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A transdisciplinary approach to reducing global plastic pollution

Zoie Diana[1], Rachel Karasik[2], Greg B. Merrill[1], Margaret Morrison[1], Kimberly A. Corcoran[1], Daniel Vermeer[3], Evan Hepler-Smith[4], Nishad Jayasundara[5], Jeremy Pare[5], John Virdin[1,2], William C. Eward[6], Jason A. Somarelli[7], Meagan M. Dunphy-Daly[1] and Daniel Rittschof[1]*

[1]Duke University Marine Lab, Nicholas School of the Environment, Beaufort, NC, United States, [2]Nicholas Institute for Energy, Environment & Sustainability, Duke University, Durham, NC, United States, [3]Fuqua School of Business, Duke University, Durham, NC, United States, [4]Department of History, Duke University, Durham, NC, United States, [5]Nicholas School of the Environment, Duke University, Durham, NC, United States, [6]Department of Orthopedics, Duke University Medical Center, Durham, NC, United States, [7]Department of Medicine, Duke University Medical Center, Durham, NC, United States

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EDITED BY
Richard M. K. Yu,
The University of Newcastle, Australia

REVIEWED BY
Siu Gin Cheung,
City University of Hong Kong,
Hong Kong SAR, China

*CORRESPONDENCE
Daniel Rittschof
ritt@duke.edu

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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

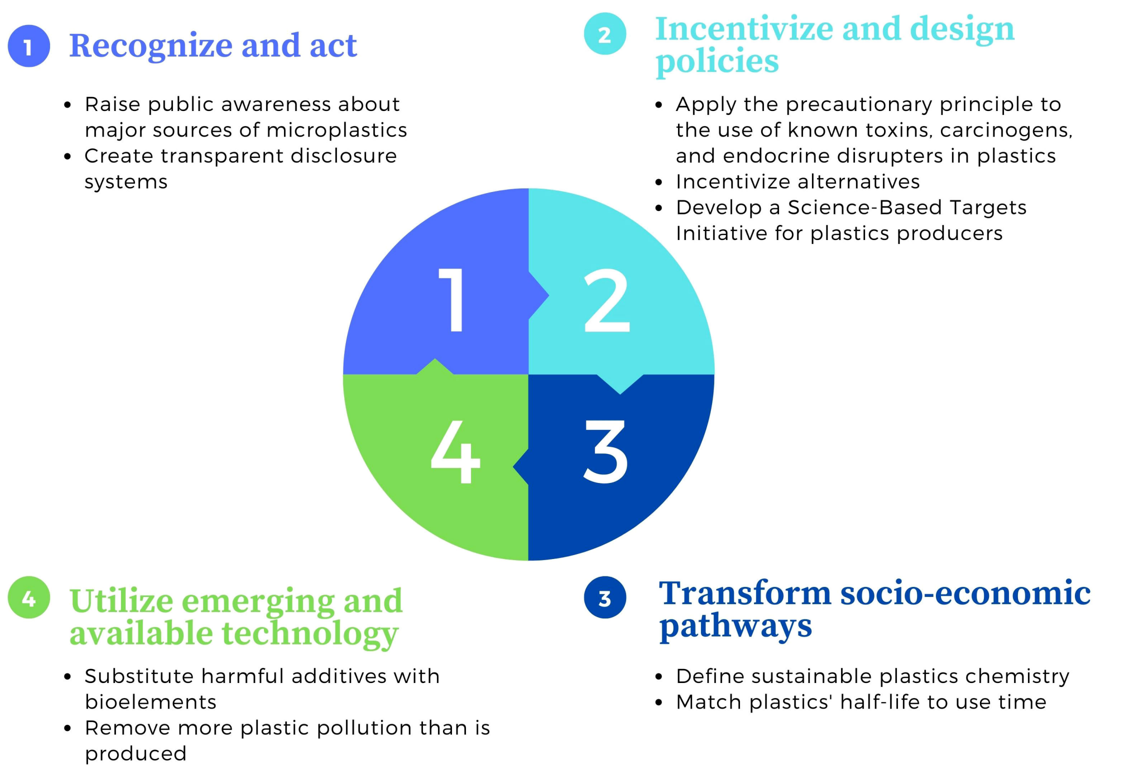

FIGURE 1
Suggested interventions organized by the four pathways toward global sustainability developed by Folke et al. (2021).

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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