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The time for ambitious action is now: Science-based recommendations for plastic chemicals to inform an effective global plastic treaty

Susanne M. Brander[a,*], Kala Senathirajah[b], Marina O. Fernandez[c], Judith S. Weis[d], Eva Kumar[e], Annika Jahnke[f,g], Nanna B. Hartmann[h], Juan José Alava[i], Trisia Farrelly[j], Bethanie Carney Almroth[k], Ksenia J. Groh[l], Kristian Syberg[m], Johanna Sophie Buerkert[n], Amila Abeynayaka[o,w], Andy M. Booth[p], Xavier Cousin[q], Dorte Herzke[r], Laura Monclús[s,x], Carmen Morales-Caselles[t], Andrea Bonisoli-Alquati[u], Rana Al-jaibachi[v], Martin Wagner[s,x]

[a] Oregon State University, Dept. Fisheries, Wildlife, Conservation Sciences; Coastal Oregon Marine Experiment Station, Newport, OR, USA
[b] School of Engineering, University of Newcastle, Callaghan, Australia
[c] Laboratory of Neuroendocrinology, Instituto de Biología y Medicina Experimental, Consejo Nacional de Investigaciones Científicas y Técnicas (IBYME-CONICET), Argentina
[d] Biological Sciences, Rutgers University, Newark, NJ, USA
[e] Department of Health Security, Finnish Institute for Health and Welfare, Kuopio, Finland
[f] Department of Exposure Science, Helmholtz-Centre for Environmental Research - UFZ, Permoserstr, Leipzig, Germany
[g] Institute for Environmental Research, RWTH Aachen University, Germany
[h] Department of Environmental and Resource Engineering, Technical University of Denmark, Bygningstorvet, Lyngby, Denmark
[i] Ocean Pollution Research Unit, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, Canada
[j] School of People, Environment and Planning, Massey University, New Zealand
[k] Department of Biological and Environmental Sciences, University of Gothenburg, Göteborg, Sweden
[l] Eawag - Swiss Federal Institute of Aquatic Science and Technology, Department of Environmental Toxicology, Duebendorf, Switzerland
[m] Department of Science and Environment, Roskilde University, Roskilde, Denmark
[n] Centre for Climate Change Law and Governance, Faculty of Law, University of Copenhagen, Denmark
[o] Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark, Bygningstorvet, Lyngby, Denmark
[p] SINTEF Ocean, Trondheim, Norway
[q] MARBEC, Univ Montpellier, CNRS, Ifremer, IRD, INRAE, Palavas, France
[r] NILU & Norwegian Institute of Public Health (NIPH), Oslo, Norway
[s] Department of Biology, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[t] Faculty of Marine and Environmental Sciences, University of Cádiz, Spain
[u] Department of Biological Sciences, California State Polytechnic University – Pomona, Pomona, CA, USA
[v] Department of Bioscience, University of Sheffield, Sheffield, United Kingdom
[w] Moore Institute for Plastic Pollution Research, Long Beach, CA, USA
[x] Norwegian University of Science and Technology (NTNU), Trondheim, Norway

* Corresponding author.
E-mail address: susanne.brander@oregonstate.edu (S.M. Brander).

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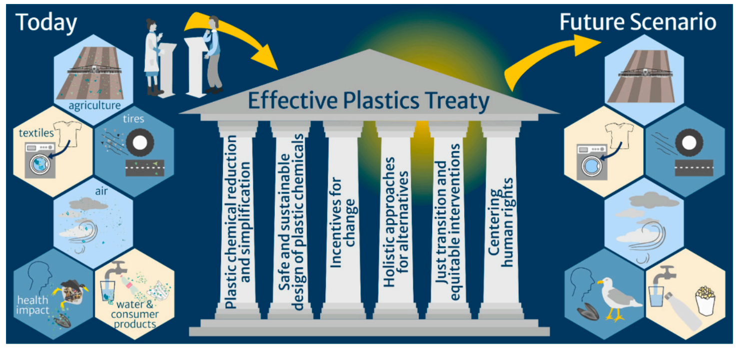
HIGHLIGHTS

- Plastic pollution is one of the greatest environmental challenges facing the planet.
- We highlight six essential components necessary to reduce plastic pollution via a global treaty.
- A holistic approach focused on reduction, simplification, and human rights is best.
- Transparency and traceability are key to resolving this transboundary global issue.

GRAPHICAL ABSTRACT



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ABSTRACT

The ubiquitous and global ecological footprint arising from the rapidly increasing rates of plastic production, use, and release into the environment is an important modern environmental issue. Of increasing concern are the risks associated with at least 16,000 chemicals present in plastics, some of which are known to be toxic, and which may leach out both during use and once exposed to environmental conditions, leading to environmental and human exposure. In response, the United Nations member states agreed to establish an international legally binding instrument on plastic pollution, the global plastics treaty. The resolution acknowledges that the treaty should prevent plastic pollution and its related impacts, that effective prevention requires consideration of the transboundary nature of plastic production, use and pollution, and that the full life cycle of plastics must be addressed. As a group of scientific experts and members of the Scientists' Coalition for an Effective Plastics Treaty, we concur that there are six essential "pillars" necessary to truly reduce plastic pollution and allow for chemical detoxification across the full life cycle of plastics. These include a plastic chemical reduction and simplification, safe and sustainable design of plastic chemicals, incentives for change, holistic approaches for alternatives, just transition and equitable interventions, and centering human rights. There is a critical need for scientifically informed and globally harmonized information, transparency, and traceability criteria to protect the environment and public health. The right to a clean, healthy, and sustainable environment must be upheld, and thus it is crucial that scientists, industry, and policy makers work in concert to create a future free from hazardous plastic contamination.

1. Background

In March 2022, the United Nations Environment Assembly (UNEA) Resolution 5/14 requested that the United Nations Environment Programme (UNEP) Executive Director convene an Intergovernmental Negotiating Committee (INC) to establish an international legally binding instrument on plastic pollution. This resolution recognises that plastic pollution and plastic chemicals (including polymers and associated chemicals; Fig. 1), in addition to micro- and nanoplastics (MNPs), have detrimental effects on the environment and the social systems dependent on it, as well as on human health and wellbeing. Plastic pollution also interferes with the economic dimension of sustainable development, and social equity, thereby jeopardizing the attainment of several Sustainable Development Goals (SDGs) and the Kunming-Montreal Global Biodiversity Framework. While it does not specifically mention plastic chemicals, Resolution 5/14 reaffirms the importance of cooperation and complementarity with other multilateral environmental agreements, including those that regulate and control toxic chemicals, noting that the treaty should aim "to prevent plastic pollution and its related risks to human health and adverse effects on human well-being and the environment." The Resolution also acknowledges that plastic pollution can be of a transboundary nature, and therefore, its effective prevention requires full consideration across all stages of the plastic life cycle.

The ecological footprint resulting from accelerated global plastic production, use, and release is an important environmental issue in modern times (Alava et al., 2023; Almroth et al., 2022; Charles & Kimman, 2023; Geyer et al., 2017; MacLeod et al., 2021; UNEP 2021; OECD, 2022). It has been proposed that plastic pollution may surpass the planetary boundary associated with "novel entities," beyond which the environment may no longer be able to self-regulate (Arp et al., 2021; MacLeod et al., 2021; Persson et al., 2022; Villarrubia-Gómez et al., 2022). Plastics can be persistent, toxic, accumulative, and highly mobile. Thus, a hazard-based approach is needed to prevent production of new harmful plastics. As scientists, we agree it is critical that plastic pollution must be prevented, reduced, redesigned, removed, prioritized, and regulated across the full life cycle, that is, from the extraction of the bio and fossil fuel feedstocks used in the production of plastics, transport, production, manufacture, use, and end of life phases, in alignment with UNEP's working definitions for plastic pollution and the full life cycle approach for plastics (United Nations Environment Programme, 2022). Ensuring adherence to the UNEP definition not only captures waste management but also reduced production, removal of plastics from ecosystems and remediation of contaminated sites. In short, nature and society will significantly benefit from a global plastics treaty that mandates ambitious and effective time-bound targets that restrict the production and consumption of non-essential, unsafe, and unsustainable plastics.

2. Plastics as chemical and physical hazards

The physical impairments of (macro)plastic pollution to humans, biodiversity, and environmental integrity are frequently evident to the naked eye. Contrarily, the hazards and impacts associated with plastic chemicals and particles, that is, MNPs, as well as the psychological, sociocultural and economic hazards and impacts of plastic pollution are less visible. In either case, the threat of plastic chemicals and particles to human and environmental health is an enormous challenge providing the impetus for treaty negotiations. According to the latest report on plastic chemicals (Wagner et al., 2024), over 16,000 chemicals have been associated with plastics, of which >4200 are of concern because they are persistent, bioaccumulative, mobile and/or toxic (PBT or PMT). These findings are supported by a large body of independent academic research (Aurisano et al., 2021; Geueke et al., 2023; Geueke et al., 2023b; Groh et al., 2019; Groh et al., 2021; Raubenheimer & Urho, 2023; United Nations Environment Programme and Secretariat of the Basel, Rotterdam, and Stockholm Conventions, 2023; Wiesinger et al., 2021). Negative impacts on human and environmental health (Galloway et al., 2017; Landrigan et al., 2023; UNEP 2021) due to the hazardous properties of plastic chemicals include carcinogenicity, mutagenicity, reproductive toxicity, specific target organ toxicity, endocrine disruption, and ecotoxicity (Charlton-Howard et al., 2023; Fernandez and Trasande, 2024; Kumar et al., 2021; Ramsperger et al., 2023; Brander

Fig. 1. Commonly used definitions in the discussion of a science-informed approach to reducing global plastic pollution and associated impacts (Baztan et al., 2024; United Nations Environment Programme, 2022; United Nations Environment Programme, 2024a; United Nations Environment Programme, 2024b; Wagner et al., 2024). Icons sourced from The Noun Project.

et al., 2024; Canals et al., 2023; Landrigan et al., 2023). In addition to their toxicity, many plastic chemicals are bioaccumulative (Alava, 2020; Ma & You, 2021; McMullen et al., 2024; Miller, 2020; Provencher et al., 2019), persistent, and/or mobile (Allen et al., 2022; Andrade et al., 2021; Dris et al., 2016; Wagner et al., 2024).

Plastic chemicals and MNPs shedded over time from macroplastics are harmful to organisms because of their physico-chemical characteristics (Athey & Erdle, 2022; Coffin et al., 2022; Everaert et al., 2020; Hampton et al., 2022a; Hampton et al., 2022b; Lambert et al., 2017; Stienbarger et al., 2021). These plastic chemicals include monomers, intentionally added chemicals, such as additives and processing aids, and non-intentionally added substances (NIAS). The chemical and biological contaminants that adsorb and absorb to MNPs and larger plastic items from the environment are an additional concern and include metals, polycyclic aromatic hydrocarbons (PAHs), and persistent organic pollutants (POPs) such as toxic polychlorinated biphenyls (PCBs), *per*- and polyfluorinated substances (PFASs), as well as associated antibiotic resistant genes (ARGs) and multi-resistant pathogenic bacteria (Guruge et al., 2024; Hartmann et al., 2017; Rasool et al., 2021; Raubenheimer & Urho, 2023; Senathirajah et al., 2022; United Nations Environment Programme and Secretariat of the Basel, Rotterdam, and Stockholm Conventions, 2023; Weis & Alava, 2023; Wiesinger et al., 2021).

In addition to their chemical toxicity, it is important to acknowledge that MNPs comprise a vast diversity of particle shapes, densities, and sizes, which alone can cause adverse responses in organisms. In composition, they range along a continuum that includes semi-synthetic to fully synthetic polymers, as well as combinations of these (e.g., (Granek et al., 2022; Hartmann et al., 2019; Siddiqui et al., 2022; Siddiqui et al., 2023)). Moreover, these particles include non-polymeric materials, such as natural materials and plastic chemicals (e.g., additives, fillers). The State of California in the U.S.A. now defines MNPs as any particle with a polymer content of >1 % by mass (CA State Water Resource Control Board Resolution 2022–0032). Evidence to date demonstrates that MNPs create both a human and an environmental health hazard and that particles increase in toxicity as they fragment into smaller sizes due to mechanical, photo-chemical, chemical and biological weathering forces (Brander et al., 2024; Chamas et al., 2020; Fotopoulou & Karapanagioti, 2019; Gewert et al., 2015; Hampton et al., 2022a; Jahnke et al., 2017; McIlwraith et al., 2021; Sait et al., 2021; Sorensen & Jovanović, 2021; Zimmermann et al., 2020). The weight of evidence, based on preliminary research and primary findings have described their potential presence, particularly for particles <10 μm, in critical organs and tissues in humans, such as the heart, placenta, liver and lungs. (Horvatits et al., 2022; Kutralam-Muniasamy et al., 2023; Leslie et al., 2022; Ragusa et al., 2021; Yang et al., 2023). Recently, possible MNP presence has even been linked to cardiovascular incidents (Marfella et al., 2024). While some concerns with the methodological approaches used in these papers have been expressed by the scientific community (e.g. (Kuhlman, 2022)), these "first of its kind" studies lay the foundation for future research that is expected to expand and improve upon current methods used for human samples, as well as understand the mechanisms of toxic action of MNPs. Furthermore, evidence does already exist across biota more generally that the continual breakdown of plastics into smaller particles facilitate their ability to move, translocate, and enter and deposit into tissues and to escape detection, while increasing the risk of bioaccumulation and the induction of toxicological responses such as reactive oxygen species production and downstream pathologies like cancer (Cunningham et al., 2023; Jomova et al., 2023; Kumar et al., 2021).

Specific concerns for organisms exposed to plastic chemicals and particles, which present a multiple-stressor scenario due to combined physical and chemical exposure, include changes in behavior, impeded growth and reproduction, respiratory stress, and changes in gene and protein expression indicating cellular and tissue-level damage. Owing to their specific physical properties, some shapes and size ranges of MNPs appear to be more toxic than others, with microfibers and tire wear particles currently of greatest toxicological concern (Au et al., 2015; Barboza et al., 2018; Besseling et al., 2013; Capolupo et al., 2020; Capolupo et al., 2021; Green et al., 2016; Hägg et al., 2023; Horn et al., 2020; Jabeen et al., 2018; Jacob et al., 2020; Jovanovic, 2017; Kim et al., 2021; Monclûs et al., 2022; Siddiqui et al., 2022; Siddiqui et al., 2023; Sørensen et al., 2023; Stienbarger et al., 2021; Tian et al., 2021). While most research is available on aquatic organisms, these impacts also encompass terrestrial ecosystems, for which fewer data exist, with nascent studies highlighting similar issues for soil organisms (e.g., earthworms) as for marine and freshwater denizens (Lwanga et al., 2016; Rillig et al., 2017; Zhu et al., 2019). Furthermore, bio-based plastics, which often use a polymer backbone made from plant or microbial carbon, are also of potential concern, with strong evidence demonstrating similar toxicological responses and chemical usage, and potentially release of more MNPs, compared to conventional plastics (Allemann et al., 2024; Emadian et al., 2017; Lambert et al., 2017; Lavagnolo et al., 2024; Narancic et al., 2018; Zimmermann et al., 2020). Although mammalian models and humans have received less attention, indications are that particles may cause a range of concerning impacts, including modulation of the microbiome and reproductive toxicity (Coffin et al., 2022; Szule et al., 2022). Additionally, 'plasticosis' is a new plastic-induced fibrotic disease discovered in the stomach tissues of seabirds (Charlton-Howard et al., 2023). Long-known negative impacts from endocrine disrupting chemicals (EDCs), many of which are plastic chemicals such as bisphenols, brominated flame retardants, and phthalates, comprise health effects on physiology, altered development, and increased disease risk (Brander, 2022; Gore et al., 2015; Vandenberg et al., 2012; Vandenberg et al., 2013). Exposure to these chemicals during vulnerable periods of development, like the prenatal, neonatal or pubertal periods, causes damages that are irreversible, consistent with the concept of "developmental origins of health and disease" (Heindel et al., 2015). In laboratory models, it becomes clear that in many cases, effects appear late in life, long after exposure (Brander, 2022; Fernández et al., 2009; Franssen et al., 2016; Rubin et al., 2006), with effects depending on the developmental period and doses used. There is also growing evidence of the transgenerational effect of EDC exposure on human and animal health (Brander et al., 2017). The socioeconomic costs of the resulting adverse human health outcomes are substantial, with the plastics-related disease burden estimated to be $249 billion in the United States in 2018 (Landrigan et al., 2023; Trasande et al., 2024).

The management of impacts from both conventional and bio-based and biodegradable plastic chemicals is exceedingly difficult, in part because no global agreement is yet in place to regulate their use and recovery across their full life cycle. Several existing multilateral environmental agreements (e.g., Stockholm Convention on POPs) regulate specific chemicals. However, they address only a small fraction of the thousands of known plastic chemicals, and in some cases have not been ratified by countries responsible for producing a large fraction of these compounds or polymers (Wagner et al., 2024). Although a precedent for regulating particles is established by restrictions under the Basel Convention on the use of materials such as asbestos, which generate carcinogenic mineral microfibers that can become embedded in human lungs (Annex I of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal [Basel Convention], 1989; Cao et al., 2024), this has not been applied to MNPs, even though inhalation of plastic microfibers with similar properties to asbestos may be one of the most important exposure routes for humans (Mohamed Nor et al., 2021). A weight of evidence assessment demonstrating similar toxicity to asbestos from MNPs with similar characteristics, such as microfibers made from polyester, is currently lacking. However, there are several similarities between the small and easily transportable fibers generated from now-banned asbestos and the fibers formed from textile shedding and dispersal (Akhbarizadeh et al., 2021; Cao et al., 2024). It is critical that precedents such as those adopted for asbestos and particulate matter, as well as currently established conventions on toxic

Fig. 2. The six science-based pillars recommended as approaches for effectively addressing and reducing plastic pollution on a global scale.

chemicals, are considered when addressing pollution by MNPs and plastic chemicals. Furthermore, it is imperative that evaluations of plastics' impacts are conducted with a focus on hazards, and categorized into families of plastic chemicals classified as hazardous in regulatory lists (Wagner et al., 2024). Indeed, the hazard-based approach should be complemented with a group-based approach to effectively address groups of chemicals rather than individual substances (Wagner et al., 2024).

3. Scientific recommendations

As scientists working on the occurrence, fate, transport, toxicity and bioaccumulation potential of plastic chemicals, polymers, MNPs and related policies, we believe that there are six essential pillars necessary to truly reduce the chemical impacts of global plastic pollution (Fig. 2):

1. Plastic chemical reduction and simplification.
2. Safe and sustainable design of plastic chemicals.
3. Incentives for change.
4. Holistic approaches for alternatives.
5. Just and equitable interventions.
6. Centering human rights.

These pillars will significantly contribute to detoxification across the full life cycle of plastics by reducing the numbers, types, complexity, volumes, and toxicity of plastic chemicals. The goal herein is to clearly communicate these recommendations that are critical to a strong and effective global treaty to reduce plastic pollution.

3.1. Plastic chemical reduction and simplification

It is essential that the global plastics treaty determines effective criteria encompassing the >16,000 known plastic chemicals (e.g. (Wagner et al., 2024)). This is a considerable challenge, especially since over a quarter of known plastic chemicals lack basic information on identity, function, or use. Much of this information is restricted, proprietary or otherwise unavailable (e.g. (Wagner et al., 2024)). As such, the challenges inherent in designating criteria are clear, but headway has been made in suggesting a path forward. Regulating by chemical class rather than individual compounds (e.g., all bisphenols, all phthalates), and adopting a hazard-based approach instead of evaluating the risk of each chemical is imperative (Brander, 2022; Maffini et al., 2023; Wagner et al., 2024). For example, 15 groups of plastic chemicals with proven hazard, which include aromatic amines, alkyl aldehydes, alkylphenols, salicylate esters, aromatic ethers, bisphenols, phthalates, benzothiazoles, organometallics, parabens, azodyes, aceto/benzophenones, chlorinated paraffins, and *per*- and polyfluoroalkyl substances, can be prioritized. Improving and strengthening regulation of these priority groups would help to overcome data gaps, avoid regrettable substitutions of chemicals with similar structures to those already deemed problematic, and encourage safe and sustainable design. Regulatory agencies are already considering such an approach for use in the regulation of PFAS, for example (Bălan et al., 2021). Furthermore, being a global issue with transboundary implications, it is essential that this challenge is addressed on a global level (Wagner, 2022; Bergmann et al., 2022; Dey et al., 2022). The PlastChem database, now publicly available to researchers and regulators, can be viewed as a starting point for harmonizing information and adopting a precautionary approach for plastic chemicals used globally (Wagner et al., 2024), as can globally sourced databases such as ToMEx, specifically focused on MNP toxicity (Hampton et al., 2022a; Hampton et al., 2022b; Hampton et al., 2022c). Agreement across nations on how to approach hazardous and/or redundant chemicals that serve the same purpose (e.g. UV stabilizers) used for plastics production, considerations of phase-outs for priority chemical groups, and to focus on their impacts across the entire life cycle, is the most effective way forward. Currently, only approximately 1 % of plastic chemicals are regulated in global multilateral environmental agreements (United Nations Environment Programme and Secretariat of the Basel, Rotterdam, and Stockholm Conventions, 2023), and unknown numbers of potentially toxic (NIAS) further contaminate plastics (Muncke et al., 2020).

The magnitude of this complexity, paired with the lack of sufficient regulations to mitigate harm, and the redundancy of chemicals that serve similar and in some cases non-essential purposes (Figuiere et al., 2023), underlie a call for polymer and chemical simplification (e.g. Kümmerer et al., 2020; Fenner & Scheringer, 2021; Wagner et al., 2024; Wang & Praetorius, 2022). The process of chemical simplification could incorporate specific bans on hazardous polymers and chemicals, based on criteria outlined in (Wagner et al., 2024). Furthermore, transparency, traceability, and reporting requirements throughout the supply chain would be essential cornerstones of an international legally binding agreement. The disclosure of information on plastic chemicals would also support the reduction and simplification of groups of plastic chemicals. At present, many of the individual substances that have been banned or regulated are replaced by similar chemicals with unknown hazard properties that, usually, have ended up equally problematic. This is the case with certain PFASs and bisphenols (e.g., BPA, BPS). However, the PFASs group contains thousands of chemicals, and although many of them have been classified as chemicals of potential concern (United Nations Environment Programme, 2022) and have been detected in plastics products (Zimmermann et al., 2021), only a small subset of PFASs are currently regulated by globally binding instruments. This allows (potentially) hazardous chemicals to be used in the market as alternatives. Given that thousands of chemicals used in plastic products are still unknown and are used in mixtures with variable composition, a hazard-based approach to regulating plastic chemicals should be included in the global plastics treaty text (Alava et al., 2023; Wagner et al., 2024; Weis & Alava, 2023).

3.2. Safe and sustainable design of plastic chemicals

The principles of safe and sustainable design include green chemistry and engineering, sustainable chemistry, and a move towards circularity of chemicals and products by design. Considerations for safety and sustainability must be incorporated across the entire life cycle, from extraction through use and end of life (European Commission, Joint Research Centre, et al., 2022). Global movement towards increased circularity and sustainably designed products is an enormous opportunity to move towards true protection of human and environmental health. To achieve these goals, we propose the adoption of three key components from the Montreal Protocol, which was adopted in 1987 to protect the ozone layer. Firstly, we support the application of the 'essential use' concept. The two elements of an essential use are that (i) it is either necessary for health and safety or critical for the functioning of society and (ii) that there are no available technically and economically feasible alternatives. Secondly, we support a time-bound global plastics production reduction target and associated national targets, similar to the time-bound targets for ozone reduction in the Montreal Protocol. Thirdly, we propose that a dedicated, independent, and trusted science-policy interface (SPI) should have the mandate to formulate such targets and effective mechanisms for their implementation (Wang & Praetorius, 2022). To that end, we propose the adoption of criteria for safety, sustainability, essentiality, and transparency as distinct yet reinforcing requirements. These criteria should be developed by independent experts to assess bio- and fossil-based feedstocks, polymers, and groupings of plastic chemicals, substitutes and alternatives, products, technologies, and systems and services. These criteria are key to the development of a comprehensive regulatory framework including open lists of plastic chemicals in the annex of the future instrument. The open lists developed from the rigorous and independently conducted scientific assessments must be regularly reviewed and adapted in response to the latest and best available science, knowledge, and technology and underpinned by precautionary and prevention principles (Scientists' Coalition Response to the Revised Zero Draft, 2024).

3.3. Incentives for change, creating a level playing field for countries and businesses

The full life cycle approach to plastic pollution overlaps with the circular economy approach and the zero waste approach expressed in some contemporary waste hierarchies. The circular economy approach emerged from William McDonough's cradle-to-cradle design framework which was later popularized by the Ellen MacArthur Foundation (MacArthur, 2017). The zero waste approach prioritizes prevention, reduction, and reuse, and repair over recycling and disposal because actions higher up the waste hierarchy are most effective at preventing waste and pollution, more cost effective and simpler to implement. Depending on a country's regulatory framework, mandatory extended producer responsibility (EPR) (or a combination of mandatory and voluntary schemes) can offer a powerful lever for plastic pollution prevention (Tumu et al., 2023; Walter et al., 2019). The schemes should be designed for just transition and transparency, and based on principles of prevention, precaution, polluter pays and non-regression, and not just serve as a fee to fund recycling. However, it is imperative that EPRs be properly enforced and not used as an attempt to provide "greenwashed" solutions or as a stand-in for true source reduction and circularity. Mandatory regulation, including EPR, has the potential to create a level playing field for plastics producers by transitioning to safer, more sustainable, and equitable plastic-free and zero waste, product technologies, systems, and services, mandated product information disclosure, and by building end-of-life costs into the price of products (Ezeudu, 2024; Ramasubramanian et al., 2023; Walter et al., 2019; Zhou & Luo, 2024). Effective mandatory plastic pollution prevention policies should incentivise the reduction of non-essential, hazardous, and unsustainable chemicals, polymers, products, technologies, and systems and services, the design of safer and more sustainable plastics materials, polymers, and products, and transparency throughout the full life cycle of plastics. Examples of mandatory fiscal incentives include tax breaks or the subsidization of safe and sustainable options, while disincentives may include restrictions, bans, taxes and fees/levies on certain non-essential, hazardous, and unsustainable options (UNEP's Life Cycle Thinking 2021: Life Cycle Initiative, 2021;Lau et al., 2020).

3.4. Holistic Life Cycle Assessment approaches to determine safe and sustainable alternatives

Life cycle Assessment (LCA) is a model-based, standardized quantitative analysis tool that aims to support decision-making by identifying options or solutions, which are associated with the lowest potential environmental impacts (Askham et al., 2023). LCA is highly likely to be an integral aspect of plastic management, assessing/comparing the sustainability of plastic products, substitutes, and alternatives that are currently available or will be developed in the future, and is already being discussed widely in relation to the plastics treaty. LCA consists of a Life Cycle Inventory (LCI) phase, part of which involves compiling all pollutants (including plastic chemicals) emitted to the environment and resources extracted from the environment at each life cycle stage of the product/process/system(s) being studied. The LCI phase of plastic products, including plastic chemicals, requires information that is often difficult or impossible to access for independent researchers. These information gaps limit the accuracy of LCA outcomes, and sometimes tend to favor existing systems, while also failing to properly account for end-of-life impacts such as environmental degradation (Suh et al., 2024). The Life Cycle Impact Assessment (LCIA) phase then characterizes the inventory flows in terms of potential impacts in multiple categories (e.g., human toxicity and ecotoxicity, land use impacts, and the climate crisis) to facilitate comparison with alternatives. Importantly, LCIA results can be further translated into the potential damages to main areas of protection, including human health and ecosystem quality (Verones et al., 2017).

There is a strong link between LCA and conventional chemical, material, environmental and human health hazard assessment because LCA requires data concerning the environmental fate, exposure and effects of the pollutants emitted from the product/process(s). Although there are published studies addressing elements of the impact assessment model that relate plastic emissions to the environment into potential impacts or damage in LCIA (Corella-Puertas et al., 2022; Maga et al., 2022; Salieri et al., 2021; Woods et al., 2021), the work remains in the development phase, with many data gaps that need filling to develop characterization factors (CFs). Critically, these data gaps/missing CFs include the impacts associated with plastic emissions, meaning an underestimation of the longer-term impacts from MNP particles (Askham et al., 2023; Gontard et al., 2022). Importantly, chemical impacts related to plastics are often merely included as a generic assessment, and do not account for their actual negative impacts. Specifically, more robust and harmonized methods for measuring and reporting plastic concentration exposure levels and for assessing the related hazard are needed, for both plastic particles and plastic chemicals associated with them (Pauna & Askham, 2022). Improved design in the sampling, testing and recording of results using harmonized, validated, and comparable methods, with more comprehensive reporting of relevant data, is critical (Jenkins et al., 2022). It is also important to consider that LCA is not a single, finished tool, but a model concept that remains under continuous development and refinement, where there is not necessarily a 'one size fits all' situation in its application. Furthermore, like any model, LCA is only as good as the data it is developed from, while the quality and quantity of the required input data available for conducting LCA is often insufficient or fragmentary, especially for plastics. For LCA to deliver on its potential concerning the application within the context of a global plastic treaty, improved models with integrated plastic pollution impacts and databases with accurate plastic polymers and plastic chemicals are needed.

3.5. Just transition and equitable interventions

Indigenous Peoples are the original architects of circular regenerative, restorative, and toxic-free economic systems (UNDP). We recommend learning from Indigenous knowledge holders about how to design truly circular systems. We also recommend learning from Indigenous communities, frontline and fenceline communities, wastepickers and others in informal and cooperative settings about how to implement a plastics treaty that ensures just transition away from hazardous plastic chemicals, polymers, products, technologies, and systems and services.

Just transition recognises that the impacts of plastic pollution are inequitably distributed across the full lifespan of plastics. It ensures decent, equitable, and sustainable work opportunities (Dauvergne, 2023) and conditions for affected communities and workers, particularly women, youth, and Indigenous communities, and leaves no-one behind in the transition towards ending plastic pollution. Just transition recognises those disproportionately impacted by plastics pollution as those with the skills, knowledge, and experience to propose the most effective, safe and healthy, just, economic, and sustainable solutions for their own communities. Socioeconomic and socioenvironmental baseline studies should be conducted and ambitious socio-targets set and reviewed regularly. Just transition centers impacted communities in the responses and enterprises designed to enable their meaningful and active involvement in preventing further plastic pollution and its impacts, improving waste management, and ensuring safe and sustainable removal and remediation. Just transition ensures that affected community members have the opportunity to contribute to ongoing and transparent monitoring, evaluation, and reporting. Finally, just transition via community-grounded solutions ensures affected communities are protected with adequate and accessible public health care and safety standards and ensures access to social services and healthcare programs, fair remuneration, inclusive EPR and other waste reduction and management systems, and financial and technical support to establish or strengthen safe and sustainable redesign, reuse, repair, and recycling facilities. More generally, an approach centered on human rights and environmental justice recognises that certain groups, such as Indigenous Peoples and other marginalised communities, may disproportionately experience negative effects (Dauvergne, 2023). Special consideration for these groups is therefore necessary to prevent injustices and achieve equitable solutions.

3.6. Centering human rights

The impacts of plastics and plastic chemicals harbor significant risks for the infringement of several human rights. These include, but are not limited to, the rights to clean water, food, and health. Recognising the negative impacts of plastics and plastic chemicals on water and food quality (by pollution), as well as human health (e.g., through endocrine disruption) (Hamley et al., 2023) and addressing the potential negative consequences for the enjoyment of related rights is therefore paramount. Furthermore, UN General Assembly (UNGA) resolution A/RES/76/300, following the Human Rights Council Resolution 48/13 explicitly recognises an independent right to a clean, healthy, and sustainable environment. The observed impacts of plastics and plastic chemicals have the potential to infringe on that right. Although the right to a healthy environment does not yet possess the status of hard law, recognising this right within the treaty is vital to maximise its impact (O'Meara, 2023).

The UNGA resolution A/76/L.75 also recalls the imperative outlined in the Guiding Principles on Business and Human Rights (A/HRC/17/31), which highlights the unequivocal responsibility of all business enterprises to uphold human rights to amplify efforts for preventing and remedying negative impacts on human rights arising from their use of hazardous substances, including plastic chemicals. When human rights are jeopardised due to the actions of businesses, the polluter pays principle should be applied, which is one of the elements that is already gaining consensus in the negotiations of the treaty but is subject to further negotiation. The environmental, human health and ecological damage and related human rights abuses that have already been inflicted by the plastics and plastic chemicals and associated corporate lobbying can only be addressed when we prioritise the most marginalised communities and countries. The human rights of present and future generations have been compromised due to continuous exposure to the plastics and their thousands of hazardous chemicals and will be further compromised due to their ubiquitous presence, persistence, accumulation, and transboundary mobility. Future generations can only be protected from the myriad social, environmental and econonomic impacts of global plastic pollution by significantly reducing the production of plastic chemicals and PPPs, as well as the use and emissions of plastics across the full life cycle of plastics. Responses to the global plastics crisis will also support human rights if they focus on the top of the waste hierarchy including safer, sustainable, and transparent reuse and refill, repair, repurpose, and remanufacture, and a shift to safe and sustainable plastic chemicals, plastic alternatives, and non-plastic substitutes.

Considering the potential for bioaccumulation of plastic chemicals (polymers and associated chemicals), including an intergenerational justice aspect in the treaty process is necessary. While there is no clear affirmation of the rights of future generations under international law yet, the significant impacts on future generations that persistent substances have, support the need for recognising the principle of intergenerational justice in the context of plastics, and has also has been proposed with regards to climate change (Promotion and Protection of Human Rights in the Context of Climate Change: A/78/255). Furthermore, our understanding of the impacts of plastics throughout their lifespan and of potential solutions going forward must be based on robust independent science. This is in accordance with the human rights to science, information, and knowledge, and is highlighted in a vision statement describing how human rights can inform a path for solutions (Turk 2023).

4. In conclusion: paving the way towards an effective plastics treaty

The latest sessions of the INC have already shown substantial discrepancies between ambitious suggestions, such as changes in plastic production, and certain industrial and political sectors defending economic growth based on plastic use (United Nations Environment Programme, 2024a; United Nations Environment Programme, 2024b). We can find some similarities with the Intergovernmental Panel on Climate Change (IPCC) discussions, given that emissions have continued to rise despite three decades of political efforts and science-informed warnings

(Stoddard et al., 2021). Likewise, perpetual increase of plastic production and use plus a limited focus only on downstream solutions may threaten chances of meeting an effective plastic treaty that protects environmental and human health and well-being. Chemical simplification and reduction, as well as safe and sustainable design and a holistic approach to assessing and mitigating plastics impacts, are critical approaches based on our current understanding of the plastic pollution challenge, to protect the environment and human health.

As already recognised during the INC process, to end plastic pollution, producers of primary and recycled plastics need to disclose globally information about on the types and quantities of materials, including the composition of polymers and plastic chemicals throughout the supply chain and the lifecycle (UNEP/PP/INC/4/3). The information needs to be publicly accessible to ensure transparency, traceability, and trackability to ensure all actors along the supply chain from extractors through to consumers and waste managers have the necessary information to make informed choices enabling them to protect the environment, economies, and public health and to enable circularity by providing information required for recycling and recovery measures and enabling informed decision-making (Aurisano et al., 2021; Senathirajah et al., 2023). Transparency and traceability can be achieved by enforcing mandatory standards and certifications and labeling requirements (Bhubalan et al., 2022; Khan et al., 2022) and establishing a monitoring system to track, trace, publish, and update, in a transparent manner, relevant information (such as types, constituents and quantities of its production, imports, and exports), potentially utilising AI technology or Digital Product Passports (CDP, 2023). Finally, in understanding the harm to the environment and to human health and well-being, including threats to future generations, caused by plastics and plastic chemicals, centering human rights can be a powerful framework for the future plastics treaty to illuminate and prevent potential harms including threats to future generations, caused by plastic pollution. The right to a clean, healthy, sustainable environment should be upheld and it is crucial that states consider the science that provides evidence of harm as well as pathways forward.

CRediT authorship contribution statement

Susanne M. Brander: Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Kala Senathirajah:** Writing – review & editing, Writing – original draft, Conceptualization. **Marina O. Fernandez:** Writing – review & editing, Writing – original draft, Conceptualization. **Judith S. Weis:** Writing – review & editing, Writing – original draft, Conceptualization. **Eva Kumar:** Writing – review & editing, Writing – original draft, Conceptualization. **Annika Jahnke:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Nanna B. Hartmann:** Writing – review & editing, Writing – original draft, Conceptualization. **Juan José Alava:** Writing – review & editing, Writing – original draft. **Trisia Farrelly:** Writing – review & editing, Writing – original draft, Conceptualization. **Bethanie Carney Almroth:** Writing – review & editing, Writing – original draft, Conceptualization. **Ksenia J. Groh:** Writing – review & editing, Writing – original draft. **Kristian Syberg:** Writing – review & editing, Writing – original draft, Conceptualization. **Johanna Sophie Buerkert:** Writing – review & editing, Writing – original draft. **Amila Abeynayaka:** Writing – review & editing, Writing – original draft, Conceptualization. **Andy M. Booth:** Writing – review & editing, Writing – original draft, Conceptualization. **Xavier Cousin:** Writing – review & editing, Writing – original draft. **Dorte Herzke:** Writing – review & editing, Writing – original draft. **Laura Monclús:** Writing – review & editing. **Carmen Morales-Caselles:** Writing – review & editing. **Andrea Bonisoli-Alquati:** Writing – review & editing. **Rana Al-jaibachi:** Writing – review & editing, Writing – original draft. **Martin Wagner:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Susanne M Brander reports financial support was provided by National Science Foundation. Andy Booth reports financial support was provided by The Research Council of Norway. Andy Booth reports financial support was provided by European Commission. Annika Jahnke reports financial support was provided by Heimholtz Association. Dorte Hertz reports financial support was provided by The Research Council of Norway. Amila Abeynayaka reports financial support was provided by European Union Horizon Europe Research and Innovation. Susanne Brander reports a relationship with Southern California Coastal Water Research Project that includes: consulting or advisory. Brander previously consulted for the Environmental Defense fund and is on advisory boards or groups for the Plastic Pollution Coalition, as well as the Department of Toxic Substances Control (California) and the San Francisco Estuary Institute. Martin Wagner is an unremunerated member of the Scientific Advisory Board of the Food Packaging Forum Foundation and received travel support for attending annual board meetings. Marina Fernandez is a member of the Endocrine Society's delegation at the Intergovernmental Negotiating Committee (INC) to develop an international legally binding instrument on plastic pollution. All authors are members of the Scientists Coalition for an Effective Plastics Treaty, and Susanne Brander, Martin Wagner, Marina Fernandez, Trisia Farrelly, Kristian Syberg, Amila Abeynayaka, and Bethanie Carney Alroth are Scientists Coalition Steering Committee Members. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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