas, J. D. L., Pickle, A., et al. (2022). The evolving global plastics policy landscape: An inventory and effectiveness review. *Environ. Sci. Policy* 134, 34–45. doi: 10.1016/j.envsci.2022.03.028

Dong, J. (2009). Policy suggestions for implementing the *Circular economy promotion law* disposable foamed plastic tableware: Problems and countermeasures (translated by authors, "贯彻《循环经济促进法》的政策建议 一次性发泡塑料餐具: 问题与对策" in Chinese). *New Economy Weekly* 3, 92–95.

Gasper, D. (1982). The Chinese National People's Congress. In: Nelson, D., and White, S. (eds) *Communist Legislatures in Comparative Perspective* (Palgrave Macmillan London). doi: 10.1007/978-1-349-06086-3_7

Global Plastic Policy Centre (2022) *New evidence finds current policies not working to end olastic pollution*. Available at: https://www.port.ac.uk/news-events-and-blogs/news/busan-global-plastics-policy-centre (Accessed 10/13/2022).

GPTS (2021). Tax policy research to promote plastic pollution control (translated by authors, "促进塑料污染治理的税收政策研究" in Chinese). *Economy Guangdong* 12, 10–15.

Guo, W., Xi, B., Huang, C., Li, J., Tang, Z., Li, W., et al. (2021). Solid waste management in China: Policy and driving factors in 2004–2019. *Resources Conserv. Recycling* 173, 105727. doi: 10.1016/j.resconrec.2021.105727

He, H. (2012). Effects of environmental policy on consumption: lessons from the Chinese plastic bag regulation. *Environ. Dev. Economics* 17 (4), 407–431. doi: 10.1017/S1355770X1200006X

Hoornweg, D., and Bhada-Tata, P. (2012). What a waste: a global review of solid waste management *Urban development series; knowledge papers no. 15.* Washington, DC: World Bank. Available at: https://openknowledge.worldbank.org/handle/10986/17388 (Accessed 11/01/2022).

Hu, A. (2013). The distinctive transition of china's five-year plans. *Modern China* 39 (6), 629–639. doi: 10.1177/0097700413499129

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347 (6223), 768–771. doi: 10.1126/science.1260352

Jiang, X., Wang, T., Jiang, M., Xu, M., Yu, Y., Guo, B., et al. (2020). Assessment of plastic stocks and flows in China: 1978-2017. *Resources Conserv. Recycling* 161, 104969. doi: 10.1016/j.resconrec.2020.104969

Karasik, R., Vegh, T., Diana, Z., Bering, J., Caldas, J., Pickle, A., et al. (2020). 20 Years of government responses to the global plastic pollution problem: the plastics policy inventory. *NI X*, 20–05. Durham, NC: Duke University.

Law, K. L., Starr, N., Siegler, T. R., Jambeck, J. R., Mallos, N. J., and Leonard, G. H. (2020). The united states' contribution of plastic waste to land and ocean. *Sci. Adv.* 6 (44), eabd0288. doi: 10.1126/sciadv.abd0288

Li, L. C. (2010). Central-local relations in the people's republic of China: Trends, processes and impacts for policy implementation. *Public administration Dev.* 30 (3), 177–190. doi: 10.1002/pad.573

Li, D. (2020). *A new understanding of the problem of marine plastic waste in China (translated by authors,* "对我国海洋塑料垃圾问题的新认识" in Chinese) (GMW). Available at: https://www.gmw.cn/xueshu/2020-11/17/content_34374205.htm (Accessed 05/20 2022).

NBS (2022) *National data* ("国家数据" in Chinese). Available at: https://data.stats.gov.cn (Accessed 06/22/2022).

O'Loughlin, M. (2010). BYOB (Bring your own bag): a comprehensive assessment of china's plastic bag policy. *Buff. Envtl. LJ* 18, 295. doi: 10.2139/ssrn.1693247

Owens, K. A., and Conlon, K. (2021). Mopping up or turning off the tap? environmental injustice and the ethics of plastic pollution. *Front. Mar. Sci.*, 1227. doi: 10.3389/fmars.2021.713385

Wang, B., and Li, Y. (2021). Plastic bag usage and the policies: A case study of China. *Waste Manage.* 126, 163–169. doi: 10.1016/j.wasman.2021.03.010

Wang, W., Themelis, N. J., Sun, K., Bourtsalas, A. C., Huang, Q., Zhang, Y., et al. (2019). Current influence of china's ban on plastic waste imports. *Waste Disposal Sustain. Energy* 1 (1), 67–78. doi: 10.1007/s42768-019-00005-z

Wan, J., Qin, C., Wang, Q., Xiao, Y., Niu, R., Li, X., et al. (2022). A brief overview of the 13th five-year plan for the protection of ecological environment. *Environ. Strategy Plann. China* (Singapore: Springer) 57–85. doi: 10.1007/978-981-16-6909-5_3

Wei, J., and Dong, J. (2008). Relevant policies and updates on food plastics, paper packaging and containers umplementing QS licensing system (translated by author, "食品用塑料、纸包装、容器等制品实施QS许可制度的相关政策与最新动态" in Chinese). *China Packaging* 2, 88–91.

Wen, Z., Xie, Y., Chen, M., and Dinga, C. D. (2021). China's plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide. *Nat. Commun.* 12 (1), 1–9. doi: 10.1038/s41467-020-20741-9

Xia, M. (1997). Informational efficiency, organisational development and the institutional linkages of the provincial people's congresses in China. *J. Legislative Stud.* 3 (3), 10–38. doi: 10.1080/13572339708420516

Xu, D., Lang, Z., and Tang, Y. (2021). Research report on the impact of replacing plastic straws with paper straws in the context of "Plastic restriction" policy (translated by authors, "'限塑令'政策背景下纸吸管取代塑料吸管后的影响调研报告" in Chinese). *Cleaning World* 37 (07), 77–78+81.

Xu, Q., Xiang, J., and Ko, J. H. (2020). Municipal plastic recycling at two areas in China and heavy metal leachability of plastic in municipal solid waste. *Environ. pollut.* 260, 114074. doi: 10.1016/j.envpol.2020.114074

Yan, X. (2013). Institutional development of the Chinese National People's Congress (1978-89): intellectual perspectives (Doctoral dissertation, University of Hull). Available at: https://hydra.hull.ac.uk/resources/hull:8022 (Accessed 11/09/2022).

Yi-chong, X., and Weller, P. (2016). The challenges of governing: The state council in China. *China J.* 76 (1), 1–23. doi: 10.1086/684857

Zhan, T. L., Chen, Y., and Ling, W. (2008). Shear strength characterization of municipal solid waste at the suzhou landfill, China. *Eng. Geology* 97 (3-4), 97–111. doi: 10.1016/j.enggeo.2007.11.006

Zhang, X. (2017). Rule of law within the Chinese party-state and its recent tendencies. *Hague J. Rule Law* 9 (2), 373–400. doi: 10.1007/s40803-017-0052-3

Zhang, D. Q., Tan, S. K., and Gersberg, R. M. (2010). Municipal solid waste management in China: status, problems and challenges. *J. Environ. Manage.* 91 (8), 1623–1633. doi: 10.1016/j.jenvman.2010.03.012

Zheng, J., and Suh, S. (2019). Strategies to reduce the global carbon footprint of plastics. *Nat. Climate Change* 9 (5), 374–378. doi: 10.1038/s41558-019-0459-z

Zhong, Y. (2003). Local Government and Politics in China: Challenges from below. (*1st ed.*). Routledge. doi: 10.4324/9781315702780

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Inequitable distribution of plastic benefits and burdens on economies and public health

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Plastic heterogeneously affects social systems – notably human health and local and global economies. Here we discuss illustrative examples of the benefits and burdens of each stage of the plastic lifecycle (*e.g.*, macroplastic production, consumption, recycling). We find the benefits to communities and stakeholders are principally economic, whereas burdens fall largely on human health. Furthermore, the economic benefits of plastic are rarely applied to alleviate or mitigate the health burdens it creates, amplifying the disconnect between who benefits and who is burdened. In some instances, social enterprises in low-wealth areas collect and recycle waste, creating a market for upcycled goods. While such endeavors generate local socioeconomic benefits, they perpetuate a status quo in which the burden of responsibility for waste management falls on downstream communities, rather than on producers who have generated far greater economic benefits. While the traditional cost-benefit analyses that inform decision-making disproportionately weigh economic benefits over the indirect, and often unquantifiable, costs of health burdens, we stress the need to include the health burdens of plastic to all impacted stakeholders across all plastic life stages in policy design. We therefore urge the Intergovernmental Negotiating Committee to consider all available knowledge on the deleterious effects of plastic across the entire plastic lifecycle while drafting the upcoming international global plastic treaty.

KEYWORDS

plastic lifecycle, human health, environmental justice, plastic pollution, economic inequality

Introduction

Plastic, a synthetic material made from fossil fuels, affects nearly every person on the planet in some way between production and disposal. Most obviously, people encounter plastic in consumer products; it is commonly used in foodware, houseware, textiles, and packaging due to its light weight, durability, flexibility, and resistance to moisture. People also encounter plastic when it becomes waste. Plastic pollution is highly visible and degrades the aesthetic value and health of the environment. Less visible, but still ubiquitous, is human exposure to microplastics, which have been detected in human blood, placentas, feces, and breast milk (Barrett et al., 2020; Zhang et al., 2020; Yan et al., 2021; Leslie et al., 2022; Ragusa et al., 2022).

All the ways in which plastic affects human and natural systems is not yet – and may never be – fully known. However, a growing body of research reveals that plastic both benefits and burdens stakeholders and communities around the world (Law et al., 2020; Owens and Conlon, 2021).

These benefits and burdens are not distributed equally. For instance, in fossil fuel extraction and petrochemical manufacturing, many stakeholders (*e.g.*, consumers) experience short-term benefits (Healy et al., 2019; Muttitt and Kartha, 2020), and some stakeholders (*e.g.*, industry executives and shareholders) experience substantial economic benefits (Healy et al., 2019). At the same time, people living near processing and manufacturing plants incur significant health burdens (Owens and Conlon, 2021). Likewise, poor communities are unequally burdened by plastic pollution, suffering more severe consequences from clogged drainage systems, increases in vector-borne diseases, and reductions in tourism compared to affluent areas (Owens and Conlon, 2021). These well-studied environmental injustices are often described for only one stage of the plastic lifecycle (Nielsen et al., 2020), which understates the full effect of plastic on socio-ecological systems.

For over two decades, national and subnational governments have addressed plastic pollution using regulatory and economic instruments (*e.g.*, bans, fees) and education and outreach initiatives (Karasik et al., 2020; Diana et al., 2022; Global Plastics Policy Centre, 2022). Now, efforts to address plastic pollution on a global scale are gaining momentum. For example, the Basel, Rotterdam, and Stockholm conventions are beginning to control the trade of hazardous plastic waste and additives (Secretariat of the Basel, Rotterdam and Stockholm Conventions, 2021), and the World Trade Organization initiated an Informal Dialogue on Plastics in 2021 to support member nations adopting trade policies on the sustainable use of plastics (World Trade Organization, 2022). Most recently in February 2022, the United Nations (UN) Environment Assembly passed a resolution to create a global, binding legal agreement by 2024 to address plastic across its entire lifecycle. Developing and incorporating a robust understanding of the distribution of benefits and burdens of plastic at each lifecycle stage is essential to ensuring the efficacy of these policy endeavors.

In this paper, we demonstrate the effects of plastic on communities and stakeholder groups by reviewing examples of benefits to and burdens on economies and public health throughout each stage of the plastic lifecycle and across diverse geographic contexts. Examples of specific burdens and benefits were collected during workshops and discussions with legal and policy experts, physicians, biologists, and other researchers comprising Duke University's Plastic Pollution Working Group. The working group includes faculty, staff, and students affiliated with Duke University who are engaged in scholarship on plastic pollution, toxicity, legal and policy frameworks, occupational risks, and environmental justice, largely in the US. Examples identified in this paper are illustrative, rather than representative or comprehensive, and reflect the working group's skewed expertise toward the US. However, these examples demonstrate the significant and varied effects plastic have on different communities and stakeholders. Finally, we discuss solutions that can mitigate some of the societal burdens of plastic and should be considered in the upcoming UN treaty on plastic pollution and in other decision-making processes.

We define seven key lifecycle stages for macroplastics (Figure 1), which are a significant form of plastic found in the environment (van Emmerik, 2021). These stages were identified using the Global Macroplastic System Map from Pew's *Breaking the Plastic Wave* report and the codebook used to characterize plastic policy design from Karasik et al., 2020, and they are consistent with UNEP, 2022. We then describe example benefits and burdens for each of these stages in the following sections.

Benefits and burdens at each lifecycle stage

Production

Benefit

Around the world, communities rely on the petrochemical industry for employment and local economic activity. Globally, the petrochemical market's expected value is 800 billion USD by 2028, growing over 500 billion USD from 2020 (Fortune Business Insights, n.d.). The US is the top oil and gas producing country in the world, and the petrochemical industry in the US brings in over 95 billion USD in revenue annually and provides nearly one hundred thousand jobs (Burns, 2022) in areas that are typically economically disadvantaged. China has the largest petrochemical industry globally, though countries in the Middle East and North

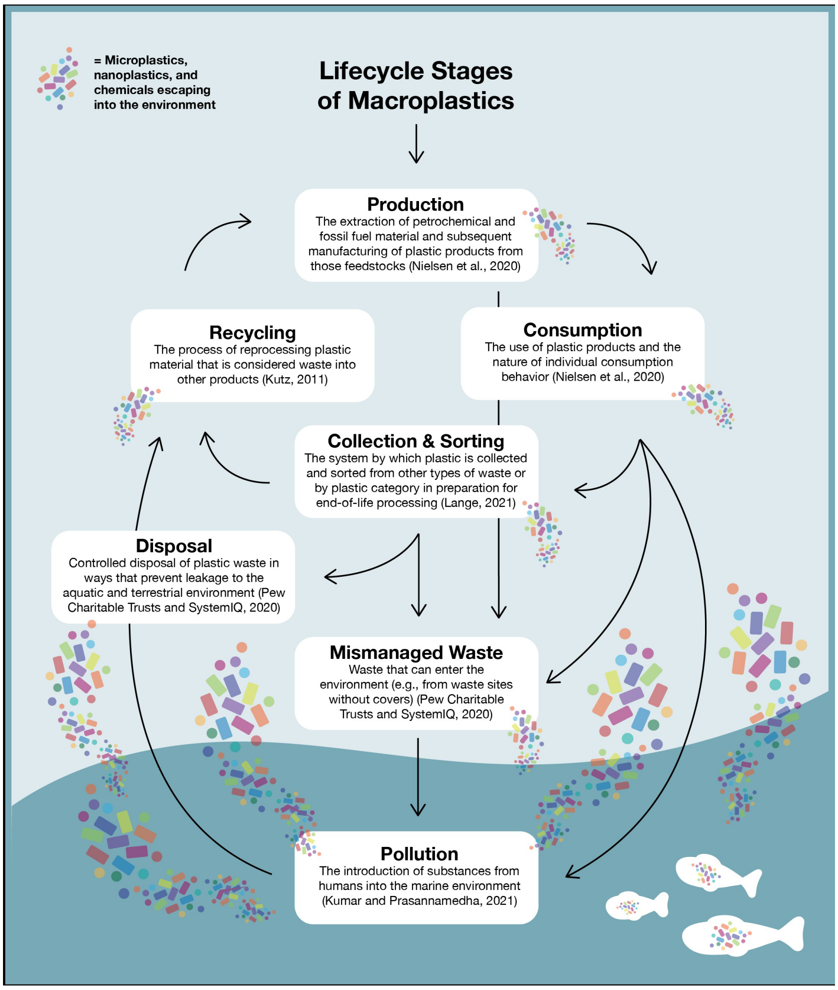

FIGURE 1
Stages of the macroplastic lifecycle.

Africa have a growing share (International Energy Agency, 2018). However, we were unable to find data on the number of jobs and revenue generated in China, the Middle East, and North Africa. Governments continue to invest in the development of petrochemical production despite making commitments to curb climate emissions (Azoulay et al., 2019; Hong et al., 2019; IHS Markit, 2021).

Burden

Communities near petrochemical plants experience substantial health burdens. For example, lung cancer rates in Louisiana's "Cancer Alley" (a corridor between Baton Rouge and New Orleans with over 150 petrochemical plants) are above the US average (Gottlieb et al., 1982; James et al., 2012; Terrell and St Julien, 2022). Similar increases in the incidence of and mortality from leukemia, brain cancer, bladder cancer; non-Hodgkin's lymphoma, and multiple myeloma have been observed in populations living near petrochemical plants in Taiwan, across Europe, and in Nigeria (Domingo et al., 2020). Additional research demonstrates an increased incidence of asthma, negative pregnancy and birth outcomes, and higher rates of attention deficit hyperactivity disorder in individuals living near petrochemical refineries in Taiwan, South Africa, Argentina, Brazil, Canada, Thailand, China, Israel, Italy, and Spain (Marquès et al., 2020; Huang et al., 2022). These studies remain limited and are largely correlational in nature;

without a formal system of epidemiological surveillance for such issues, the true impact remains unknown (Domingo et al., 2020).

Consumption

Benefit

Plastic is inexpensive, can be sterilized and molded, provides a moisture barrier, and has mechanical strength, flexibility, and softness (Sivaram et al., 2021). These qualities make plastic ideal for food packaging and medical instruments where sanitation is essential. Medical devices such as hearing aids, joint replacements, catheters, transparent IV tubes, pacemakers, contact lenses, and straws are often comprised of plastic (US PIRG, 2018). The use of medical plastic rose during the COVID-19 pandemic when medical-grade personal protective equipment proved critical for preventing the spread of disease (Adyel, 2020).

Burden

Over 10,000 chemical additives have been found in plastic products (Wiesinger et al., 2021), of which nearly 25% are considered hazardous to humans if consumed. Women and menstruating people may have increased exposure to plastics with toxins due to higher interactions, on average, with household items and feminine hygiene products than men and non-menstruating people (Park et al., 2019; Ding et al., 2022; Munoz et al., 2022; Upson et al., 2022), further worsening gender-related inequalities (United Nations Environment Programme, 2021, Azoulay et al., 2019). One such additive, Bisphenol A (BPA), is an endocrine-disrupting chemical released from plastic food and beverage containers including baby bottles (Proshad et al., 2018, Zwierello et al., 2020). During consumption, BPA is able to enter human blood or tissue (Kumar et al., 2022), and it can impair the function of multiple body systems (*e.g.*, endocrine, reproductive, renal; Zwierello et al., 2020). It also increases the risk of various chronic diseases, such as breast, prostate, and liver cancers. Investigative research has discovered products labeled as BPA-free still contain BPA (International Pollutants Elimination Network (IPEN), 2022), suggesting that industry efforts to protect humans from BPA exposure are insufficient.

Collection & sorting

Benefit

The collection and sorting of plastic waste is a source of income for both informal and formal waste workers who are paid to collect and sort waste from households or in material recovery facilities. Community-driven material recovery facilities improve solid waste management at the neighborhood scale by formalizing and paying scrap collectors and waste pickers (Budihardjo et al., 2022). For example, in Semarang City, Indonesia, 37 community-driven material recovery facilities with an average of 197 members each collected over 137,000 kilograms of waste from households, offices, and restaurants. This provided up to 37.78 USD in monthly income per person (Budihardjo et al., 2022). Similar social enterprises in Vietnam, Sri Lanka, the Philippines, and Nigeria (Adebiyi-Abiola et al., 2019; Plastic Smart Cities, 2020; Mathis et al., 2022) have created jobs while collecting thousands of metric tons of plastic that may have otherwise been mismanaged (Mathis et al., 2022). Such benefits are not guaranteed, as membership and waste volume must be optimal to ensure sustainability (Budihardjo et al., 2022).

Burden

Formal and informal waste workers focused on the collection and sorting of waste experience occupational hazards. Common injuries include ankle sprains, fractures, ocular trauma, and bites (Dorevitch and Marder, 2001; Battini et al., 2018). Municipal door-to-door waste collectors in Italy have heightened risk of musculoskeletal disorders (Battini et al., 2018) due to handling of waste containers, and waste sorters in southern India reported musculoskeletal disorders and pain in the lower back, shoulder, and neck from manually sorting waste in a squatting position (Emmatty and Panicker, 2022).

Recycling

Benefit

Efforts in the informal sector to support plastic recycling can benefit local economies by fostering entrepreneurship and creating jobs. These social enterprises recycle or upcycle collected waste locally and create local marketable goods, including construction materials, toys, jewelry, furniture, and shredded material for other goods. Effects of these programs have been measured and reported in Mexico City and Toluca City, Mexico (Rivera-Huerta and López-Lira, 2022), Makassar, Indonesia (Kubota et al., 2020), Jenin, Palestine (Bonoli et al., 2019), Port-au-Prince, Haiti (Haney and Bodenman, 2017), and across the African continent (UpCycleAfrica). Such efforts create value for recycled materials, foster a competitive market, employ marginalized people, provide social benefits, and stimulate local economic activity (Mathis et al., 2022: Rivera-Huerta and López-Lira, 2022).

Burden

In recent years, the cost of waste management and recycling for municipal governments has dramatically increased in the US. This is attributed to higher landfill costs (Vedantam et al., 2022), fewer buyers for recyclable material (in part due to China's 2018 plastic waste import ban), and high operational costs for recycling companies (Di et al., 2021). As a result, some US cities have temporarily or permanently suspended recycling programs that reach all households (Corkery, 2019; Cochran, 2020), instead opting for programs where households pay a fee to retain curbside collection services. This fee is an additional cost burden on low-wealth communities and allows plastics producers to evade responsibility for the plastic pollution crisis.

Disposal

Benefit

In many parts of the world, solid waste management services (including landfilling) are contracted out to private or publicly traded firms. Globally, landfill services have a projected value of 149.2 billion USD, with over 40% of the landfilling services market in Asia Pacific and 30% in North America. Comparatively, South America, the Middle East, and Africa combined have under 5% of the total market share for landfilling services. The US has the highest share of the waste management market (24%), and its two leading companies, Waste Management and Republic Services, had a combined revenue of close to 30 billion USD and employed over 82,000 people in 2021 (Republic Services, 2021; Waste Management, 2021). Most of this revenue is from trucks delivering garbage to landfills. Firms participating in waste-to-energy programs, in which methane gas produced in landfills is captured and used as energy, may accrue additional benefits through subsidies (EPA, 2022).

Burden

Microplastics, nanoplastics, and hazardous chemical toxins from macroplastic waste in landfills or disposal areas escape into soil, groundwater, and air (Abiriga et al., 2020; Ozbay et al., 2021). In the US, landfills and other solid waste facilities are often sited in low-wealth and frontline communities (Norton et al., 2007), increasing localized health risks in already marginalized populations (Mattiello et al., 2013; Ozbay et al., 2021). Correlational data demonstrate these risks across the globe (Azoulay et al., 2019); for example, surveyed residents living within 500 and 1,000 meters of a garbage disposal area in Kolkata, India, had high rates of asthma, skin irritation, and gastrointestinal diseases (De and Debnath, 2016), as well as chronic heart, gastrointestinal, respiratory, ocular, and autoimmune conditions (Kar and Basunia, 2020), respectively.

Mismanaged waste

Benefit

The existence of mismanaged waste may encourage the creation of decentralized circular economies (Joshi et al., 2019). One example of this is Precious Plastic, a community-based recycling effort that provides communities with small recycling workspaces to capture, shred, melt, and ultimately upcycle plastic goods, such as water sanitation products (Diehl et al., 2018; Precious Plastic, 2020). This model provides benefits to local economies around the world, enabling communities to create for-profit businesses that generate an average of nearly 7,000 USD annually in revenue from otherwise landfill-bound material.

Burden

In some cases, mismanaged plastic waste is openly burned. Incineration releases particulate matter, BPA, phthalates, and dioxins into air, soil, and water, posing health risks for nearby communities and waste workers (Velis and Cook, 2021; Wu et al., 2021; Ramadan et al., 2022). Studies of open waste burning have measured toxin concentrations at hazardous levels in Abeokuta, Nigeria (Oguntoke et al., 2019); Londrina, Brazil (Krecl et al., 2021); Telok Panglima Garang City, Malaysia (Yu et al., 2022); and other communities in low and lower-middle income countries (Velis and Cook, 2021).

Pollution

Benefit

A growing market exists for ocean plastic as upcycled material in consumer products (Watt et al., 2021). These products often have price premiums and are favorably perceived by consumers (Magnier et al., 2019). Large companies (*e.g.*, Adidas, Coca-Cola, SC Johnson) and small and mid-sized ocean entrepreneurs (*e.g.*, Odyssey Innovation, Triwa) make kayaks, shoes, watches, and backpacks using ocean plastic (Dijkstra et al., 2021). Adidas has sold over 15 million pairs of shoes made of ocean plastic and is expected to generate over one billion USD in revenue from this venture (Aziz, 2018). Another company, Plastic Bank, intends to create a direct market for ocean plastic while addressing poverty: collectors in developing countries are offered digital tokens in exchange for ocean plastic (Katz, 2019). Plastic Bank has engaged with over 500 self-identified communities to exchange currency for ocean plastic.

Burden

Nations and communities that rely on clean marine environments (*e.g.*, tourism, fishing) for income bear the burden of marine plastic pollution. In the Asia Pacific region,

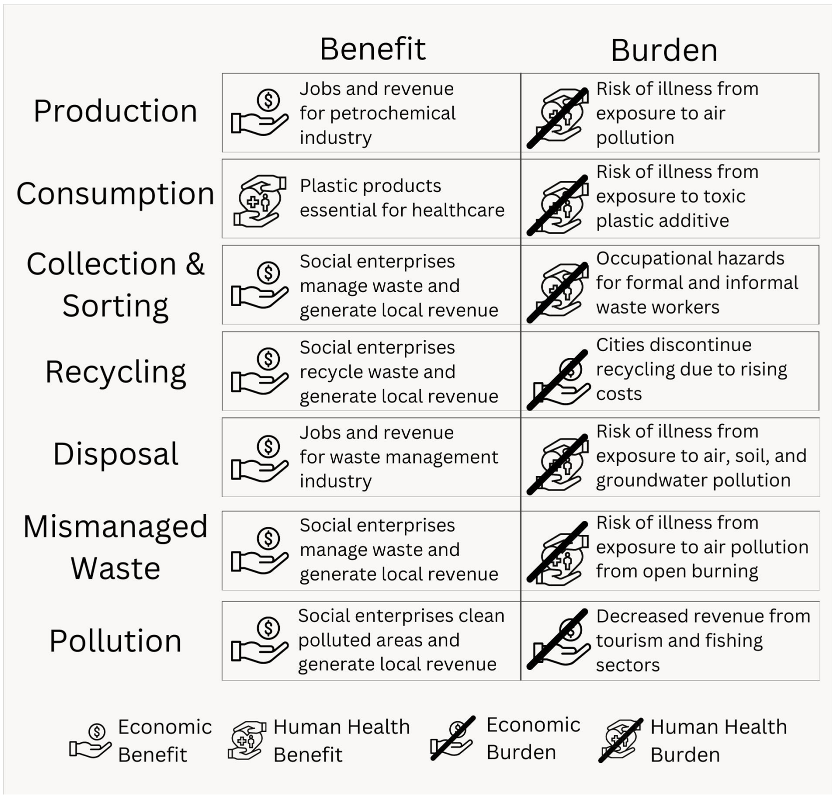

FIGURE 2
Example benefits and burdens across the macroplastic lifecycle. puchongart and WiStudio Elements.

marine debris causes an annual loss of 622 million USD in the marine tourism sector (McIlgorm et al., 2011). A severe marine pollution event decreased beach visitors in Geoje Island, South Korea by 50% over 15 days in July 2011, leading to a loss of 29-37 million USD in tourism revenue (Jang et al., 2014). One study found that reductions in marine debris in the US would generate hundreds of millions of dollars in economic activity from stimulated beach tourism (English et al., 2019).

Discussion

Trends in benefits and burdens

Most societal benefits of plastic identified are economic (Figure 2). Multiple stages of the plastic lifecycle develop and maintain markets and industries that create jobs, generate revenue, and stimulate economies. Some of these industries generate billions of dollars in revenue, in part by drawing on incentives in subsidies, private investment, tax breaks, and public trading (Tickner et al., 2021; Charles et al., 2021). However, such industries increase fossil fuel dependence and contravene efforts to combat climate change (Erickson and Achakulwisut, 2021). Poor communities burdened by plastic waste can incur economic benefits through bottom-up endeavors developed in the absence of state-supported infrastructure, but these do not generate the same magnitude of wealth and instead shift the responsibility for waste management away from producers. Therefore, the economic benefits are not distributed equitably.

Concurrent to the economic benefits of plastic are the burdens on human health at almost every plastic lifecycle stage (Azoulay et al., 2019). Pollution causes nine million premature deaths annually, with an increasing share of those deaths associated with the chemicals found in plastic (Landrigan et al., 2018; Fuller et al., 2022). Because the most at-risk communities tend to be low-wealth and systematically marginalized, people who incur these burdens may not have the means or access to address them (Collins et al., 2016). In most cases, and without substantial litigation, economic benefits from one plastic lifecycle stage are not spent on mitigating the consequential health issues, demonstrating a fundamental gap between who benefits and who is harmed throughout the plastic lifecycle.

In some cases, however, the same stakeholders and communities benefit from and are burdened by the plastic lifecycle. For example, waste collectors and sorters profit off plastic while simultaneously facing occupational hazards. This tension is also evident in areas where petrochemical industries provide employment for communities while jeopardizing their health with air pollution (*e.g.*, Cancer Alley, Louisiana and Houston, Texas). These intertwined benefits and burdens bind communities into systems in which they live, work, and are harmed, complicating efforts to regulate the petrochemical industry through grassroots activism.

Health burdens associated with each plastic lifecycle stage incur significant economic costs on the public. These economic losses are associated with cost of healthcare, loss of workforce, and cost of clean-up. Recent estimates based on limited available epidemiological data suggest that the annual social cost of plastic-related chemical exposure exceeds 100 billion USD and the annual cost of micro- and nano-plastic exposure is 10 billion USD (Merkl and Charles, 2022). Estimates of annual health costs for the effect of prenatal BPA exposure on childhood obesity are over 1.5 billion USD in Europe alone (Legler et al., 2015).

Solutions

Experts suggest the economic costs of health burdens eclipse the short-term economic gains made by plastic manufacturing and waste management industries, though many knowledge gaps of these costs remain (Azoulay et al., 2019; DeWit et al., 2021). Importantly, these costs are not captured in dominant frameworks to inform policy making, such as cost benefit analysis, that can weigh easily quantifiable economic benefits over health data, which remains largely correlative. This merits precautionary approaches to reduce the circulation of plastic and enhance corporate accountability (Figure 3). The precautionary principle in environmental ethics posits that decision-makers can address environmental hazards, despite knowledge gaps, by regulating or prohibiting activities or pollutants to protect human and environmental health (Pinto-Bazurco, 2020). One example in environmental policy is the setting of catch limits in data-poor fisheries based on historic catch only (Dowling et al., 2008), thereby applying the precautionary principal to protect

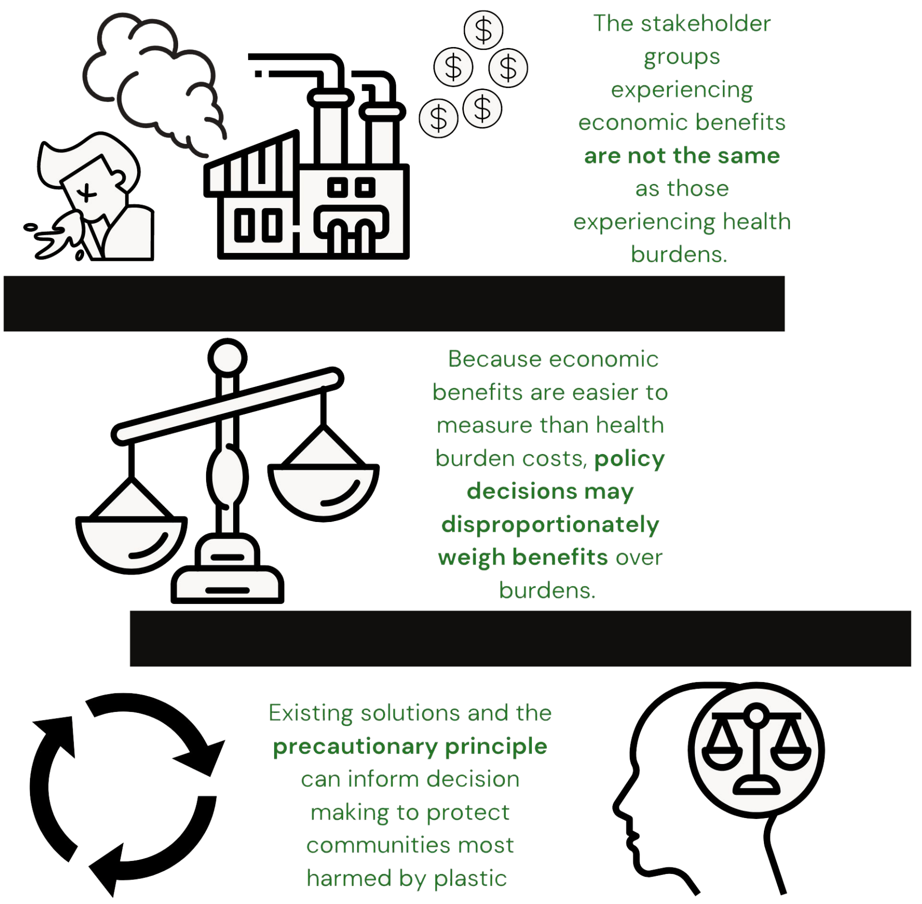

FIGURE 3
Key takeaways from assessment of benefits and burdens. iconsy, ninjastudio, Icons8, narathip, pongsakornjun, anna design A4, and Graphic Nehar.

fish stocks. Although the precautionary principle has not yet been applied to address plastic pollution (Tickner et al., 2021), it would minimize health burdens where causal data or analyses are not yet available (Persson et al., 2022).

Interventions that maximize the efficient use of resources, minimize exposure to toxins, and reduce waste can enable a safe and circular economy (Simon et al., 2021). Proposed solutions include reducing or eliminating toxins and hazards during production, standardizing labeling to inform consumers of toxins and recyclability, and providing incentives for retrieval to remediate ocean pollution (Farrelly and Fuller, 2021). There have been calls for a cap on virgin plastic production to reduce plastic volume from the source (Simon et al., 2021; Bergmann et al., 2022), though such policy reforms must support an equitable transition away from fossil fuels so as not to harm communities reliant on the industry for employment.

The private sector can drive circular economy programs to simultaneously reduce both plastic pollution (OECD, 2022) and negative effects on human health. For example, NextWave Plastics' Social Responsibility Framework seeks to improve and assess supply chain maturity in ocean-bound plastic supply chains for its member companies by emphasizing fair and predictable pay, freely chosen employment, health and safety conditions, strong business ethics, transparency, support for marginalized communities, and prioritized child welfare (NextWave Plastics, 2021). These frameworks enable companies to adopt ethical standards and practices, thereby reducing plastic pollution and alleviating some socioeconomic burdens. However, systems-wide implementation is unlikely without wider participation from governments, the private sector, and individuals.

Conclusion

We provide examples of benefits and burdens of the plastic lifecycle to be considered in the upcoming UN plastic treaty negotiations. Our urgency has limited the scope of the study in several ways. For one, many examples are from the US, highlighting unequal economic, health, and quality of life conditions in the wealthiest country. A comprehensive literature review, supported by stakeholders and experts, will be crucial for understanding the socioeconomic effects of plastic. Likewise, standardized definitions of the plastic lifecycle stages will be essential for the upcoming UN treaty to ensure consistency in national policy implementation and assessment and for clear communication about risks to the public. In addition, humans' relationship to plastic at each stage of the lifecycle is evolving, and the ways in which individuals and communities benefit from or are harmed by plastic will change as new products are invented, or as manufacturing or waste management facilities are established or removed. Evolving benefits and burdens, and in particular their ramifications for population health, must be incorporated into decision-making. As the global plastic treaty negotiations begin, understanding how stakeholders are impacted at each lifecycle stage will increase the efficacy of policy design, implementation, evaluation, and adaptation.

Author contributions

RK conceived and designed the work. RK, NaEL, NiEL, AEB, WE, and KF contributed to the content collection comprising the body of the manuscript. RK, NiEL, and AEB wrote the first draft of the report. NaEL, JAS, and MD-D helped revise the paper significantly. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abiriga, D., Vestgarden, L. S., and Klempe, H. (2020). Groundwater contamination from a municipal landfill: Effect of age, landfill closure, and season on groundwater chemistry. *Sci. total Environ.* 737, 140307. doi: 10.1016/j.scitotenv.2020.140307

Adebiyi-Abiola, B., Assefa, S., Sheikh, K., and García, J. M. (2019). Cleaning up plastic pollution in Africa. *Science* 365 (6459), 1249–1251. doi: 10.1126/science.aax3539

Adyel, T. M. (2020). Accumulation of plastic waste during COVID-19. *Science* 369 (6509), 1314–1315. doi: 10.1126/science.abd9925

Appalachian Regional Commission (2020) *Economic overview of Appalachia-2011*. Available at: https://www.arc.gov/wp-content/uploads/2020/06/EconomicOverviewSept2011.pdf.

Aziz, A. (2018). The power of purpose: how adidas will make $1 billion helping solve the problem of ocean plastic. *Forbes*. Available at: https://www.forbes.com/sites/afdhelaziz/2018/10/29/the-power-of-purpose-how-adidas-will-make-1-billion-helping-solve-the-problem-of-ocean-plastic/?sh=7454ec4ad215.

Azoulay, D., Villa, P., Arellano, Y., Gordon, M., Moon, D., Miller, K., et al. (2019). *Plastic & health: The hidden costs of a plastic planet*. Available at: https://www.ciel.org/reports/plastic-health-the-hidden-costs-of-a-plastic-planet-february-2019/, Center for International Environmental Law.

Barrett, J., Chase, Z., Zhang, J., Holl, M. M. B., Willis, K., Williams, A., et al. (2020). Microplastic pollution in deep-sea sediments from the great Australian bight. *Front. Mar. Sci.* 7, 808. doi: 10.3389/fmars.2020.576170

Battini, D., Botti, L., Mora, C., and Sgarbossa, F. (2018). Ergonomics and human factors in waste collection: Analysis and suggestions for the door-to-door method. *IFAC-PapersOnLine* 51 (11), 838–843. doi: 10.1016/j.ifacol.2018.08.443

Bergmann, M., Almroth, B. C., Brander, S. M., Dey, T., Green, D. S., Gundogdu, S., et al. (2022). A global plastic treaty must cap production. *Science* 376 (6592), 469–470. doi: 10.1126/science.abq0082

Bonoli, A., Zanni, S., and Awere, E. (2019). Organic waste composting and sustainability in low-income communities in Palestine: Lessons from a pilot project in the village of Al jalameh, jenin. *Int. J. recycling organic waste Agric.* 8 (3), 253–262.). doi: 10.1007/s40093-019-0264-8

Budihardjo, M. A., Ardiansyah, S. Y., and Ramadan, B. S. (2022). Community-driven material recovery facility (CdMRF) for sustainable economic incentives of waste management: Evidence from semarang city, Indonesia. *Habitat Int.* 119, 102488. doi: 10.1016/j.habitatint.2021.102488

Burns, J. (2022). Plastic & resin manufacturing in the US. *IBIS World Industry Rep.*, 32521.

Charles, D., Kimman, L., and Saran, N. (2021). *The plastic waste makers index* (Minderoo foundation).

Cochran, T. (2020). *EPA Recycling strategy local government associations comment letter*. Available at: https://www.nlc.org/wp-content/uploads/2020/12/EPA-Recycling-Strategy-Local-Government-Associations-Comment-Letter-12-04-20.pdf, The U.S. Conference of Mayors.

Collins, M. B., Munoz, I., and JaJa, J. (2016). *Linking 'toxic outliers' to environmental justice communities* (Environmental Research Letters) 11 (1), 015004.

Corkery, M. (2019). *As costs skyrocket, more U.S. cities stop recycling* (The New York Times). Available at: https://www.nytimes.com/2019/03/16/business/local-recycling-costs.html.

De, S., and Debnath, B. (2016). Prevalence of health hazards associated with solid waste disposal-a case study of kolkata, India. *Proc. Environ. Sci.* 35, 201–208. doi: 10.1016/j.proenv.2016.07.081

DeWit, W., Burns, E. T., Guinchard, J. C., and Ahmed, N. (2021). *Plastics: The costs to society, the environment, and the economy* (Gland, Switzerland: World Wide Fund for Nature).

Diana, Z., Vegh, T., Karasik, R., Bering, J., Caldas, J. D. L., Pickle, A., et al. (2022). The evolving global plastics policy landscape: An inventory and effectiveness review. *Environ. Sci. Policy* 134, 34–45. doi: 10.1016/j.envsci.2022.03.028

Diehl, J. C., Stroober, M., Majumdar, P., and Mink, A. (2018). Do-it-Yourself (DIY) workspaces run by local entrepreneurs that transform plastic waste into valuable water and sanitation products. In 2018 IEEE Global Humanitarian Technology Conference (GHTC). 1–8 (IEEE).

Dijkstra, H., van Beukering, P., and Brouwer, R. (2021). In the business of dirty oceans: Overview of startups and entrepreneurs managing marine plastic. *Mar. pollut. Bull.* 162, 111880. doi: 10.1016/j.marpolbul.2020.111880

Ding, N., Lin, N., Batterman, S., and Park, S. K. (2022). Feminine hygiene products and volatile organic compounds in reproductive-aged women across the menstrual cycle: A longitudinal pilot study. *J. Women's Health* 31 (2), 210–218. doi: 10.1089/jwh.2021.0153

Di, J., Reck, B. K., Miatto, A., and Graedel, T. E. (2021). United states plastics: Large flows, short lifetimes, and negligible recycling. *Resources Conserv. Recycling* 167, 105440. doi: 10.1016/j.resconrec.2021.105440

Domingo, J. L., Marquès, M., Nadal, M., and Schuhmacher, M. (2020). Health risks for the population living near petrochemical industrial complexes. 1. cancer risks: a review of the scientific literature. *Environ. Res.* 186, 109495. doi: 10.1016/j.envres.2020.109495

Dorevitch, S., and Marder, D. (2001). *Occupational hazards of municipal solid waste workers* Vol. 16 (Philadelphia, Pa: Occupational medicine), pp.125–pp.133.

Dowling, N. A., Smith, D. C., Knuckey, I., Smith, A. D., Domaschenz, P., Patterson, H. M., et al. (2008). Developing harvest strategies for low-value and data-poor fisheries: case studies from three Australian fisheries. *Fisheries Res.* 94 (3), 380–390. doi: 10.1016/j.fishres.2008.09.033

Emmatty, F. J., and Panicker, V. V. (2022). Workplace-based assessment and intervention design for waste sorting tasks in a developing country. *Sādhanā* 47 (1), 1–13. doi: 10.1007/s12046-022-01804-7

English, E., Wagner, C., and Holmes, J. (2019). *The effects of marine debris on beach recreation and regional economies in four coastal communities: A regional pilot study* (Silver Spring, MD 20910).

EPA (2022) *Basic information about landfill gas*. Available at: https://www.epa.gov/lmop/basic-information-about-landfill-gas.

Erickson, P., and Achakulwisut, P. (2021). *Risks for new natural gas developments in Appalachia* (Ohio River Valley Institute).

Farrelly, T., and Fuller, S.. (2021). *A safe(r) circular economy for plastics in the pacific region* (UN Environment Programme).

Fortune Business Insights *The global petrochemicals market is projected to grow from $582.4 billion in 2021 to $888.3 billion in 2028 at a CAGR of 6.2% in forecast period 2021-2028*. Available at: https://www.fortunebusinessinsights.com/petrochemicals-market-102363.

Fuller, R., Landrigan, P. J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., et al. (2022). *Pollution and health: a progress update* (The Lancet Planetary Health).

Global Plastics Policy Centre (2022). "A global review of plastics policies to support improved decision making and public accountability," in *Revolution plastics*. Eds. A. March, S. Salam, T. Evans, J. Hilton and S. Fletcher (UK: University of Portsmouth).

Gottlieb, M. S., Shear, C. L., and Seale, D. B. (1982). Lung cancer mortality and residential proximity to industry. *Environ. Health Perspect.* 45, 157–164. doi: 10.1289/ehp.8245157

Haney, J., and Bodenman, J. (2017). Creating markets for recyclable materials: The case of municipal solid waste in Haiti. *Middle States Geographer* 50, pp.17–27.

Healy, N., Stephens, J. C., and Malin, S. A. (2019). Embodied energy injustices: Unveiling and politicizing the transboundary harms of fossil fuel extractivism and fossil fuel supply chains. *Energy Res. Soc. Sci.* 48, 219–234. doi: 10.1016/j.erss.2018.09.016

Hong, S., Jie, Y., Li, X., and Liu, N. (2019). *China's chemical industry: new strategies for a new era* (McKinsey & Company).

Huang, C. C., Pan, S. C., Chin, W. S., Chen, Y. C., Hsu, C. Y., Lin, P., et al. (2022). Living proximity to petrochemical industries and the risk of attention-deficit/hyperactivity disorder in children. *Environ. Res.* 212, 113128. doi: 10.1016/j.envres.2022.113128

HIS Markit (2021). *Petrochemical capacity in China and middle East: Growth amid challenges.*

International Energy Agency (2018). *The future of petrochemicals: Towards more sustainable plastics and fertilisers* (Paris: IEA). doi: 10.1787/9789264307414-en

International Pollutants Elimination Network (IPEN) (2022). *How plastics poison the circular economy: Data from China, Indonesia, and Russia and others reveal the dangers* (IPEN). Available at: https://ipen.org/sites/default/files/documents/ipen-plastic-poison-circ-econ-v1_4w-en.pdf.

James, W., Jia, C., and Kedia, S. (2012). Uneven magnitude of disparities in cancer risks from air toxics. *Int. J. Environ. Res. Public Health* 9 (12), 4365–4385. doi: 10.3390/ijerph9124365

Jang, Y. C., Hong, S., Lee, J., Lee, M. J., and Shim, W. J. (2014). Estimation of lost tourism revenue in geoje island from the 2011 marine debris pollution event in south Korea. *Mar. pollut. Bull.* 81 (1), 49–54. doi: 10.1016/j.marpolbul.2014.02.021

Joshi, C., Seay, J., and Banadda, N. (2019). A perspective on a locally managed decentralized circular economy for waste plastic in developing countries. *Environ. Prog. Sustain. Energy* 38 (1), 3–11. doi: 10.1002/ep.13086

Karasik, R., Vegh, T., Diana, Z., Bering, J., Caldas, J., Pickle, A., et al. (2020). *20 years of government responses to the global plastic pollution problem: The plastics policy inventory. NI X 20-05* (Durham, NC: Duke University).

Kar, R., and Basunia, P. (2020). Prevalence of diseases among people living near a landfill in kolkata: An exploratory survey. *Ann. Trop. Med. Public Health* 23, 231–762. doi: 10.36295/ASRO.2020.231762

Katz, D. (2019). Plastic bank: launching social plastic® revolution. field actions science reports. *J. Field Actions* Special Issue 19), 96–99.

Krecl, P., de Lima, C. H., Dal Bosco, T. C., Targino, A. C., Hashimoto, E. M., and Oukawa, G. Y. (2021). Open waste burning causes fast and sharp changes in particulate concentrations in peripheral neighborhoods. *Sci. Total Environ.* 765, 142736. doi: 10.1016/j.scitotenv.2020.142736

Kubota, R., Horita, M., and Tasaki, T. (2020). Integration of community-based waste bank programs with the municipal solid-waste-management policy in makassar, Indonesia. *J. Material Cycles Waste Manage.* 22 (3), 928–937. doi: 10.1007/s10163-020-00969-9

Kumar, R., Manna, C., Padha, S., Verma, A., Sharma, P., Dhar, A., et al. (2022). Micro (nano) plastics pollution and human health: How plastics can induce carcinogenesis to humans? *Chemosphere* 298, 134267. doi: 10.1016/j.chemosphere.2022.134267

Kumar, S., and Prasannamedha, G. (2021). Biological and chemical impacts on marine biology. *Modern Treat Strategies Mar. pollut.* 1 (2), 11–27. doi: 10.1016/B978-0-12-822279-9.00006-3

M. Kutz (Ed.) (2011). *Applied plastics engineering handbook: processing and materials* (William Andrew).

Landrigan, P. J., Fuller, R., Acosta, N. J., Adeyi, O., Arnold, R., Baldé, A. B., et al. (2018). The lancet commission on pollution and health. *Lancet* 391 (10119), 462–512. doi: 10.1016/S0140-6736(17)32345-0

Lange, J. P. (2021). Managing plastic waste─ sorting, recycling, disposal, and product redesign. *ACS Sustain. Chem. Eng.* 9 (47), 15722–15738. doi: 10.1021/acssuschemeng.1c05013

Law, K. L., Starr, N., Siegler, T. R., Jambeck, J. R., Mallos, N. J., and Leonard, G. H. (2020). The united states' contribution of plastic waste to land and ocean. *Sci. Adv.* 6 (44), eabd0288. doi: 10.1126/sciadv.abd0288

Legler, J., Fletcher, T., Govarts, E., Porta, M., Blumberg, B., Heindel, J. J., et al. (2015). Obesity, diabetes, and associated costs of exposure to endocrine-disrupting chemicals in the European union. *J. Clin. Endocrinol. Metab.* 100 (4), 1278–1288. doi: 10.1210/jc.2014-4326

Leslie, H. A., Van Velzen, M. J., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., and Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environ. Int.* 163, 107199. doi: 10.1016/j.envint.2022.107199

Magnier, L., Mugge, R., and Schoormans, J. (2019). Turning ocean garbage into products–consumers' evaluations of products made of recycled ocean plastic. *J. cleaner production* 215, 84–98. doi: 10.1016/j.jclepro.2018.12.246

Marquès, M., Domingo, J. L., Nadal, M., and Schuhmacher, M. (2020). Health risks for the population living near petrochemical industrial complexes. 2. adverse health outcomes other than cancer. *Sci. total Environ.* 730, 139122. doi: 10.1016/j.scitotenv.2020.139122

Mathis, J. E., Gillet, M. C., Disselkoen, H., and Jambeck, J. R. (2022). Reducing ocean plastic pollution: Locally led initiatives catalyzing change in south and southeast Asia. *Mar. Policy* 143, 105127. doi: 10.1016/j.marpol.2022.105127

Mattiello, A., Chiodini, P., Bianco, E., Forgione, N., Flammia, I., Gallo, C., et al. (2013). Health effects associated with the disposal of solid waste in landfills and incinerators in populations living in surrounding areas: a systematic review. *Int. J. Public Health* 58 (5), 725–735. doi: 10.1007/s00038-013-0496-8

McIlgorm, A., Campbell, H. F., and Rule, M. J. (2011). The economic cost and control of marine debris damage in the Asia-pacific region. *Ocean Coast. Manage.* 54 (9), 643–651. doi: 10.1016/j.ocecoaman.2011.05.007

Merkl, A., and Charles, D. (2022). *The price of plastic pollution: Social costs and corporate liabilities* (Minderoo Foundation).

Munoz, L. P., Baez, A. G., Purchase, D., Jones, H., and Garelick, H. (2022). Release of microplastic fibres and fragmentation to billions of nanoplastics from period products: preliminary assessment of potential health implications. *Environ. Science: Nano* 9 (2), 606–620. doi: 10.1039/D1EN00755F

Muttitt, G., and Kartha, S. (2020). Equity, climate justice and fossil fuel extraction: principles for a managed phase out. *Climate Policy* 20 (8), 1024–1042. doi: 10.1080/14693062.2020.1763900

NextWave Plastics (2021). *A framework for socially responsible ocean-bound plastic supply chains.* (NextWave Plastics) Available at: https://www.nextwaveplastics.org/social-responsibility.

Nielsen, T. D., Hasselbalch, J., Holmberg, K., and Stripple, J. (2020). Politics and the plastic crisis: A review throughout the plastic life-cycle. *Wiley Interdiscip. Reviews: Energy Environ.* 9 (1), e360. doi: 10.1002/wene.360

Norton, J. M., Wing, S., Lipscomb, H. J., Kaufman, J. S., Marshall, S. W., and Cravey, A. J. (2007). Race, wealth, and solid waste facilities in north Carolina. *Environ. Health Perspect.* 115 (9), 1344–1350. doi: 10.1289/ehp.10161

OECD (2022). *Global plastics outlook: Economic drivers, environmental impacts and policy options* (Paris: OECD Publishing). doi: 10.1787/de747aef-en

Oguntoke, O., Emoruwa, F. O., and Taiwo, M. A. (2019). Assessment of air pollution and health hazard associated with sawmill and municipal waste burning in abeokuta metropolis, Nigeria. *Environ. Sci. pollut. Res.* 26 (32), 32708–32722. doi: 10.1007/s11356-019-04310-2

Owens, K. A., and Conlon, K. (2021). Mopping up or turning off the tap? environmental injustice and the ethics of plastic pollution. *Front. Mar. Sci.* 8, 1227. doi: 10.3389/fmars.2021.713385

Ozbay, G., Jones, M., Gadde, M., Isah, S., and Attarwala, T. (2021). Design and operation of effective landfills with minimal effects on the environment and human health. *J. Environ. Public Health* 2021, 13. doi: 10.1155/2021/6921607

Park, C. J., Barakat, R., Ulanov, A., Li, Z., Lin, P. C., Chiu, K., et al. (2019). Sanitary pads and diapers contain higher phthalate contents than those in common commercial plastic products. *Reprod. Toxicol.* 84, 114–121. doi: 10.1016/j.reprotox.2019.01.005

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., et al. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environ. Sci. Technol.* 56 (3), 1510–1521. doi: 10.1021/acs.est.1c04158

Pew Charitable Trusts and SYSTEMIQ (2020). *Breaking the plastic wave: A comprehensive assessment of pathways towards stopping ocean plastic pollution.* (Pew Charitable Trusts) Available at: https://www.pewtrusts.org/-/media/assets/2020/07/breakingtheplasticwave_report.pdf.

Pinto-Bazurco, J. F. (2020). *Brief # 4: The precautionary principle* (IISD Earth Negotiation Bulletin).

Plastic Smart Cities (2020) *A community-based approach in phu quoc, Vietnam*. Available at: https://plasticsmartcities.org/blogs/media/a-community-based-approach-in-phu-quoc-vietnam.

Precious Plastic (2020). *Global impact report*. (Precious Plastic). https://preciousplastic.com/impact.html.

Proshad, R., Kormoker, T., Islam, M. S., Haque, M. A., Rahman, M. M., and Mithu, M. M. R. (2018). Toxic effects of plastic on human health and environment: A consequences of health risk assessment in Bangladesh. *Int. J. Health* 6 (1), 1–5. doi: 10.14419/ijh.v6i1.8655

Ragusa, A., Notarstefano, V., Svelato, A., Belloni, A., Gioacchini, G., Blondeel, C., et al. (2022). Raman microspectroscopy detection and characterisation of microplastics in human breastmilk. *Polymers* 14 (13), 2700. doi: 10.3390/polym14132700

Ramadan, B. S., Rachman, I., Ikhlas, N., Kurniawan, S. B., Miftahadi, M. F., and Matsumoto, T. (2022). A comprehensive review of domestic-open waste burning: recent trends, methodology comparison, and factors assessment. *J. Material Cycles Waste Manage.* 24, 1–15. doi: 10.1007/s10163-022-01430-9

Republic Services (2021). *Sustainability in action 2021 summary annual report.* (Republic Services). Available at: https://investor.republicservices.com/static-files/8e17c8a8-4dea-46f3-9253-10abd83d9cb4.

Rivera-Huerta, R., and López-Lira, N. (2022). Innovation in the informal sector: The case of plastic recycling firms in Mexico. *Afr. J. Science Technology Innovation Dev.* 14 (2), 291–301. doi: 10.1080/20421338.2020.1864881

Secretariat of the Basel, Rotterdam and Stockholm Conventions (2021) *Briefing by the Basel, Rotterdam and Stockholm conventions secretariat on the plastics-related outcomes of the conferences of the parties (COP).* Available at: https://www.wto.org/english/tratop_e/ppesp_e/brs.pdf.

Simon, N., Raubenheimer, K., Urho, N., Unger, S., Azoulay, D., Farrelly, T., et al. (2021). A binding global agreement to address the life cycle of plastics. *Science* 373 (6550), 43–47. doi: 10.1126/science.abi9010

Sivaram, S., Roy, A., and Ray, S. K. (2021). "The paradox of plastics in healthcare and health," in *Climate change and the health sector* (India: Routledge), 215–223.

Terrell, K. A., and St Julien, G. (2022). Air pollution is linked to higher cancer rates among black or impoverished communities in Louisiana. *Environ. Res. Lett.* 17 (1), 014033. doi: 10.1088/1748-9326/ac4360

Tickner, J., Geiser, K., and Baima, S. (2021). Transitioning the chemical industry: The case for addressing the climate, toxics, and plastics crises. *Environment: Sci. Policy Sustain. Dev.* 63 (6), 4–15. doi: 10.1080/00139157.2021.1979857

UNEP (2022). *Plastics science: Note by the secretariat. UNEP/PP/INC.1/7* (UNEP). Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/40767/K2221533%20-%20%20UNEP-PP-INC.1-7%20-%20ADVANCE.pdf.

United Nations Environment Programme (2021). *Neglected: Environmental justice impacts of marine litter and plastic pollution* (Nairobi).

UpCycleAfrica. Available at: https://upcycleafrica.org/our-mission-2/.

Upson, K., Shearston, J. A., and Kioumourtzoglou, M. A. (2022). Menstrual products as a source of environmental chemical exposure: A review from the epidemiologic perspective. *Curr. Environ. Health Rep.* 9, 1–15. doi: 10.1007/s40572-022-00331-1

US PIRG (2018) *Plastic waste is a public health issue*. Available at: https://uspirg.org/blogs/blog/usp/plastic-waste-public-health-issue.

van Emmerik, T. (2021). Macroplastic research in an era of microplastic. *Microplastics Nanoplastics* 1 (1), 1–2. doi: 10.1186/s43591-021-00003-1

Vedantam, A., Suresh, N. C., Ajmal, K., and Shelly, M. (2022). Impact of china's national sword policy on the US landfill and plastics recycling industry. *Sustainability* 14 (4), 2456. doi: 10.3390/su14042456

Velis, C. A., and Cook, E. (2021). Mismanagement of plastic waste through open burning with emphasis on the global south: A systematic review of risks to occupational and public health. *Environ. Sci. Technol.* 55 (11), 7186–7207. doi: 10.1021/acs.est.0c08536

Waste Management (2021). *2021 annual report*. (Waste Management). Available at: https://investors.wm.com/static-files/6f36d219-fd4c-43ce-93f6-35f5928eb2eb.

Watt, E., Picard, M., Maldonado, B., Abdelwahab, M. A., Mielewski, D. F., Drzal, L. T., et al. (2021). Ocean plastics: environmental implications and potential routes for mitigation–a perspective. *RSC Adv.* 11 (35), 21447–21462. doi: 10.1039/D1RA00353D

Wiesinger, H., Wang, Z., and Hellweg, S. (2021). Deep dive into plastic monomers, additives, and processing aids. *Environ. Sci. Technol.* 55 (13), 9339–9351. doi: 10.1021/acs.est.1c00976

World Trade Organization (2022) *Plastics pollution and environmentally sustainable plastics trade*. Available at: https://www.wto.org/english/tratop_e/ppesp_e/ppesp_e.htm.

Wu, D., Li, Q., Shang, X., Liang, Y., Ding, X., Sun, H., et al. (2021). Commodity plastic burning as a source of inhaled toxic aerosols. *J. Hazardous Materials* 416, 125820. doi: 10.1016/j.jhazmat.2021.125820

Yan, Z., Liu, Y., Zhang, T., Zhang, F., Ren, H., and Zhang, Y. (2021). Analysis of microplastics in human feces reveals a correlation between fecal microplastics and inflammatory bowel disease status. *Environ. Sci. Technol.* 56 (1), 414–421. doi: 10.1021/acs.est.1c03924

Yu, H. L., Chen, B. H., Kim, K. S., Siwayanan, P., Choong, S. T., and Ban, Z. H. (2022). Source localization for illegal plastic burning in Malaysia *via* CFD-ANN approach. *Digital Chem. Eng.* 3, 100029. doi: 10.1016/j.dche.2022.100029

Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T., and Sillanpää, M. (2020). Atmospheric microplastics: A review on current status and perspectives. *Earth-Science Rev.* 203, 103118. doi: 10.1016/j.earscirev.2020.103118

Żwierełło, W., Maruszewska, A., Skórka-Majewicz, M., Goschorska, M., Baranowska-Bosiacka, I., Dec, K., et al. (2020). The influence of polyphenols on metabolic disorders caused by compounds released from plastics-review. *Chemosphere* 240, 124901. doi: 10.1016/j.chemosphere.2019.124901

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Engineering a microbiosphere to clean up the ocean – inspiration from the plastisphere

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Plastic is a ubiquitous material that has become an essential part of our lives. More than one hundred million tons of plastic has accumulated in the world's oceans as a result of poor waste management. This plastic waste gradually fragments into smaller pieces known as microplastics and nanoplastics. These small plastic particles can cause significant damage to marine ecosystems, and negatively impact human health. According to a recent review of international patents, the majority of ocean-cleaning inventions are limited to microplastics larger than 20 µm. Furthermore, such technologies are ineffective for nanoplastics, which measure less than 1000 nm, or even fibrous plastics. Alternative solutions need to be considered for the large-scale *in situ* removal of microplastics and nanoplastics from the ocean. In this perspective, we present the concept of engineering a microbial ecosystem, which we term the microbiosphere. The concept is based on key observations that have been made for natural plastic-based ecosystems known as plastispheres. These observations relate to the solid support material, self-sustainability, attachment to plastic, degradation of plastic, and risk of pathogenicity. Inspiration can be taken from the plastisphere whereby a novel microbial ecosystem could be designed and engineered as a bioremediation tool to rid the ocean of micro- and nanoplastics. Such an engineered system could outcompete pathogens for marine plastic waste and potentially reduce the risk of infectious diseases.

KEYWORDS

plastic, bioremediation, marine, microorganism, ecosystem, community, microbial

Introduction

Poor waste management of plastic has led to the accumulation of almost 150 million tons of plastics in the ocean, much of which emanates from landfills (Eunomia, 2016; World Economic Forum, 2016). It has been estimated that the content of one garbage truck, which can hold 12 to 14 tonnes of plastic, is released into the ocean every minute (World Economic Forum, 2016). At the present rate of plastic consumption and disposal, plastic mass will outnumber the fish biomass in the ocean by 2050 (World Economic Forum, 2016). Marine plastic waste, through exposure to heat, seawater and sunlight, becomes brittle over time and is fragmented into smaller pieces known as microplastics, which have particle sizes of 1 to 1000 µm (Hartmann et al., 2019). Microplastics can also enter the oceans directly from waste-containing paint-based materials, textiles and cosmetic products (Eunomia, 2016). These plastic pieces are ingested by marine organisms, which can negatively impact ocean ecosystems. Further fragmentation of microplastic leads to the formation of nanoplastics which range in size from 1 to 1000 nm. On account of their greater surface area-to-volume ratio, microplastics and nanoplastics can permeate cell membranes, disrupt cellular functions, and cause health issues (Ter Halle et al., 2017; Tetu et al., 2020).

After several decades of exposure to synthetic plastic, a relatively new type of ecosystem has emerged in nature known as the 'Plastisphere.' This terminology, coined by Zettler et al. (2013), describes a community of microbial species distinct from its surrounding environment in which the plastic debris forms the heart of the community. By studying the plastispheres at molecular, cellular and community levels, one could potentially design and engineer marine-based microbial ecosystems to clean up the ocean. In this article, we will put forward the notion of engineering a microbial ecosystem for the purpose of removing plastic waste from the ocean, which we will refer to as a microbiosphere. We will describe five key design features that would need to be incorporated into a microbiosphere to make such a concept environmentally feasible (Figures 1, 2).

Design feature 1 - a biodegradable material to support the microbiosphere

The core part of any plastisphere community is the plastic waste itself (Zettler et al., 2013). Thus, an obvious starting point for engineering a microbiosphere would be the use of a solid support to accommodate the microbial species that constitute the microbiosphere community. Like synthetic plastic, the supporting material would need to be resilient, durable, colonizable, and light enough to access different parts of the oceans. Unlike synthetic plastic, however, the solid support would need to be prone to degradation so that it does not persist in the natural environment for too long and lead to pernicious interactions with marine life. The most logical choice of material for supporting a microbiosphere would be an environment-friendly material with physical properties similar to conventional synthetic plastics. One ideal candidate in this regard would be polyhydroxybutyrate (Leong et al., 2014). This well-studied bioplastic can serve as energy and carbon sources for microorganisms. Furthermore, it can be synthesised and degraded through natural means (Leong et al., 2014). Lott et al. (2021) observed that, under laboratory conditions, as much as 81% of a polyhydroxybutyrate film could be degraded over a 1-year period in the presence of seawater. Other polyester-based plastics such as polylactic acid and polycaprolactone could also make excellent candidates as support materials for microbiospheres due to their biodegradable properties (Suzuki et al., 2020; Wang et al., 2020). The support material for the microbiosphere would serve two primary functions. Firstly, it would enable the microbiosphere to access different parts of the ocean. Denser solids such as sand could be mixed into the support material to create variations in buoyancy and allow the microbiosphere to operate at different ocean depths (Michels et al., 2018). Secondly, it would sustain the growth and viability of the microbiosphere by providing nutrients to the microbiosphere community.

Design feature 2 – self-sustainable community of microbial species

Plastisphere communities are able to endure the harsh conditions of the ocean environment over long periods from several months to years (De Tender et al., 2017). The robustness of these communities can be attributed to the multi-species arrangement which can impart a number of beneficial traits to the community. Firstly, it enables a division of labor which reduces the metabolic burden imposed on a single member of the community (Zhang and Wang, 2016). Secondly, it increases the diversity of nutrients that can be acquired from the environment and utilized within the community. Thirdly, it reduces the stress that would inevitably

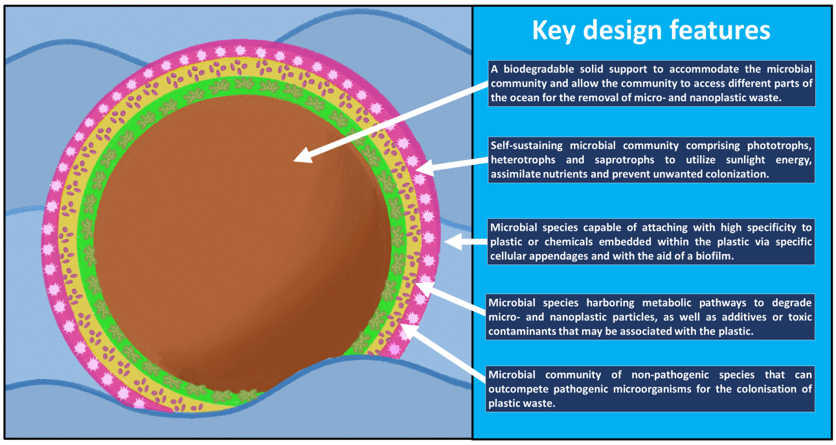

FIGURE 1
Key design features of the proposed microbiosphere.

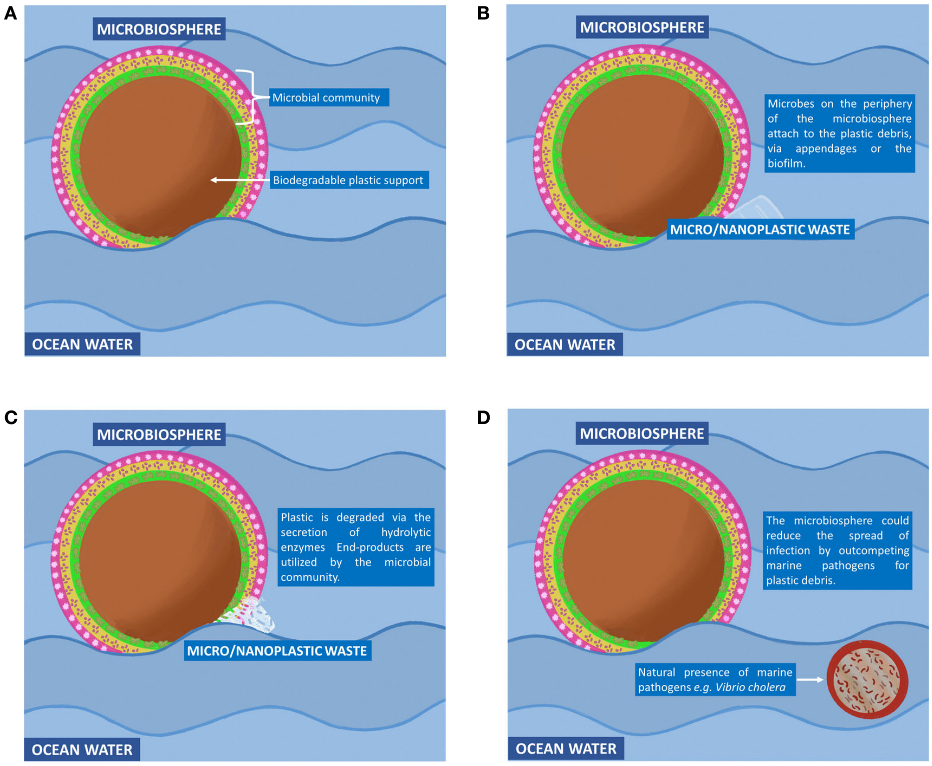

FIGURE 2
The concept of the microbiosphere. **(A)** A biodegradable solid support (central brown circle) would be used to accommodate a rationally engineered community of microbial species known as the microbiosphere. This community would include phototrophic and heterotrophic species to ensure self-sustainability (green, orange and pink areas). A solid support would be critical for transporting the microbiosphere across the ocean as well as providing nutrients to the microbiosphere. **(B)** Micro- and nanoplastic waste that is too small to be filtered off and collected by conventional technologies could potentially cause harm to marine life, as well as humans. To remove these small plastic waste particles, microbiospheres would be released into the ocean. These biological entities would attach themselves to micro- and nanoplastic waste debris with the aid of cellular appendages and the adhesive property of the community biofilm. **(C)** Hydrolytic enzymes would be secreted into the extracellular environment to break down the plastic polymer into its monomers. The monomers would be taken up by microbial cells *via* protein transporters and converted to metabolites that support the growth and survival of the microbiosphere. **(D)** By outcompeting pathogenic microbial species (small circle outlined in brown) for the plastic waste, the microbiosphere could potentially reduce the risk of infectious diseases.

arise from the dynamic conditions of the marine environment. Lastly, it prevents colonization by microbial species that may threaten the survival of the community (Pamer, 2016). Many of the members of the plastisphere community are bacterial species but also include other types of microorganisms such as archaea, fungi and microbial eukaryotes (Oberbeckmann et al., 2014; Oberbeckmann et al., 2016; Oberbeckmann et al., 2018). For a comprehensive list of species associated with plastispheres, refer to Wallbank et al., (2022). Two main groups of microorganisms, known as the photoautotrophs e.g. diatoms (*Mastogloia*, *Navicula*, *Nitzschia*), cyanobacteria (*Phormidium*, *Rivularia*, and *Leptolyngbya*) and heterotrophs, e.g. bacteria (*Pseudomonas, Azotobacter, Bacillus*), are typically encountered in plastisphere communities (Dey et al., 2022; Wallbank et al., 2022). The co-cultivation and coexistence of these organisms within a microbiosphere could be achieved with a symbiotic arrangement of these species (Zuñiga et al., 2020). Photoautotrophic species, in the presence of light, convert inorganic carbon CO_2 into organic molecules; this would be required by heterotrophs under conditions where a source of organic carbon is not readily available. In exchange, the heterotrophs would provide the photoautotrophs with additional CO_2 resulting from the heterotrophic metabolism of organic nutrients. This resulting symbiosis would confer a survival advantage to the entire community (Zuñiga et al., 2020). Another intriguing, yet poorly studied, group observed in plastisphere communities is the saprotroph (Zeghal et al., 2021). These species recycle dead organic matter within the community and typically include the Ascomycota, Basidiomycota and Chytridiomycota phyla of the fungal community (Oberbeckmann et al., 2016; Zeghal et al., 2021). An important and key point here is that mutualistic arrangement and interaction of multiple microbial species would be critical for the development of stable and robust communities that can endure the marine environment.

Design feature 3 – cellular attachment to marine plastic waste

In a 21-month experiment using artificial seawater conditions, Kirstein et al. (2019) screened the plastisphere community for microbial species that were able to attach themselves to different types of plastics. The authors, in accordance with previous studies, observed that bacterial species from the *Roseovarius*, *Erythrobacter*, *Ulvibacter* and *Parvularcula* genera were closely associated with plastic materials (Zettler et al., 2013; Oberbeckmann et al., 2016; Viršek et al., 2017; Oberbeckmann et al., 2018). Though it could be speculated that these bacteria species may possess affinity for the chemical additives or contaminants within the plastic waste, rather than the plastic chemical itself, these initial studies nonetheless provide a preliminary indication that biological features do exist within microorganisms that promote attachment to plastic material. The underlying mechanism by which microorganisms attach specifically to plastic materials has not been established, but is likely to be facilitated in two ways. The first is with the aid of cellular appendages such as flagella, pili, fimbriae, and curli fibers (Kreve and Reis, 2021). This mechanism of attachment is known to occur within minutes and is thought to involve strong non-covalent interactions (Shteindel et al., 2019; Parreira and Martins, 2021). The second is *via* the extracellular matrix known as the biofilm, the formation of which can be initiated by appendage attachment (Koczan et al., 2011). The underlying core structure of the biofilm is the extracellular polymeric substance, also known as the EPS. The mixture of polymeric compounds present within the EPS, e.g. polysaccharides, proteins, lipids and DNA, generate the adhesive forces such as hydrogen bonds and London Dispersion forces which would promote surface attachment (Flemming et al., 2016). The process of attachment is known to be influenced to a great extent by the pre-conditioning of the attachment surface, as well as the type of plastic material (Eich et al., 2015). Based on these possible modes of attachment, it could be speculated that microbial species with cellular appendages or biofilms with a greater degree of hydrophobicity would be more effective at penetrating plastic surfaces. Microbial species that possess a high affinity for plastics would most certainly be an important design feature to ensure that plastic materials are specifically targeted (Gabriel et al., 2019).

Design feature 4 – degradation of the plastic material and its associated compounds

Surprisingly, very few studies have identified the marine species responsible for plastic degradation within plastisphere communities. Gao and Sun, (2021) recently isolated three bacterial species, *Exiguobacterium* sp., *Halomonas* sp. and *Ochrobactrum* sp., capable of degrading polyethylene terephthalate and polyethylene, while Khandare et al. (2021) isolated polyvinyl chloride (PVC)-degrading bacterial species belonging to the *Vibrio*, *Alteromonas* and *Cobetia* genera. How have these microorganisms achieved this remarkable capacity to utilize plastic waste as a source of nutrient? There is a general consensus now that since the establishment of the plastic industry during the fifties, microorganisms have slowly evolved over the last few decades to metabolise plastic waste (Zrimec et al., 2021). This status of evolution has been made possible with the diverse range of hydrolytic enzymes that are secreted into the extracellular environment and able to degrade various plastic substrates. In a landmark study, Kohei Oda's research team (Yoshida et al., 2016) had previously shown that the PETase and MHETase enzymes were responsible for polyethylene degradation within the soil bacterium *Ideonella sakiensis*. Enzyme-mediated degradation of other types of plastics such as polypropylene and polystyrene, which are the most commonly encountered plastics on the ocean surface, have also been demonstrated (Auta et al., 2017; Kaushal et al., 2021). Research is currently underway to engineer plastic-hydrolysing enzyme to improve their catalytic rates and substrate specificities for the treatment and recycling of plastics (Zhu et al., 2022).

Aside from the bulk plastic material, chemicals added to plastics to enhance their properties, e.g. antioxidants, fillers, flame retardants, UV-light stabilisers, impact modifiers, heat stabilisers, would also need to be remediated to reduce their cellular toxic effects (Hahladakis et al., 2018). This also applies to organic pollutants adsorbed to the plastic waste (Karkanorachaki et al., 2022). Several microbial species have been reported in the literature that are capable of degrading plastic additives, e.g. bisphenol, diethylhexyl-phthalate, or organic pollutants, e.g. polycyclic aromatic hydrocarbons, textile dyes (Suyamud et al., 2018; Wang et al., 2018; John et al., 2020; Wright et al., 2020). Within the context of designing and engineering a microbiosphere, both plastic- and toxin-degrading microbial species would be necessary for the complete bioremediation of marine plastic waste.

Design feature 5 – a community of non-pathogenic microbial species

Marine plastispheres can harbor pathogenic bacterial species such as *Vibrio cholera*. This raises the concern that waste plastic in the ocean could serve as a vehicle for the spread of infection diseases though recent evidence suggests that *Vibrio* species may simply be opportunistic colonizers of the plastic rather than core, stable members of the community (Kirstein et al., 2016; Kesy et al., 2021). Another worrying concern is that plastispheres may enrich antimicrobial resistance genes *via* gene transfer and increase the likelihood of certain members acquiring resistance to a wide spectrum of drugs (Moore et al., 2020). To ensure that an engineered microbiosphere itself does not pose a threat to marine or human environments, non-pathogenic microbial species would need to be incorporated into the design of a microbiosphere in order to prevent the colonization of microbes that have the potential to become pathogenic. On this particular point of pathogenicity, artificially engineered communities therefore present a distinct advantage over natural communities for the degradation of plastic waste. One interesting group of microorganisms that could reduce the potential of pathogenicity is the 'predator' which can consume bacteria. Members of this group have been observed in plastispheres and include choanoflagellates, radiolaria, and *Micromonas* (Dey et al., 2022). Incorporation of predators into the microbiosphere could potentially be an effective strategy for reducing the infiltration and unwanted colonization of pathogenic species within the microbiosphere. *Bdellovibrio bacteriovorus*, for example, is a well-studied bacterial predator that could be used to lower the risk of colonization by pathogens such as *Vibrio cholerae* (Richards et al., 2012). Integration of anti-pathogenic features into the design of a microbiosphere could therefore potentially reduce the spread of infectious diseases.

Concluding remarks

Currently, there are no commercially viable technologies for the effective removal of microplastics or nanoplastics. Given the ongoing work relating to the engineering of microbial communities, one possible solution for the removal of marine waste plastic is to design and engineer microbial ecosystems capable of ocean bioremediation (Mee and Wang, 2012; Tsoi et al., 2019). As highlighted in this perspective, biological features, inspired from observations of the plastisphere community, could be used to design and engineer such systems.

It could be reasoned that plastisphere communities, which have evolved within the natural marine environment for the colonization and degradation of plastic, could be applied for the *in situ* removal of marine plastic waste. Clearly, they would hold an advantage with regard to immediate implementation and practical application. The main concern, however, is the risk of colonization by pathogenic microbial species in plastisphere communities. A microbiosphere, on the other hand, could be designed and engineered to significantly reduce this risk. Moreover, the efficiency and functionality of such ecosystems could be greatly improved using rational and customised approaches.

Still, a host of questions, from both application and fundamental standpoints, would need to be addressed through further experimental work in order to assess not only the technical feasibility of this concept but also its ethical implications. How rapidly could an engineered microbiosphere degrade plastic under natural conditions? Could they be engineered for plastic degradation in different ocean environments? How would these engineered ecosystems compare against plastisphere communities in terms of their plastic-degrading trait? How stable would microbiospheres be over time within the natural environment and how long would they retain their plastic-degrading property within the natural environment? Could the release of an engineered microbiosphere pose even more of a threat to the marine environment than the plastisphere itself?

To understand the enormous remedial potential of microbial ecosystems, one needs only to look at the famous explosion of the Deepwater Horizon oil rig. Nature's response to this environmental disaster at the microbial level has been phenomenal and inspiring to the point that it has set off intensive activities in engineering more efficient microbial systems for the clean-up of oil spillages (Ganesan et al., 2022). Likewise, nature has presented its own solution to dealing with plastic in the form of plastispheres. Scientists can take inspirations from these natural microbial ecosystems in order to develop novel technologies for the large-scale removal of micro- and nanoplastics from the ocean.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials. Further inquiries can be directed to the corresponding author.

Author contributions

MKA conceived the idea. MKA drafted and edited the final manuscript. KAA, LWA and MKS composed the figure. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Auta, H. S., Emenike, C. U., and Fauziah, S. H. (2017). Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions. *Environ. Int.* 102, 165–176. doi: 10.1016/J.ENVINT.2017.02.013

De Tender, C., Devriese, L. I., Haegeman, A., Maes, S., Vangeyte, J., Cattrijsse, A., et al. (2017). Temporal dynamics of bacterial and fungal colonization on plastic debris in the north Sea. *Environ. Sci. Technol.* 51, 7350–7360. doi: 10.1021/ACS.EST.7B00697/SUPPL_FILE/ES7B00697_SI_001.PDF

Dey, S., Rout, A. K., Behera, B. K., and Ghosh, K. (2022). Plastisphere community assemblage of aquatic environment: plastic-microbe interaction, role in degradation and characterization technologies. *Environ. Microbiome 2022* 17, 1–21. doi: 10.1186/S40793-022-00430-4

Eich, A., Mildenberger, T., Laforsch, C., and Weber, M. (2015). Biofilm and diatom succession on polyethylene (PE) and biodegradable plastic bags in two marine habitats: Early signs of degradation in the pelagic and benthic zone? *PloS One* 10(9):e0137201. doi: 10.1371/journal.pone.0137201

Erni-Cassola, G, Wright, RJ, Gibson, MI, and Christie-Oleza, JA (2019). Early colonization of weathered polyethylene by distinct bacteria in marine coastal seawater. *Micro Ecol.* 79 (3), 517–526. doi: 10.1007/s00248-019-01424-5

Eunomia (2016). *Plastics in the marine environment: Where do they come from? where do they go*? Available at: https://www.eunomia.co.uk/reports-tools/plastics-in-the-marine-environment/.

Flemming, H. C., Wingender, J., Szewzyk, U., Steinberg, P., Rice, S. A., and Kjelleberg, S. (2016). Biofilms: An emergent form of bacterial life. *Nat. Rev. Microbiol. 2016 149* 14, 563–575. doi: 10.1038/nrmicro.2016.94

Ganesan, M., Mani, R., Sai, S., Kasivelu, G., Awasthi, M. K., Rajagopal, R., et al. (2022). Bioremediation by oil degrading marine bacteria: An overview of supplements and pathways in key processes. *Chemosphere* 303, 134956. doi: 10.1016/J.CHEMOSPHERE.2022.134956

Gao, R., and Sun, C. (2021). A marine bacterial community capable of degrading poly (ethylene terephthalate) and polyethylene. *J. Hazard. Mater.* 416, 125928. doi: 10.1016/J.JHAZMAT.2021.125928

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., and Purnell, P. (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J. Hazard. Mater.* 344, 179–199. doi: 10.1016/J.JHAZMAT.2017.10.014

Hartmann, N. B., Hüffer, T., Thompson, R. C., Hassellöv, M., Verschoor, A., Daugaard, A. E., et al. (2019). Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. *Environ. Sci. Technol.* 53, 1039–1047. doi: 10.1021/ACS.EST.8B05297/ASSET/IMAGES/MEDIUM/ES-2018-05297K_0006.GIF

John, J., Dineshram, R., Hemalatha, K. R., Dhassiah, M. P., Gopal, D., and Kumar, A. (2020). Bio-decolorization of synthetic dyes by a halophilic bacterium *Salinivibrio* sp. *Front. Microbiol.* 11. doi: 10.3389/FMICB.2020.594011/BIBTEX

Karkanorachaki, K., Tsiota, P., Dasenakis, G., Syranidou, E., and Kalogerakis, N. (2022). Nanoplastic generation from secondary PE microplastics: Microorganism-induced fragmentation. *Microplastics 2022 Vol. 1 Pages 85-101* 1, 85–101. doi: 10.3390/MICROPLASTICS1010006

Kaushal, J., Khatri, M., and Arya, S. K. (2021). Recent insight into enzymatic degradation of plastics prevalent in the environment: A mini - review. *Clean. Eng. Technol.* 2, 100083. doi: 10.1016/J.CLET.2021.100083

Kesy, K., Labrenz, M., Scales, B. S., Kreikemeyer, B., and Oberbeckmann, S. (2021). *Vibrio* colonization is highly dynamic in early microplastic-associated biofilms as well as on field-collected microplastics. *Microorganisms* 9, 1–13. doi: 10.3390/MICROORGANISMS9010076

Khandare, S. D., Chaudhary, D. R., and Jha, B. (2021). Bioremediation of polyvinyl chloride (PVC) films by marine bacteria. *Mar. pollut. Bull.* 169, 112566. doi: 10.1016/J.MARPOLBUL.2021.112566

Kirstein, I. V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Löder, M., et al. (2016). Dangerous hitchhikers? Evidence for potentially pathogenic vibrio spp. on microplastic particles. *Mar. Environ. Res.* 120, 1–8. doi: 10.1016/J.MARENVRES.2016.07.004

Kirstein, I. V., Wichels, A., Gullans, E., Krohne, G., and Gerdts, G. (2019). The plastisphere – uncovering tightly attached plastic "specific" microorganisms. *PloS One* 14, e0215859. doi: 10.1371/JOURNAL.PONE.0215859

Koczan, J. M., Lenneman, B. R., McGrath, M. J., and Sundin, G. W. (2011). Cell surface attachment structures contribute to biofilm formation and xylem colonization by *Erwinia amylovora*. *Appl. Environ. Microbiol.* 77, 7031. doi: 10.1128/AEM.05138-11

Kreve, S., and Reis, A. C. D. (2021). Bacterial adhesion to biomaterials: What regulates this attachment? a review. *Jpn. Dent. Sci. Rev.* 57, 85. doi: 10.1016/J.JDSR.2021.05.003

Leong, Y. K., Show, P. L., Ooi, C. W., Ling, T. C., and Lan, J. C. W. (2014). Current trends in polyhydroxyalkanoates (PHAs). *J. Biotechnol.* 180, 52–65. doi: 10.1016/j.jbiotec.2014.03.020

Lott, C., Eich, A., Makarow, D., Unger, B., van Eekert, M., Schuman, E., et al. (2021). Half-life of biodegradable plastics in the marine environment depends on material, habitat, and climate zone. *Front. Mar. Sci.* 8. doi: 10.3389/FMARS.2021.662074/BIBTEX

Mee, M. T., and Wang, H. H. (2012). Engineering ecosystems and synthetic ecologies. *Mol. Biosyst.* 8, 2470–2483. doi: 10.1039/C2MB25133G

Michels, J., Stippkugel, A., Lenz, M., Wirtz, K., and Engel, A. (2018). Rapid aggregation of biofilm-covered microplastics with marine biogenic particles. *Proc. R. Soc B* 285. doi: 10.1098/RSPB.2018.1203

Moore, R. E., Millar, B. C., and Moore, J. E. (2020). Antimicrobial resistance (AMR) and marine plastics: Can food packaging litter act as a dispersal mechanism for AMR in oceanic environments? *Mar. pollut. Bull.* 150. doi: 10.1016/J.MARPOLBUL.2019.110702

Oberbeckmann, S., Kreikemeyer, B., and Labrenz, M. (2018). Environmental factors support the formation of specific bacterial assemblages on microplastics. *Front. Microbiol.* 8. doi: 10.3389/FMICB.2017.02709/BIBTEX

Oberbeckmann, S., Loeder, M. G. J., Gerdts, G., and Osborn, M. A. (2014). Spatial and seasonal variation in diversity and structure of microbial biofilms on marine plastics in northern European waters. *FEMS Microbiol. Ecol.* 90, 478–492. doi: 10.1111/1574-6941.12409

Oberbeckmann, S., Osborn, A. M., and Duhaime, M. B. (2016). Microbes on a bottle: Substrate, season and geography influence community composition of microbes colonizing marine plastic debris. *PloS One* 11. doi: 10.1371/JOURNAL.PONE.0159289

Pamer, E. G. (2016). Resurrecting the intestinal microbiota to combat antibiotic-resistant pathogens. *Science* 352, 535–538. doi: 10.1126/SCIENCE.AAD9382

Parreira, P., and Martins, M. C. L. (2021). The biophysics of bacterial infections: Adhesion events in the light of force spectroscopy. *Cell Surf.* 7, 100048. doi: 10.1016/J.TCSW.2021.100048

Richards, G. P., Fay, J. P., Dickens, K. A., Parent, M. A., Soroka, D. S., and Boyd, E. F. (2012). Predatory bacteria as natural modulators of *Vibrio parahaemolyticus* and *Vibrio vulnificus* in seawater and oysters. *Appl. environ. Microbiol.* 78, 7455. doi: 10.1128/AEM.01594-12

Shteindel, N., Yankelev, D., and Gerchman, Y. (2019). High-throughput quantitative measurement of bacterial attachment kinetics on seconds time scale. *Microb. Ecol.* 77, 726–735. doi: 10.1007/S00248-018-1254-5

Suyamud, B., Inthorn, D., Panyapinyopol, B., and Thiravetyan, P. (2018). Biodegradation of bisphenol a by a newly isolated *Bacillus megaterium* strain ISO-2 from a polycarbonate industrial wastewater. *Water Air Soil pollut. 2018 22911* 229, 1–12. doi: 10.1007/S11270-018-3983-Y

Suzuki, M., Tachibana, Y., and Kasuya, K.i. (2020). Biodegradability of poly(3-hydroxyalkanoate) and poly(ϵ-caprolactone) *via* biological carbon cycles in marine environments. *Polym. J. 2020* 53, 47–66. doi: 10.1038/s41428-020-00396-5

Ter Halle, A., Jeanneau, L., Martignac, M., Jardé, E., Pedrono, B., Brach, L., et al. (2017). Nanoplastic in the north Atlantic subtropical gyre. *Environ. Sci. Technol.* 51, 13689–13697. doi: 10.1021/ACS.EST.7B03667/SUPPL_FILE/ES7B03667_SI_001.PDF

Tetu, S. G., Sarker, I., and Moore, L. R. (2020). How will marine plastic pollution affect bacterial primary producers? *Commun. Biol. 2020 31* 3, 1–4. doi: 10.1038/s42003-020-0789-4

Tsoi, R., Dai, Z., and You, L. (2019). Emerging strategies for engineering microbial communities. *Biotechnol. Adv.* 37, 107372. doi: 10.1016/J.BIOTECHADV.2019.03.011

Viršek, M. K., Lovšin, M. N., Koren, Š., Kržan, A., and Peterlin, M. (2017). Microplastics as a vector for the transport of the bacterial fish pathogen species *Aeromonas salmonicida*. *Mar. pollut. Bull.* 125, 301–309. doi: 10.1016/J.MARPOLBUL.2017.08.024

Wallbank, J. A., Lear, G., Kingsbury, J. M., Weaver, L., Doake, F., Smith, D. A., et al. (2022). Into the plastisphere, where only the generalists thrive: Early insights in plastisphere microbial community succession. *Front. Mar. Sci.* 9. doi: 10.3389/FMARS.2022.841142/BIBTEX

Wang, G. X., Huang, D., Ji, J. H., Völker, C., and Wurm, F. R. (2020). Seawater-degradable polymers - fighting the marine plastic pollution. *Adv. Sci.* 8, 2001121. doi: 10.1002/ADVS.202001121

Wang, W., Wang, L., and Shao, Z. (2018). Polycyclic aromatic hydrocarbon (PAH) degradation pathways of the obligate marine PAH degrader *Cycloclasticus* sp. strain P1. *Appl. Environ. Microbiol.* 84, e01261–18. doi: 10.1128/AEM.01261-18

World Economic Forum (2016). *The new plastics economy: Rethinking the future of plastics*. Available at: https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics.

Wright, R. J., Bosch, R., Gibson, M. I., and Christie-Oleza, J. A. (2020). Plasticizer degradation by marine bacterial isolates: A proteogenomic and metabolomic characterization. *Environ. Sci. Technol.* 54, 2244–2256. doi: 10.1021/acs.est.9b05228

Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., et al. (2016). A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science* 351, 1196–1199. doi: 10.1126/SCIENCE.AAD6359

Zeghal, E., Vaksmaa, A., Vielfaure, H., Boekhout, T., and Niemann, H. (2021). The potential role of marine fungi in plastic degradation – a review. *Front. Mar. Sci.* 8. doi: 10.3389/FMARS.2021.738877/BIBTEX

Zettler, E. R., Mincer, T. J., and Amaral-Zettler, L. A. (2013). Life in the "Plastisphere": Microbial communities on plastic marine debris. *Environ Sci Technol.* 47 (13), 7137–7146. doi: 10.1021/es401288x

Zhang, H., and Wang, X. (2016). Modular co-culture engineering, a new approach for metabolic engineering. *Metab. Eng.* 37, 114–121. doi: 10.1016/J.YMBEN.2016.05.007

Zhu, B., Wang, D., and Wei, N. (2022). Enzyme discovery and engineering for sustainable plastic recycling. *Trends Biotechnol.* 40, 22–37. doi: 10.1016/J.TIBTECH.2021.02.008

Zrimec, J., Kokina, M., Jonasson, S., Zorrilla, F., and Zelezniak, A. (2021). Plastic-degrading potential across the global microbiome correlates with recent pollution trends. *MBio* 12, e021552. doi: 10.1128/MBIO.02155-21/SUPPL_FILE/MBIO.02155-21-ST003.TXT

Zuñiga, C., Li, T., Guarnieri, M. T., Jenkins, J. P., Li, C. T., Bingol, K., et al. (2020). Synthetic microbial communities of heterotrophs and phototrophs facilitate sustainable growth. *Nat. Commun.* 11, 1–13. doi: 10.1038/s41467-020-17612-8

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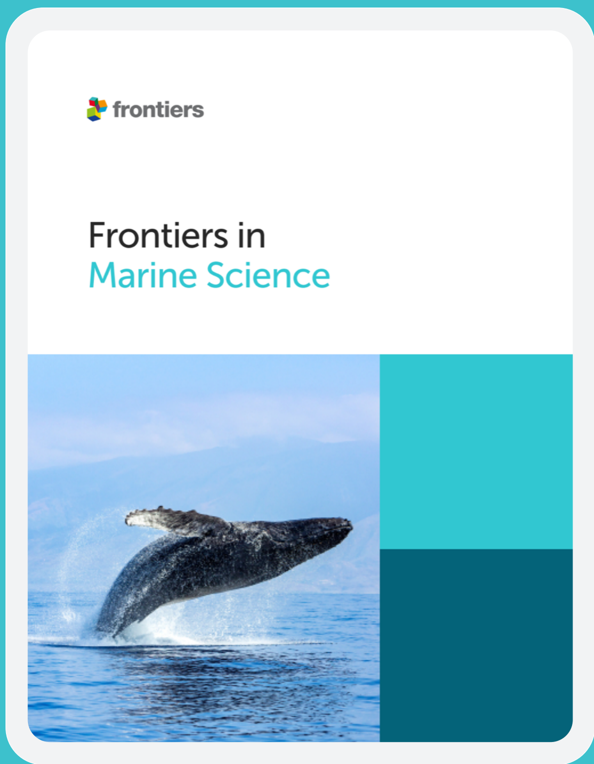

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