Title: Identifying and overcoming social-ecological barriers to ending plastics pollution

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Abstract

Plastics are deeply embedded in contemporary life, and their production and pollution contribute to irreversible harm across ecological and social systems. Recognized as a "novel entity" in the Planetary Boundaries framework, plastics challenge traditional governance models due to their chemical complexity and diversity, cross-sectoral impacts, and pushback from powerful political and economic actors. This study addresses urgent science-policy gaps through a structured expert elicitation, conducted during the ongoing negotiations on the global plastics treaty.

We present the Experts Multi-Issue Knowledge Elicitation (EMIKE) method - a flexible, co-productive approach that addresses social-ecological dimensions of plastics pollution. Through a three-phase process involving 21 interdisciplinary experts, we identified 21 critical issue areas spanning toxic chemical use, social inequality, overconsumption, climate impacts, and financing and policy incoherence, among others. The EMIKE process generated a matrix of interrelated indicators across plastics' life cycle to inform adaptive, more comprehensive, just, and evidence-based policymaking.

EMIKE offers a methodology for surfacing often neglected issues in natural science driven studies, fostering interdisciplinary dialogue, and advancing policy-relevant knowledge. It enables structured elicitation - attuned to power, uncertainty, and evolving political contexts - to better integrate diverse science inputs into global governance. This approach is essential not only for plastics governance, but also for any multifaceted sustainability issue requiring intersectional, systems-based solutions.

Key findings highlight the inseparability of ecological and social concerns, the limits of technocratic quantification, and the need to democratize science-policy interfaces. Experts emphasized the importance of precautionary action, transparency, and justice-based governance to counteract corporate influence and systemic inertia. Our study also illustrates how scientific frameworks can support policy development by adequately considering the complexity of global sustainability challenges.

Teaser

Expert insights reveal overlooked social-ecological risks of plastics, urging systemic, just, and science-informed global policy action.

Introduction

Plastics shape culture, capitalism and colonialism (*1–3*) while causing ecological harm from subcellular (*4*) to planetary levels (*5*). The governance of plastics pollution (from local to global scales) is fractured and incomplete (*6*, *7*). This study addresses critical knowledge gaps in the global science-policy dialogue on plastics through an interdisciplinary expert elicitation process, responding to growing concerns over the risks of over-simplification and highlighting the need for systemic understandings and solutions.

Researchers use the Planetary Boundaries framework (*8*, *9*) to describe the current unsustainability of "novel entities," including synthetic chemicals and materials such as plastics. This framework identifies nine Earth systems perturbations (e.g., climate change, biodiversity loss) that place the Holocene-like "safe operating space for humanity" at risk. It is important to note that while the Planetary Boundaries framework assesses evidence from past Earth system conditions, it cannot guarantee future stability, as the co-evolution of climate and life is not a reversible process. Unlike other boundaries, "novel entities" lack a Holocene baseline (10,000 years) and defined thresholds, leading some to argue for a precautionary approach: zero release of synthetic chemicals and other novel entities unless proven safe and continuously monitored (*10*).

Plastics span countless polymers and additives, posing scientific and regulatory challenges due to their structural and chemical complexity and diversity (*11–13*). Plastics are particularly concerning due to irreversible and therefore cumulative planetary exposure and impacts (*5*, *14*). Plastics research and governance measures have focused on ecotoxicological effects, which vary widely across polymer types, additives, and context. Some scholars, policymakers, civil society organizations, and corporate stakeholders now call for defining a quantifiable planetary threshold (*8*, *15*) to inform policy decisions and track global progress. For plastics, this entails different suggestions for which stocks or flows to use as defining metrics (*16*, *17*). However, a singular quantification risks oversimplification, ignores diverse viewpoints, and may delay transformative political action (*18–20*).

While some advocate biophysically defined "safe limits," others call for a broader approach that addresses injustice, wellbeing, and inequality (*15*, *21*). Efforts to establish a quantifiable "social foundation" alongside planetary boundaries (*15*, *22–24*) have been made. Many sustainability frameworks do not address politics and power in a debatable attempt to maintain neutrality and scientific objectivity (*18–20*). Approaches that protect social equity, especially those related to vulnerable populations from disproportionate impact, are needed (*19*, *25*, *26*). Current frameworks lack gender analyses (*27*), and ignore colonial and capitalist power structures that embed race (*28–30*). Sjåfjell and Cornell (*18*) argue that confronting the root causes of unsustainability demands radical, adaptive policy leadership and critically reflexive transdisciplinary engagement by a wider range of scholars and actors.

Regulatory strategies to plastics are currently being developed at national, regional and global levels (e.g., G20, EU Plastics Economy, UNEP Plastics Treaty), yet plastics' interrelated socio-economic and environmental justice impacts remain underexplored. Plastics pollution is a complex, multidimensional issue (*31*). It is a "globally relational, intersectional, and intersectoral" challenge (*1*), deeply linked with "environmental justice, climate, pollution, multigenerational health, extractivism, Land rights, workers' rights, systemic racism, and toxic colonialism - across local, urban, regional, national and planetary scales" via their raw fossil fuel material, among others (*32*, *33*). At this pivotal moment, plastic must be recognized as a multi-faceted sustainability issue (*31*), with policies designed to systematically integrate relevant key aspects including human rights and equity, to facilitate a just transition.

The adoption of UNEA Resolution 5/14 (End Plastic Pollution: Towards an International Legally Binding Instrument) in June 2022 and the multi-stakeholder engagement in the Intergovernmental Negotiating Committee (INC) process toward establishing a legally binding Global Plastics Treaty (*34*) (hereafter referred to as the Plastics Treaty) have prompted scientists to reconsider how plastics pollution issues are researched and communicated to policymakers. We are seeing a shift from an end-of-life "marine litter" focus towards a more interdisciplinary, full lifecycle-based approach that includes chemical composition, production, and health impacts, aligning with the needs of policy, civil society, and business. In this context, recognizing that plastics pollution breaches planetary boundaries and demands data-informed, integrated governance (*16*, *17*), we aim to highlight underexplored environmental and socio-economic dimensions across the plastics life cycle that need to be taken into account in policy-making. To address this issue, we conducted a multidisciplinary expert elicitation of socio-ecological barriers to developing effective, integrated policies for tackling plastics pollution.

We developed the Expert Multi-Issue Knowledge Elicitation (EMIKE) method to gather and structure quantitative and qualitative insights. This iterative co-productive process enables a critical, context-sensitive assessment of sustainability issues and generates statements that are rooted in contributory science and reworked through an interdisciplinary integrative lens, challenging conventional categories. Based on this process, we propose initial guidelines for integrating research on complex, adaptive social-ecological challenges into policymaking. Our approach offers methodological flexibility that attends to contextual factors, such as the timing and needs of global policy negotiations, like the Plastics Treaty.

Results: **Multi-Issue Knowledge Elicitation**

In this section, we report all social-ecological issues identified during the expert elicitation by presenting the co-produced text from EMIKE Phase 2 (Methods section). Box 1 provides background information consolidated from common elements identified by experts during the issue identification phase. Summaries of the textual data are provided in Table 1, Table 2, and Figure 1.

Environmental, and Socio-economic issue identifications

1. Problem framing: fundamental knowledge gaps related to plastics pollution

Plastics are versatile materials with a complexity that extends from chemical structure to waste management along supply chains. Their diverse chemical composition poses challenges including finding consensus on definitions, standardized methodologies, metrics, and resource management. Moreover, plastics intersect multiple domains of human life, economy, society and politics, environment, industry, commerce, health care, law, psychology, science and design, with each field developing their own definitions, further complicating plastics regulation and participatory processes (*35*, *36*). Notably, the definitions of 'litter' and 'waste' according to economic value under circular perspectives. International policy documents and standards (e.g. Marine Strategy Framework Directive - 2008/56/EC, ISO 24187:2023; California's Senate Bill No. 1147) reflect this diversity of definitions. Misleading narratives complicate problem-framing, such as the popular perception that plastics are inert materials, or the reliance on removal activities as the main solution to plastics pollution.

Narrow knowledge frameworks can exacerbate problems related to plastics pollution. For example, many local authorities rely on a rapid visual assessment of waste to estimate plastics pollution. Yet, in many local contexts, where open burning is rampant, there is often no visible waste left to assess, thus resulting in significant plastics pollution and chemical residues going under-counted and amiss from public knowledge (*37*). In some countries, burning turns visible waste into less detectable forms of pollution to the human eye (e.g., ash, toxic & greenhouse gases, particulate matter, or liquid solutions), adversely impacting human, animal, and environmental health. These underreported pollutants can also pose further challenges to civil society advocacy, impairing policy development and enforcement (*37*–*39*).

Box 1: Plastics Pollution consensus.

Plastics are materials made of polymers, chemical additives and non-intentionally added substances (NIAs). *Primary plastic polymers (PPP)* are synthetic and semi-synthetic polymers used to create plastics products. They are derived from fossil or bio-based feedstocks, including thermoplastics, thermosets, elastomers, and composite resins.

Plastics are well documented to affect Earth systems via physical ecosystems (e.g. entanglement, smothering, and ingestion by biota) and chemical impacts (e.g. emissions of greenhouse gases and acid gases from manufacturing and processing). Through the multitude of chemicals present in plastics (*13*) they also have biological impacts (e.g. 6-PPDQ is lethal for spawning Coho Salmon(*40*) although the understanding of the evidence of these impacts remains fragmented.

Over 16,000 chemicals are used in plastics; over 9,000 lack public data, and over 10,700 lack hazard data in regulatory databases, while more than 4,200 are classified as hazardous (*13*). Less than 6% are regulated in existing multilateral environmental agreements (*41*). Many of these, such as Endocrine-Disrupting Chemicals (EDCs), and carcinogens pose major health and biodiversity risks, emphasizing the need for urgent interdisciplinary research.

Global plastics pollution reflects systemic over-extraction and resource consumption, in pursuit of indefinite economic growth, pushing humanity beyond the biophysical safe operating space for plastics (*16*). It contributes directly to the Triple Planetary Crisis: climate change, biodiversity loss, and pollution (*42*, *43*) impacting the natural environment, and all living things alike.

Plastics are ubiquitous in the environment (*44*, *45*) in all sizes, shapes and forms, and are present throughout the human body (*46*). Pollution occurs across the full plastics life cycle - from fossil fuel extraction to global shipping (*47–49*), reaching even the remotest regions (*50*, *51*). Fossil fuel-associated pollutants, such as greenhouse gas emissions and chemical additives, have long-term environmental consequences. Ninety-nine percent of plastics are fossil fuel-derived (i.e., oil, natural gas and carbon); annual production exceeds 500 million tons (*17*).

Since the 1950s, over 11 trillion tons have been produced (*17*). The widespread use of additives has increased plastics' utility while raising serious concerns (*32*, *52*, *53*). Producer behaviour and societal and economic drivers fuel increased production (*3*) and pollution (*54*). Plastics are framed differently in different practical contexts (e.g., policy, industry, law, etc.) and scientific disciplines, which highlight issues of knowledge and power.

2. The colonial legacy of plastics pollution

Plastics pollution is not solely an environmental crisis; it is intricately linked to poverty and colonialism. Assessments often neglect non-chemical and material intangible externalities, such as systemic discrimination and economic inequality, obscuring their true impacts in policy frameworks. Vulnerable populations, particularly low-income communities in the Global South, disproportionately suffer from plastics pollution, while policy remains driven by industry perspectives from the Global North. These policies reinforce economic systems focused on short-term profit, externalizing environmental and human health costs, thus perpetuating poverty and structural injustice (*55*).

This crisis is rooted in historical exploitation, environmental injustice and economic disparity (*32*, *33*). The plastics industry, encompassing production and recycling sectors, along with state actors, often treats land merely as a resource - disregarding the complex relationships it sustains (*56*). Fossil fuels for plastics production are extracted from lands inhabited by marginalized groups, like Indigenous communities, resulting in forced displacement and impoverishment (*57*, *58*). Post-consumption plastics are transferred to vulnerable regions, transforming, for example, Indigenous lands into "profitable dumps" (*59–61*). This reflects an ongoing colonial dynamic prioritizing corporate profit over human and ecological well-being, perpetuating environmental harm and socio-economic marginalization (*1*, *62*, *63*).

Potential quantifiable metrics:

- *Plastics waste exports* (e.g., Mt/year)
- *Human impact of plastic waste trade* (e.g., nº of affected population): as individuals within vulnerable or marginalized communities directly impacted by plastics waste imports.
- *Expropriated land area* (ha/km²): area of land expropriated or appropriated for plastic supply chain

- *Livelihoods affected by land expropriation and exploitation* (e.g., livelihood disrupted or lost) for plastic supply chain.
- *Displacement of Indigenous and local and others with land tenure landholders* (e.g., nº individuals/families displaced) due to land seizure for activities related to the plastic supply chain.
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3. From apex quantitative target to a more holistic policy making

Drawing parallel with the 1.5°C climate change target, a biodiversity apex target was proposed for the post-2020 Biodiversity Framework (*64*, *65*). Apex targets aim to describe a real-world desirable state, a simple, socially resonant cross-sectoral message, and align accountability, preventing marginal incrementalism and goal-slippage. To end plastics pollution, a "global target" on plastics is prompting calls for an analogue apex target for such quantification (*66*). The INC zero draft introduced the possibility of a plastics polymers production (PPP) reduction (UNEP/PP/INC.3/4) (*67*). Establishing this production target can be an essential initial step. However, alone, it cannot fully address critical social safety and justice aspects. A holistic approach with multiple targets is required for a deep and comprehensive understanding of the complexities of the Earth and its social systems as well as the material complexities of plastics, including essential uses of chemicals of concern, environmental releases, and removal/remediation.

Another key metric is capital allocation. While a diverse range of proposed solutions vary widely in terms of efficiency, effective and political viability, downstream strategies (e.g., waste management practices such as recycling) have dominated investments, contributing to delaying and shifting the burdens rather than addressing root causes, and creating an illusion of progress (*68*). From 2018 to 2022, 88% of the capital invested in circularity solutions to end plastics pollution went towards recycling and recovery activities (*69*). This misallocation inverts the waste hierarchy, further exacerbating the problem. Without appropriate capital allocation to support implementation, the treaty risks devolving to a waste management agreement, mirroring failures observed in global climate governance, by shifting burdens, and compromising social wellbeing and justice (*70*).

Potential metrics:
- *Plastics production* (e.g., Mt tons)
- *Plastics consumption* (e.g., Mt tons)
- *Financial resource allocation* (e.g., EUR, USD): track financial resources, private and public, allocated at interventions at all levels compared to the waste hierarchy.

4. Science can be weaponized to delay action

The public and most scientists recognize that global and practically irreversible contamination of the environment by plastics is unacceptable, and that it is a high priority issue that demands urgent and aggressive action (e.g., Earth.org (*71*)). In contrast, some stakeholders and a minority of scientists have expressed skepticism about whether plastics pollution really is an urgent problem (e.g. (*72*, *73*)). They argue that public concern about plastics pollution has run-out ahead of science, and that actions to curtail production and emissions are not necessary until more scientific studies and cost/benefit analyses are conducted. Bad faith actors go further to weaponize science by moving the goalposts to demand ever-increasing levels of "proof" based on "sound science," an industry term (*74*), which could delay regulatory action indefinitely. The actions and arguments of "Merchants of Doubt" (*75*), who purposefully muddy the waters to undermine scientific understanding, must be recognized. Some media give bad faith actors

Table 2: Matrix of metrics. Potential indicators identified during this expert elicitation. This does not include all possible indicators. All indicators can apply at all scales from local, to regional, to global, using metrics from national and corporate reporting.

Indicators	Indicator metrics (e.g.,)	Impact pathway "directed to"	Issues impacted
Plastics production	Mt /year	Extraction, production, and use; and economics and governance	2, 3, 5.2., 6.1., 14, 16
Percentage of chemicals with toxicity data	% of known/used chemicals	Extraction, production, and use; and economics and governance	6.1.
Plastics consumption	Mt /year	Extraction, production, and use; and economics and governance	3
Plastics waste exports masses	Mt /year	Waste management, releases and leakage; economics and governance	2, 5.2.
Human impact of plastic waste trade	Nº of affected individuals	Extraction, production, and use, waste management, release and leakage	2
Expropriated land area	ha, km^2	Extraction, production, and use, waste management, release and leakage	2
Livelihoods affected by land expropriation	Nº livelihoods disrupted or lost	Extraction, production, and use, waste management, release and leakage	2
Displacement of Indigenous and local and others with land tenure landholders	Nº individuals/families displaced	Extraction, production, and use, waste management, release and leakage	2
Emission of GHG	Gt CO_2, Mt CH_4, $NO_{x/year}$	Extraction, production, and use; waste management, release and leakage; and Earth systems effects	5.1., 5.2.
Water footprint of plastics production for petrochemicals and alternatives	m^3/ton of plastics produced	Extraction, production, and use	5.3.

Branded products wasted found in the environment for brand company	% by brand/company	Waste management, releases and leakages	5.2.
Products with transparent reporting	Nº of products with transparent / total nº of products	Extraction, production, and use; and waste management, releases and leakage	6.1.
Quantification of the combined toxic effects	Toxicity Equivalency Factor (TEF), Hazard Index (HI), Combined Toxicity Index (CTI)	Waste management, releases and leakages, Earth system effects	6.1.
Unregulated plastics chemicals	Nº of unregulated plastics chemicals	Extraction, production, and use; waste management, releases and leakages	6.1.
Mass of plastic waste chemically recycled through chemical recycling	Mt /year	Waste management, releases and leakages; human health and well-being; and Earth system effects	6.2.
Volatile organic compounds (VOCs) and other hazardous emissions	[VOCs], [PM2.5], [PM10]	Waste management, releases and leakages; human health and well-being; and Earth system effects	6.2.
Share of output from recycling processes used as fuel	% yield	Waste management, releases and leakages	6.2.
Energy requirements of plastics full life cycle	MJ/ton/year	Extraction, production, and use; waste management, releases and leakages	8
Fossil fuel dependency of the plastics supply chain	% of dependency	Extraction, production, and use; waste management, releases and leakages	8
Characterization of material and quantity	Polymer type/Mt	Extraction, production, and use; waste management, releases and leakages	8
Characterization of material collection at city-level	Mt/year, percent collection or percent coverage	Extraction, production, and use; waste management, releases and leakages	8
Percent and mass of Recycled Materials	%, Mt/year	Extraction, production, and use; waste management, releases and leakages	8
Overall material uses per capita	Mt kg/person /year	Extraction, production, and use	12

Countries using holistic metrics of societal success	cf. Gross National Product	Extraction, production, and use	12
Use of single-use plastics in the food and beverage industry	Mt/year	Extraction, production, and use	13
Quantity of plastics released into the environment (e.g., *Global Pollutant Release and Transfer Register (G-PRTR)*	Mt/year, type source	Extraction, production, and use; waste management, releases and leakages, Earth system effects	14
Rates of plastics degradation of products and polymers	Degradation rate (% and days)	Extraction, production, and use; waste management, releases and leakages	14
Quantity of plastics in all compartments	Items/m^3 (air, water), items/kg (sediment), items/kg/ha (soil), items/m^2 (land), items per individual, items per gram (organisms)	Waste management, releases and leakages, Earth system effects	14
Plastics fragments cross-boundary interaction (e.g., *Chemical* Stre*ss Index)*	Index score	Waste management, releases and leakages	14
Plastic-Chemical Interaction Index	Nº or mass of chemicals/tons of plastics	Extraction, production, and use; waste management, releases and leakages, Earth system effect	15
Cumulative Boundary Interaction Index	Nº of intercepted boundaries	Earth system effect	15
Cumulative Hazard Quotient	∑HQs for multi-chemical exposure	Earth system effects	15
Temporal Accumulation Rate	% accumulation / year	Waste management, releases and leakages, Earth system effects	15
Spatial Overlap Index	Index score	Waste management, releases and leakages, Earth system effects	15
Remote sensing and GIS technologies	Plastic density, ha land/water affected	Waste management, releases and leakages, Earth system effects	15

Financial resource allocation (public & private) of interventions along the full life cycle.	Euros, USD, % of GDP	Extraction, production, and use consumption, and economics and governance	3
Lobbying expenditures by fossil fuel companies	Euros, USD	Extraction, production, and use consumption; waste management, releases and leakages; Earth system effect, human health and well-being, and economics and governance	7.1, 7.2, 10
Propagation of social media posts, hashtags and memes spreading disinformation about plastics	Pageviews	Extraction, production, and use consumption; waste management, releases and leakages; Earth system effect, human health and well-being, and economics and governance	7.1, 7.2., 10

equal coverage in the interest of "presenting both sides". They can be highly influential on social media (*76*) and shape public perception and political ambition.

Potential metrics:

- *Lobbying expenditures by fossil fuel companies* (e.g., USD, EUR)
- *Propagation of social media posts, hashtags and memes spreading disinformation about plastics* (e.g., Pageviews)

5. Plastics Production, fossil fuels and climate change

5.1 Plastics and climate change: Plastics are derived almost entirely from fossil sources – petroleum, fossil gas, and coal serve as both feedstock (70%) and energy source (30%) (*77*). Plastic supply chains are locked into fossil fuel dependence through infrastructural, institutional, and behavioural mechanisms, making plastics production a major source of greenhouse gas (GHG) emissions: 2.24 Gt CO_2e in 2019, which represents 5.3% of the global CO2 emissions (more that the aviation sector) (*47*), mainly as CO_2, with smaller contributions from other GHGs (*77*). Additionally, plastics combustion such as incineration, co-processing in cement kilns, landfill fires, plastic-to-fuel, and open burning contributes ~0.1 Gt CO_2e annually (*78*, *79*). Plastic waste in the environment exacerbates climate change through decomposition into GHGs (*80*) and through. interference with the biological carbon cycling and photosynthetic rates (*81*) cryosphere albedo (*82*), radiative effects (*83*), and atmospheric condensation processes (*84*, *85*), but the magnitude of these effects is currently unknown. Decarbonizing plastics production requires more than transitioning to renewable energy (*86*), which remains limited for some processes. Two primary strategies have been proposed: bio-based feedstock and carbon capture and storage (CCS). Both face significant challenges in responding at the scale and pace needed.

Bio-based plastics have a similar carbon footprint to fossil-based plastics, due to the industrialized nature of modern agriculture, and converting large areas of arable land to plastic feedstock production would have deleterious implications for food prices and deforestation (*87–89*). Producing plastics from captured carbon is technically possible but costly and competes with renewable energy needs (*90*). Carbon capture and storage is a high-risk technology given its slow development, and there are many barriers to deployment, such as the necessary support infrastructures, especially for retrofits of complex process industries such as plastics production. The accelerated growth of plastics production suggests that it will consume its allocated share of the 1.5ºC carbon budget by 2030 and exhaust the entire budget by 2060 (*91*).

A potential quantifiable metric:

- *Quantity of GHGs released* (e.g., Gt CO_2, Mt CH_4)

5.2. Preventing externalities of plastics pollution through reduced and improved production:

The plastics supply chain generates significant environmental and social externalities, largely driven by the over-extraction of fossil fuels in pursuit of infinite economic growth. For example, cancer alleys in the fossil feedstock extraction and production sites would expand and further disproportionately impact low-income and BIPOC people (i.e., Black, Indigenous, People of Colors) (*92–94*). For-profit companies lack incentives to reduce plastics production, as plastics are artificially cheap due to subsidies and externalized costs, and because of their high profitability in comparison to fossil carbon feedstock. Upstream source control, which means redesigning waste infrastructure and materials to prevent harm, is key to preventing plastics pollution (*95*). However, industries are unlikely to act without political pressure or economic incentives, as recycled feedstock is more expensive than virgin material. Few policies limit virgin plastics production or mandate recycled feedstock, and lawsuits against corporate greenwashing are only beginning (*96–100*). Nearly half of companies fail to meet their own plastics reduction targets (*101*).

Global plastics production and consumption are expected to rise under the flawed assumptions that waste management and recycling alone can address plastics pollution (*102*). Inequitable waste trades will exacerbate environmental and social challenges, with workers throughout the plastics value chain, especially in the informal sector, continuing to bear health risks and economic disadvantages. Consumers also experience a mental burden and frustration when looking for safe and sustainable alternatives and substitutes while companies make misleading claims, such as "biodegradable" packaging (*103*), upholding the business-as-usual model. Consumers also face economic burdens when alternatives and substitutes are inconvenient and comparatively expensive.

Potential quantifiable metrics:

- *Plastics production* (e.g., Mt tons/yr)
- *Emission of pollution released and* emitted (e.g. GtCO2-equivalent)
- *Plastics waste exports masses* (e.g., Mt tons/yr)
- *Percentages of branded products wasted in the environment for brand companies* (e.g., %)

5.3. The water footprint of petrochemical-based and alternative plastics production processes:

Projections indicating a rapid growth of plastics production in the coming decades will also considerably increase the impacts on the water resources required for plastics production. Water scarcity affects two-thirds of the world's population, and nearly 4 billion people live in severe water scarcity, posing a risk to biodiversity and human welfare (*104*). The Pacific Institute documented a 50% increase in water-related conflicts from 2022 to 2023 (*105*). Although plastics pollution has gained attention through its impacts on our oceans via landfill leakages and microplastics, upstream extraction and chemical production for plastic feedstocks significantly contribute to industrial emissions and releases entering waterways as one of the leading causes of eutrophication (*106*). North America and Europe account for 15-20% of global water withdrawals for primary chemical production (*106*). Contaminated water streams, affecting surface waters, groundwater, fisheries, and fields constitute sources of violence upon communities by international oil operations leading to worsening social destabilization in impacted areas (*107*). Industry solutions further exacerbate water stress (*108*). Ensuring that the entire supply chain of plastic is included would increase information exchange on water allocation and efforts on transboundary water cooperation toward broader sustainable development goals. Currently, 60% of transboundary river basins agreements and only six aquifer agreements have been adopted at the international level (*109*).

A potential quantifiable metric:

- *Water footprint of plastics production for petrochemicals and proposed alternatives* (e.g., m3/ton of plastics produced): to understand the impact on water demand, stress, and scarcity in vulnerable communities where plastics production is located.

6. Plastics chemical composition: health and hazard impacts

6.1 Hazardous composition of plastics and toxicity impacts on the environment and humans

Plastics' complex composition, including polymer matrices, additives, and non-intentionally added substances (NIAS), affect their safety, recyclability, and usability. However, the biological effects of plastic chemicals across their life cycle, from extraction and production, to leakage and emission, and environmental remediation, are poorly understood. Toxic chemicals in plastics harm human health, biodiversity, and food chains (see Box 1). Many of these chemicals are Endocrine-Disrupting Chemicals (EDCs), which can disrupt hormonal systems, causing developmental, reproductive, neurological, and immune issues at extremely low doses, with exposure during critical periods, e.g. neonatal and prenatal stages, breastfeeding, affecting adults long after exposure ends (*110*). Thus, the interpretation of Paracelsus' principle 'the dose makes the poison' is outdated, because it does not account for the low dose effects and non-monotonic dose-response curves of chemicals that are hazardous at extremely low doses (Ibid.), especially during vulnerable periods of development (*111*). Traditional risk assessments fail to capture these effects. Toxic plastics chemicals, including additives and NIAS, and their byproducts such as dioxins released during burning, disproportionately burden marginalized communities, including frontline and fenceline communities near production and waste management sites, small island developing states and other developing countries, waste pickers, and women and children.

Exposure to toxic plastics chemicals stems, in part, from the unregulated rise in plastics production, lack of chemicals regulations, and lack of transparency in plastics composition. Most chemicals in plastics are not regulated in existing multilateral environmental agreements (*126*) (see Box 1). Only a few countries test, assess, monitor, and regulate the biological impacts of plastics, particularly those caused by plastic chemicals, and their alternatives/substitutes (*13*). Further, no existing multilateral environmental agreements specifically address the hazards or risks of EDCs (*112*).

Potential quantitative metrics:

- *Plastics production (*e.g., M tons/year) including monomer and other chemical production
- *Percentage of chemicals with toxicity data* (e.g., % chemicals): for chemicals used or present in plastics
- *Percentage of products with transparent reporting* (e.g., % products with transparent reporting): global testing, labelling and other standards need to be adapted specific to chemicals in plastics along the full life cycle of plastics
- *Quantification of the combined toxic effects* (e.g., Toxicity Equivalency Factor (TEF), Hazard Index (HI), Combined Toxicity Index (CTI): enables comparisons of plastic chemicals on key species across ecosystems
- *Unregulated plastics chemicals* (e.g., nº of unregulated plastics chemicals): at the global scale, including additives and non-intentionally added substances (NIAS).

6.2 Frontline and fenceline communities' impacts by chemicals from chemical recycling of plastics

The rapidly growing interest for chemical/advanced recycling from actors such as fossil and petrochemical companies are already harming fenceline communities. Appropriate regulations for these novel facilities are not yet in place in many regions or are being ignored (*113*).

Chemical recycling (also known as advanced recycling) of plastics is rapidly gaining attention. Although an umbrella term for many different technologies, different forms of pyrolysis processes are among the most common alternatives for chemical recycling (*114*). These processes generate a large and uncontrollable number of chemicals, both in the exhaust gases and in the liquid product, many of which are toxic and/or carcinogenic (*115*). Many of the toxic chemicals in products and emissions from chemical/advanced recycling belong to the group of novel entities, which cause harm to human health and ecosystems. As chemical recycling facilities start operating, there is a high risk that air emissions and the products themselves will introduce new toxicants with negative health impacts on fenceline communities. This risk is likely to be higher for small to medium-scale facilities in low- and middle-income countries, which may opt for simpler and cheaper technologies, but is also evident in other countries, as evidenced by the US, where plants have received EPA approval despite extreme health risks documented to local communities (*116*). Using the output as fuel introduces further risks as its fuel properties are not well defined.

Global level governance can establish criteria, standards, and/or guidelines for acceptable chemical recycling practices and measures to ensure that they do not cause further harm to fenceline communities.

Potential quantifiable metrics:

- *Mass of plastic waste chemically recycled through chemical recycling* (e.g., Mt tons)
- *Volatile organic compounds (VOCs) and other emissions* (e.g., [VOCs] [PM2.5], [PM10]) to air and water from pyrolysis plants.
- *Share of output from pyrolysis to be used as fuel* (e.g., % yield)

7. Lack of transparency and corporate capture

7.1 Lack of transparency and access to scientific information

The regrettable outcomes of plastics, like some other industrial innovations (e.g., CFCs, thalidomide, and tobacco) have been enabled by legal frameworks that protect the proprietary information of the plastics industry. For example, companies are allowed to withhold critical data and deny the public access to information about the presence, sources, pathways, exposure, and effects of plastics on human and environmental health, and economies (*117*). The public, including most plastics supply chain actors, cannot access hazard information related to the plastics they buy, manufacture, sell, consume, handle, transport, manage, and remove from contaminated environments. And yet, it is the public who disproportionately bear the externalized burdens of the full life cycle of plastics. The lack of regulatory requirement leads to information poverty and thus lower levels of alarm and political will to address the problem.

For decades, industry narratives have diverted attention away from the hazards of plastics to exaggerate plastics' benefits and consumer responsibility, to generate dis- and misinformation about the hazards of plastics, and to block increased transparency on the basis of proprietary information (*53*). These industry narratives have served to distract attention away from robust independent science and policy actions with the potential to protect human and planetary health (*118*). Given the hazards plastics pose to human and environmental health, information about the full-life-cycle impacts of plastics, including their chemical composition, should not be considered proprietary and must be openly disclosed by plastics producers (*119*). The failure to provide access to information and to engage with multiple stakeholders and rightsholders, independent scientists, Indigenous knowledge holders, citizen scientists, and impacted workers and communities, limits fully-informed decision-making, regulation, and other effective independent, evidence-based responses.

Potential quantifiable metrics:

- *Lobbying expenditures by fossil fuel companies* (e.g., USD, EUR)

- *Propagation of social media posts, hashtags and memes spreading disinformation about plastics* (e.g., Pageviews)

7.2 Corporate capture harm on effective measures addressing plastics pollution

Addressing plastics pollution requires a justice lens that safeguards civil society participation, public interest, and environmental and societal sustainability. The influence of corporate actors through industry groups and associations, indirect lobbying, and industry-backed research, can lead to misalignment on global commitments and, ultimately, undue corporate influence (*120*). Moreover, the undue influence exerted by corporations on government decision-making processes potentially leads to policies that benefit corporate interests at the expense of the public good and human rights. The plastics industry promotes linear, growth-driven production systems that emphasize economic benefits while neglecting the environmental and social dimensions of sustainable development.

Lack of corporate transparency and reliance on voluntary initiatives such as corporate social responsibility programs, and the non-binding Global Framework on Chemicals, worsen and contribute to gaps in knowledge and capacity-building, hampering effective regulation. To ensure meaningful action is taken, it is vital to adopt transparency and disclosure frameworks (*41*, *121*) and establish mechanisms to mitigate conflict of interest in policy making (e.g. UNGA's Financial Disclosure Programme) (*122–124*). Corporate interests have attempted to influence scientific research via research funding (*75*), similar to tactics used by the tobacco industry (*125*), mislead the public and obstruct meaningful progress (*126*). Private interests can shape public perception through media and law via lobbying (*127*, *128*). Forms of lobbying has included shifting the narrative toward individual responsibility for plastics pollution rather than addressing the systemic issue of plastics hyperproduction, particularly involving unknown and potentially hazardous chemical compositions.

Potential quantifiable metrics:

- *Lobbying expenditures by fossil fuel companies* (e.g., USD, EUR)
- *Propagation of social media posts, hashtags and memes spreading disinformation about plastics* (e.g., Pageviews)

8. Circular economy and the blind focus on recycling

The concept of the "circular economy" (CE) is often promoted by corporations, governments and researchers as a strategy to reduce plastics pollution. Its appeal lies in its conceptual simplicity, analogy to ecosystem functioning, and potential to "future proof" the plastics industry. However, more than 200 definitions of CE have been proposed with consensus on its goals but notable disagreements over its focus, metrics, and implementation and feasibility persist (*129*). The dominating models, typically promoted by industry, emphasize almost exclusively recycling and other downstream interventions as the solution (*130*), whereas other approaches focus on reduction of consumption and measures higher up in the value chain. Other approaches to CE promote a more holistic solution, with aims of facilitating transition to restorative and regenerative economies, by emphasizing upstream measures prior to downstream interventions, and thus promoting an actual shift in the material flow throughout the value chain.

Recycling plastics is energy-intensive and expensive, involving costly waste collection systems and complex physical-chemical recycling procedures, while producing virgin plastics from underpriced and subsidised fossil fuels remains artificially cheap. The dominant focus on recycling as "the" solution to the global plastics pollution crisis is a problematic end-of-life technofix. It locks us into the current socio-technical system, delays transitions to less polluting systems, provides a false sense of safety, perpetuating unsustainable plastics production and consumption. This approach impacts climate change, pollution, and biodiversity while overshadowing more fundamental solutions. It is also important to note its inefficiency in terms of material and energy loss. To date, technology for sufficient recycling of plastics does not exist at large scale (e.g., dealing with polymer complexity, additives, contaminants). While safe and sustainable innovations in recycling are vital, no recycling innovations should be seen as replacements for significantly more effective, efficient, safer, and sustainable upstream solutions that reduce plastic production, use and waste.

Alternatives like reuse systems are promising but require design for equitable accessibility. Primarily investing scarce resources and financing in recycling means less resources where responses will have the greatest effect including plastics production reduction incentives, systems and material design, and regulatory mechanisms. In addition to justice and equity, significant challenges include satisfying consumer expectations, avoiding regrettable substitution, and ensuring that reuse materials and systems meet appropriate criteria for safety and sustainability.

Potential quantifiable metrics:

- *Energy requirements of plastics full life cycle* (e.g., MJ/year) including for chemicals, and recycled plastics.
- *Fossil fuel dependency of the plastics supply chain* (e.g., % of dependency)
- *Characterization of material and quantity* (e.g., polymer type/Mt tons used): including product type, replacement materials, the number of reuse cycles, the number of people with access to them, and the economics surrounding the system
- *Characterization of material collection at city-level* (e.g., Mt tons/year): before and after the implementation of any reuse system
- *Percent and mass of recycled materials* (e.g., % and Mt tons)

9. Need to address challenges brought by community-level opportunistic uses of plastics waste

Households and communities regularly reuse and repurpose plastic objects. From reusing polyethylene carrier bags to repurposing paint containers as buckets, small-scale frugal, creative endeavours are practiced globally, not least in low-and-middle-income countries. These are driven by gendered domestic labour making use of an abundant supply of discarded plastics in the context of poverty and lack of other material resources. Such continued use of plastic objects can, however, lead to mundane toxic exposure.

Another practice of reducing plastic waste involves open burning by setting a pile of plastic waste on fire. This is a common global practice where public or private waste collection infrastructures are inadequate, such as many low and middle-income countries (LMICs) and small island-states. The burning of plastic waste also provides communities temporary relief from a range of other problems, like repelling disease-causing mosquitoes with plastic-burning smoke or providing warmth. Fuelled by the benefits of the abundance of flammable plastic waste, communities and countries are distracted from the need to address structural problems such as a lack of government support for disease prevention, heating and grid connectivity, to alleviate poverty and source waste management alternatives. A popular, yet merely a band-aid solution, plastic burning has severe negative impacts on ecosystems, and human health and wellbeing, including further toxic chemical pollution, CO_2 emissions, biosphere degradation, soil and freshwater pollution.

This issue supports the need to design and make accessible safer and more sustainable materials, products, and delivery systems. Furthermore, it highlights the need to reassess the health and ecological hazards of open burning, particularly in the context of survival, disease prevention, and limited well-being. It underscores the role of global governance in promoting chemical simplification by reducing toxic chemicals present in plastics, and implementing effective monitoring systems to minimize harm.

10. Social context, recycling, and circular economy on the plastic supply chain

Effective management of plastics, including value and supply chains, requires clear, accessible terminology understood across stakeholders. Terms like "sustainable development" and "sustainability" are often used interchangeably, yet they differ. Sustainable development includes social, economic and environmental dimensions, while sustainability sometimes solely refers to economic feasibility (*131*). This distinction has socio-economic implications in the plastics value and supply chains, including the emission and pollutant releases. The perception that plastics are inexpensive overlooks hidden costs such as fossil fuel extraction, international trade of virgin material, end-of-life waste management, and long-term human health and environmental costs.

These unaccounted costs affect global quality of life and are intensified by limited environmental and financial literacy. Misinformation, disinformation and greenwashing - often amplified by mass media - hamper critical thinking, regardless of socio-economic background or geography. These factors, along with knowledge gaps, contribute to issues like contamination in recycling processes and poor consumer choices. Corporate hyperproduction and hyperconsumption, particularly in high-income countries, further exacerbates global waste management, while international waste exports promote a "not in my backyard" mindset (*132*).

Potential quantifiable metrics:

- *Lobbying expenditures by fossil fuel companies* (e.g., USD, EUR)
- *Propagation of social media posts, hashtags and memes spreading disinformation about plastics* (e.g., Pageviews)

11. Unequal access to alternatives to single-use plastics and non-plastic substitute products

Unequal access to alternatives to conventional single-use plastics is yet another problem. Currently, there are some alternative delivery systems (e.g., Loop developed by TerraCycle) or alternative materials (e.g., AirCarbon PHA) to traditional or current "mainstream" material. However, these options are only available to certain sectors of society and limited to certain cities/stores/areas. The drivers of single-use plastics use are often affordability and convenience. In addition, these alternatives tend to be more expensive than plastic packaged items, falling out of reach for many, even if they are near stores that carry alternatives and bulk goods. To transition away from plastic use, the system should ensure that alternatives are available to everyone, especially people who are limited by transportation and other constraints. Limited alternatives are often observed in discount stores, corner markets, or convenience stores that carry primarily fast-moving consumer goods or stock only a small quantity of items affordably. Lack of access to viable plastics alternatives stems from larger inequities around income, ethnicity, and underserved communities, so as also mentioned in previous sections, addressing these larger social inequities could help to address plastics pollution through systemic change.

12. Plastics hyperconsumption

The rise in plastics production and use is tied to a global trend toward hyperconsumption, originating in the US post-WWII and then spreading to the global middle class. Capitalism (*3*, *32*), advertising and wealth displays fuel the demand for disposable goods, straining planetary boundaries.
Plastics' artificial affordability has propelled the rise of disposable goods even in societies with incomes significantly below levels in high income countries. However, efforts to limit plastics production and use without addressing overall consumption could lead to the increased use of other materials (e.g., metal, glass, paper) that might cause similar or greater environmental harm, or to consumer backlash. Tackling hyperconsumption culture is politically challenging, as illustrated by US President George HW Bush's 1992 statement "The American way of life is not up for negotiation" (*133*), Additionally, many leaders in developing countries view efforts to curb hyperconsumption as colonial attempts to keep them impoverished. Even defining hyperconsumption is challenging as the line between adequate and excessive consumption is unclear. Alternatives to hyperconsumption, such as "de-growth" and "buen vivir" have generated significant academic and popular interest, but have largely gone unimplemented (*134*), There are few examples of societies that have successfully curbed hyperconsumption.

Efforts to address plastics overproduction have focused on demand reduction through voluntary corporate efforts or regulations such as plastic bag or take-out container bans. However, these measures have proven ineffective (*101*) at curbing global plastics production, leading to calls for global and national legal controls on primary plastics production.

Potential quantifiable metrics:

- *Overall material used per capita* (e.g., Mt Kg/person /year)
- *Number of countries using holistic metrics of societal success* (e.g., Gross National Happiness, cf. Gross National Product)

13. Prioritising durable materials, products, as well as supportive policies, systems, and technologies for food and water delivery

Plastics have become deeply embedded in socio-economic transitions, including urbanization and the privatization of common goods. For instance, in some low-income countries, plastic water sachets are used to provide safe, potable water where infrastructure is lacking. However, mismanaged plastics sachets significantly exacerbate water pollution, with an estimated 50-60 million water sachets littering Nigeria's streets annually (*135*). Water sachets as a temporary solution highlight the need for longer-term, more durable and equitably accessible materials, products, and infrastructure. Another example is the extensive use of plastics in food packaging, based on the claim that plastics increase the lifespan of foods by improving preservation, transportation, and hygiene (*136*). Yet they generate waste, emit GHGs and other pollutants, and support ultra-processed food production (*137*) with evidence linking to deterioration in diet quality and higher risk of chronic diseases, while exacerbating food waste (*138*). Single-use plastics are enmeshed in the delivery of food and water, while contributing to its contamination with micro- and nano-plastics (MNPs) and associated chemicals over the life-cycle of those plastics, compromising the ecosystems upon which food availability, safety and nutrition relies. Innovation and investment in regenerative and restorative circular systems including plastic-free food and water delivery systems, and safe, durable, and more sustainable materials and products for reuse systems for food and water containers as a public good is needed to ensure the delivery of safe food and water while minimizing plastics pollution and food and water waste.

Potential quantifiable metrics:

- *Use of single-use plastics in the food and beverage industry* (e.g., Mt tons)

14. Cross-scale interactions of micro- and nanoplastics

Micro/nanoplastics (MNPs) in the environment fragment through weathering processes and expose humans and wildlife to plasticizers, polymers, and monomers (*139*). Airborne MNPs - emitted, for example, from plastic production, abrasion of tyres and brakes, textiles, polymer-coated surfaces, carpets, and recycling, increase exposures and transport to remote areas (*140*, *141*). Atmospheric deposition delivers them to terrestrial and aquatic food webs, impacting crops, food security, biogeochemistry and functioning of soil ecosystems (*81*, *142*). In the cryosphere, coloured MNPs are likely to reduce the albedo effect, accelerating ice melting and climate change (*82*, *143*) while hydrophilic MNPs in the atmosphere could influence cloud formation (*144*), heat trapping and weather (*145*).

MNPs are absorbed via the skin, inhalation and can cross the gut barrier and translocate to tissues and organs. In exposed animals, MNPs can cause reproductive, behavioral and physiological effects, oxidative stress and inflammation, and disrupt motility and feeding (*146–148*). MNPs have been detected in different parts of the human body, including the placenta (*149*), blood (*150*), lungs (*151*), gastrointestinal tract and brain (*152*, *153*). Inhaled airborne MNPs can accumulate in respiratory systems, particularly among workers exposed to plastics (*154*). Though human health effects continue to emerge, evidence suggests oxidative stress and inflammation, and a correlation with inflammatory bowel disease (*155*).

Potential quantifiable metrics:

- *Production of plastics* (e.g., Mt/year, type source)
- *Quantity of plastics released into the environment* (e.g., Mt/year)**:** monitoring sources and sinks. A *Global Pollutant Release and Transfer Register (G-PRTR)* that would quantify releases to air, water, soil and sediment, as well as transfer of litter and waste across continents
- *Rates of plastics degradation of products and polymers* (e.g., Mt/year, type source): estimating the continuous release of microplastics
- *Quantity of plastics in all compartments* (e.g., items/m^3 (air, water), items/kg (sediment)): monitoring inputs and outputs of MNPs to identify pathways, rates of accumulation and sequestration, in biota, air, terrestrial or aquatic systems. E.g.: *The Environmental Plastic Load Threshold* defines maximum acceptable levels in various compartments
- *Cross-boundary metrics* (e.g., Index score): showing how the impacts intersect with other planetary boundaries. E.g., *Chemical* Stre*ss Index* which aggregates plastic-derived chemicals to biogeochemical cycles.

15. Interconnected cumulative effects plastics pollution

The utilisation of plastics and chemicals has attained levels that may compromise the Earth's capacity to sustain safe limits (*17*, *156*). In assessing these planetary transgressions, boundaries are generally classified as exceeding or falling below safe limits (Ibid.). However, the interconnectivity among these boundaries necessitates examining cumulative impacts collectively. Evaluating interconnected cumulative impacts could offer insights into aggregate ecological risks and societal implications beyond the

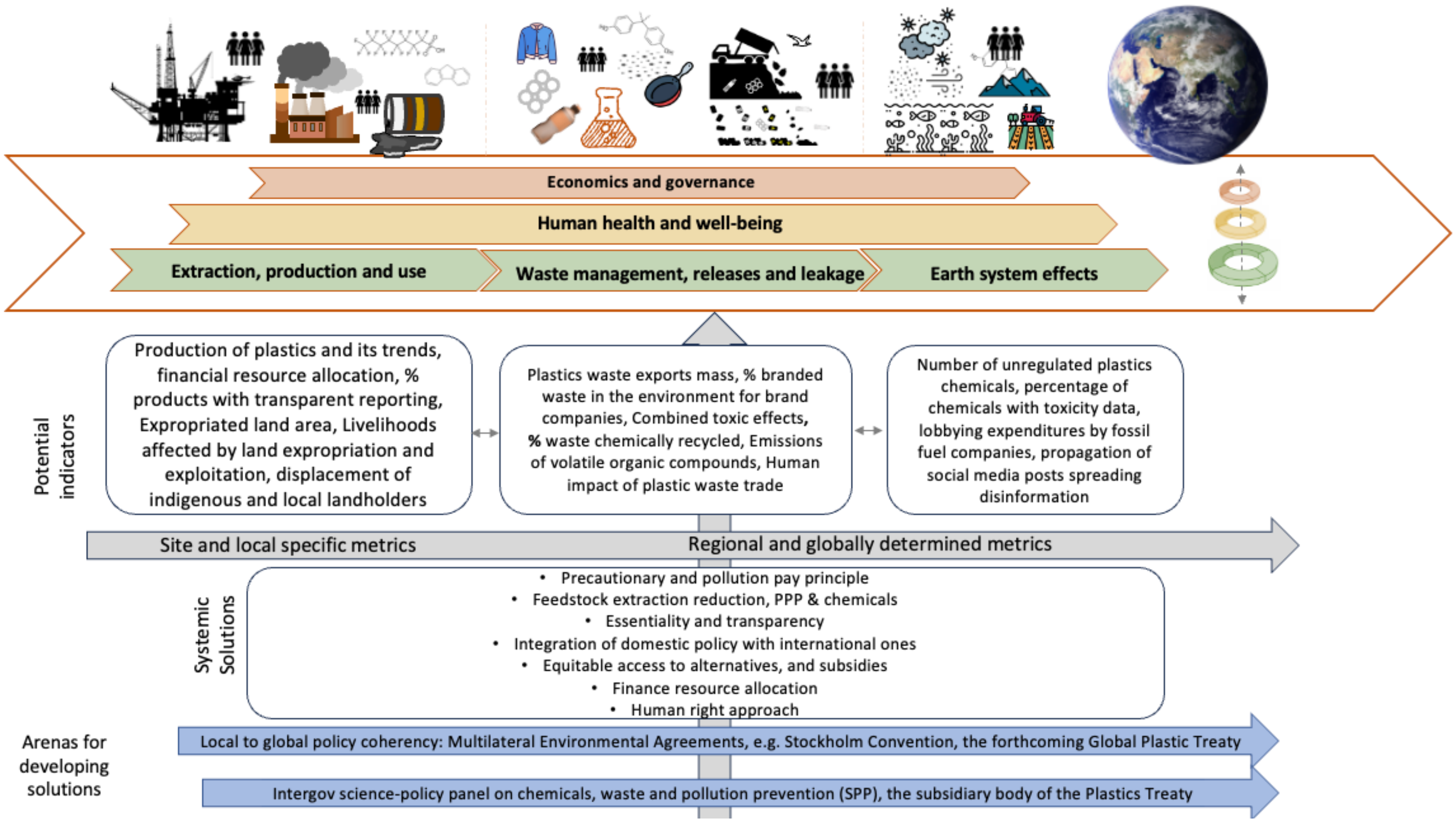

Figure 1: The Plastics Pollution Impact-Pathway with a social-ecological framing. The science-policy interface now recognizes environmental impacts (green pathway) from extraction, production, and use, waste management, releases and leakage, and Earth system effects at global scale, but policy responses need also to recognize the inseparable social aspects: human health and wellbeing (yellow pathway), and the governance and economics of the plastics life cycle (red pathway). Indicators need to better reflect that economic and social dimensions are embedded in the biosphere, and cover the whole impact-pathway (example indicators from Table 2 are shown). Note that each potential indicator represents the point of intervention, although the effects may extend along the full impact pathway Adapted from Carney Almroth et al. (2022).

assessment of isolated boundaries (*8*, *15*). Nevertheless, operationalizing this cumulative approach remains methodologically complex and warrants further empirical investigation.

Potential metrics:

- *Plastic-chemical interaction index* (e.g., number/mass of chemicals/tons of plastics): quantifies how plastics and their chemicals enhance the toxicity
- *Cumulative boundary interaction index* (e.g., nº of intercepted boundaries)**:** integrates the impacts of plastics with other planetary boundary exceedances (i.e., freshwater use and land system change)
- *Temporal accumulation rate* (e.g., % accumulation/year) to track the temporal increase of plastic pollutants within ecosystems
- *Spatial Overlap Index* (e.g., Index score)**:** spatial co-occurrence of plastics pollution with other environmental stressors
- *Remote sensing and GIS technologies* (e.g., plastic density, distributions, ha of land/water affected): number of pollution hotspots, pollutant concentration distributions

16. Plastics pollution is global in scale and not reversible

Plastics pollution represents an existential threat to humanity because it is global in scale and is practically irreversible (*5*). Although plastics pollution is already known to be causing environmental impacts, the existential threat arises from the potential for a currently unknown effect to manifest itself and be irreversible. The unknown effect may resemble a past global crisis such as ozone layer depletion, or be a large-scale disruption of ecosystem function, or a direct impact on human health.

Irreversibility of plastics pollution and its associated effects stems from society's hyper-dependence on plastic production and use, which inevitably results in emissions. As production grows, so too do emissions, environmental accumulation (*54*), and human exposure (*157*) and thus the risk of triggering currently unknown global-scale effects (*5*). A meaningful reduction or reversal of the increasing trend in plastics production could signal decreased societal dependence and potential to prevent or reverse environmental contamination, and/or potential to avoid triggering unknown impacts.

Potential quantitative metrics:

- *Plastics production* (e.g., Mt tons)

17. Policy spillovers and policy leakages

Policy spillovers and policy leakage refer to unintended consequences of policy interventions. While spillovers and policy leakage refer to unintended consequences of policy interventions. While policy leakage specifically describes negative policy intervention outcomes, policy spillovers involve both positive and negative effects of the policy across sectors (i.e., economy) and geographies. In the context of plastics, poor policy coherence across local, national and international levels can undermine intended policy outcomes. For instance, plastics policies may inadvertently shift environmental and social burdens across territories and jurisdictions. Plastics policy leakage impacts can include toxic waste trade to poorer countries; climate impacts of the full life cycle of plastics including extraction and production phases, human rights abuses, compromised food safety and sovereignty, lock-in investment in polluting waste management technologies, and public and negative environmental health impacts.

Policy effectiveness and the avoidance of policy leakage relies on accurate data. While standardised and harmonised criteria, standards, assessments, and universal targets are critical for transparency and accurate reporting; overreliance on quantitative data can obscure critical socio-cultural and economic needs, challenges, and impacts of policy leakage.

Policy effectiveness, avoidance of policy leakage and drivers of positive policy spillover also rely on horizontal and vertical policy integration and coherence (*35*).

Recommendations

Although experts were not explicitly asked to propose solutions or recommendations, all did so. This likely reflects their active role in the science-policy interface. All experts agreed that, after more than 20 years of research on plastics pollution sources, bioaccumulation, and impacts, it is urgent to overcome global regulatory delays (*158*). The following summarizes the expert-proposed recommendations throughout the plastics impact-pathway:

Experts emphasized the urgent need for holistic, multidisciplinary, consensual life cycle frameworks that accounts for plastics' interconnected impacts on ecosystems, human health, and producer economic concerns. Plastics pollution remains shaped by narrow knowledge frameworks and misleading narratives, that frequently deflect responsibility onto consumers and reinforce business-as-usual practices (*159*). Some experts highlighted that current policy gaps, and at times regulatory non-compliance, enables the continued production and use of untested and undisclosed chemicals and products at massive and uncertain quantities. Plastics governance should engage at all levels, from local to global, and be grounded in the precautionary, prevention and polluter-pays principles. A full life cycle perspective is essential: one that critically addressed every stage of the plastics system from raw material extraction (i.e., fossil carbon and biobased feedstocks), through transport, production, consumption and use, to waste disposal, management and remediation, attending to the prevention of further environmental, economic and societal harms.

Measures should aim to significantly reduce feedstock extraction, primary polymers production, and associated chemicals of concern, to address the persistence of plastics pollution and rising concentrations (*160*, *161*), precautionary measures should aim to significantly reduce feedstock extraction, primary polymers production, and associated chemicals of concern. Essentiality of use assessments can control the production**,** supporting reuse, recycling, and pollution reduction to mitigate risks and prevent irreversible harm. Ambitious plastics production reduction target are also needed to reduce GHG emissions and meet the climate goals (*47*), and reduce chemical and MNP exposure, human health and ecosystem damages and other externalities. Developing robust global standards for assessing chemicals of concern, including EDCs, across the full life cycle can help identify substances for phase-out.

All experts emphasize promoting transparency, alongside strengthening monitoring and reporting systems. A systemic shift supported by international cooperation and improved communication is needed to balance economic, social, and environmental priorities. Improving transparency requires data disclosure, product labelling, traceability, trackability, and a common mandatory reporting system, along with chemical simplification, and reducing toxic additives in plastics, enabling more informed decisions across the supply chain, including by policymakers and the public to support safer and sustainable alternatives while reducing unnecessary plastic consumption. Public trust is enhanced when data transparency and inclusivity underpin science-policy processes. The public's right to access scientific information and to participate in shaping knowledge generation is vital, especially when human health, ecosystems and communities are at stake. However, existing transparency mechanisms remain limited, prompting calls for better monitoring, bans on hazardous substances in plastics and products, and stricter controls. Given the growing global scale of plastics production, use and pollution, international coordination is vital for effective management and regulation.

Experts also highlighted democratizing the discussions at the science-policy interface of plastics pollution as critical. This requires broad expert participation (including the public)**,** including frontline and fenceline communities, Indigenous knowledge holders, and multi- and interdisciplinary experts. Transparency is a core element of democratizing science, ensuring information accessibility, inclusivity, accountability, and addressing conflicts of interest. Public assessments of plastics' 'essential uses' - defined as groupings of plastics chemicals, polymers, and products necessary for health, safety, or critical societal functioning - can help identify what is currently truly indispensable. Where safer, more sustainable alternatives or non-plastic solutions (such as reuse and refill models) exist, these assessments can guide the phase-out of non-essential plastics**.** Moreover, diverse forms of expertise need to be recognised, public influence and equitable participation in science and science-policy bodies are encouraged, where transparency of data and process is key (*162*). It also serves the human rights to access to information, and participation, and benefit from scientific research and progress (*163*). It also invites critical thinking and diverse perspectives (*164*) all of which are crucial for protecting universal and Indigenous rights (*165*).

Most experts emphasized the need for a policy framework grounded in justice, and managing potential conflict of interest of actors involved. They raised concerns about corporate influence (or capture) in decision-making. The Plastics Treaty must protect civil society participation, the public interest, and finite resources, while minimizing undue corporate influence that undermines human rights and exacerbates ecological harm. Regarding the Plastics Treaty process, some experts stressed the importance of strong safeguards to protect against profit-driven interests while strengthening an inclusive, participatory democratic process.

Governments should integrate domestic plastics policies with health, environmental, trade, cultural, and social policies, aligning them with regional and international agreements. Although many governments have implemented some policies addressing plastics pollution, these often lack alignment across ministries (e.g., trade vs environment, compliance, monitoring or enforcing). Government restrictions often face private sector resistance and lack of state capacity, hindering enforcement. Improved integration reduces policy leakage risks and promotes beneficial spillovers, although experts acknowledge that this may not be supported by stakeholders benefiting from single-use plastics.

Some experts advocate for global policies to enable equitable access to plastics alternatives, such as subsidies for alternative materials (upon approval of being essential for its use, and sustainable and chemically safe), or delivery systems. Taxation of fossil carbon-based plastics or subsidies for alternatives can also contribute to addressing cost parity.

Many experts emphasize aligning finance resource allocation (e.g., national and global scale) with the waste hierarchy principles to ensure a just transition. Without this alignment, interventions could reinforce plastics production while neglecting alternatives, particularly in low-income or marginalized communities near fossil fuel facilities and informal waste sites, where human health is severely compromised. Public participation in decision-making on plastics pollution's health, socio-economic, and environmental impact is crucial to identifying and avoiding impacts. Preventative measures should be prioritized, especially those high up in the waste hierarchy, and ensuring diverse knowledge systems to avoid regrettable substitutes or false solutions. Without clear provisions guiding responses high up the waste hierarchy, there is a significant risk that the future treaty could default to a waste management agreement, missing the opportunity to comprehensively address global plastics pollution and minimize harm in a way that encourages a new and better relationship with plastics. A just transition to a circular, resilient economy that internalizes externalities requires global cooperation, clear communication, and systemic changes balancing economic, social and environmental priorities. Well-designed extended producer responsibility schemes including, deposit or container return schemes, reuse and refill scheme and systems strategies based on precautionary, prevention, and polluter pays principles and guided by the waste hierarchy can mitigate plastics-related including detrimental impacts on fisheries, and the agriculture sectors livestock and farming (*81*, *166–168*), and aesthetic value and tourism (*169*, *170*), as well as damage to marine vessels (*171*, *172*), occupational injuries (*173*) and illegal dumping (*174*, *175*).

Discussion

This study has identified multiple issues associated with planetary plastics pollution and the current and possible use of quantifiable indicators and metrics to support experts and policymakers in better understanding the challenge, and explored them from an interdisciplinary and social-ecological systemic perspective. We did not aim for, nor did we achieve consensus on all of the issues that arose in the elicitation.

There was a general consensus among experts that strong policies require strong data, but not all data serves policy equally. Data is not neutral and the systems that produce data have biases and blind spots (*176–178*). Quantitative data alone 'lacks the depth and context needed to drive positive real-world change'. Experts underscored the importance of both quantitative and qualitative data - generated by diverse actors - to capture the complexity of socio-ecological challenges such as plastics pollution. Underlined was the need for metrics that uphold human rights and environmental justice, including indicators on health, safe environments, and just job transitions (*179*, *180*). While quantitative data are essential, experts agreed it must be accurately interpreted and contextualised, or they risk oversimplifying reality and misrepresenting the lived experiences of individuals and communities (*181*). Therefore, proposing interdisciplinary approaches can provide complementary, context-rich, and socially grounded data to better inform policy design and assess effectiveness. As Spash and Vatn (*182*) caution, decision-makers must be challenged, not catered to, when they rely on data stripped of theoretical or practical meaning.

Experts acknowledge the usefulness of indicators to assess effectiveness of policies, technologies, systems to further innovate and implement solutions through an iterative process as new knowledge is generated and as impacts in the biogeophysical system and socio(economic) systems change. More efforts on development and implementation of interventions or measures, at system, business, service, economic, social and technical and political level. Experts further advocated for data frameworks that enable long-term, equitable governance and prevent intergenerational harm, especially for vulnerable populations, by reflecting uneven responsibilities and impacts across systems. Therefore, the recommended indicators and metrics derived in this work can be used by scientists to analyse the causal relationships between plastics, people, and the environment, and by policy-makers to monitor the effectiveness of regulations. Most experts shared concerns about a single quantifiable metric when informing policy. In the context of the Plastics Treaty, not all countries or communities contribute to the problem nor are impacted in the same way.

Experts highlighted the highly politicized and contested definitions of what plastics pollution is, and its full lifecycle, along with themes such as reduction in production of primary plastics, the need for chemical transparency, application of essentiality of use paradigms, or impacts on human health effects, and financing in plastics policy development as a central driver of other adverse impacts. The strategic allocation of financial resources across the plastic lifecycle is critical especially in vulnerable economies (*70*), requiring careful consideration to ensure an equitable, sustainable and effective outcome. Thoughtful allocation of financing, appropriate safe and sustainable technology transfer and capacity building is essential for supporting a just and resilient transformation of plastics supply chains (including plastic-free systems), supporting affected workers and communities to navigate the transition away from problematic plastics in equitable and sustainable ways. These must prioritize upstream interventions for systemic redesign, not focus merely on waste management as they so far have tended to do.

Decision makers at all levels of governance rely on expert input to inform evidence-based decision-making. Calls for science to support decision-making can be found in numerous declarations, covenants, and treaties. This includes delegates to the United Nations, where the human right to science is enshrined in the Universal Declaration of Human Rights (*183*) and the International Covenant on Economic, Social and Cultural Rights (*184*). Applying monodisciplinary, narrow, and reductionist approaches to complex social-ecological problems risks ignoring complex system dynamics including power and politics, and identification, integration, and interactions of emergent properties. Bringing diverse experts together, including Indigenous rights and knowledge holders, is vital for identifying under-represented or obscured information where full and inclusive data are needed for effective policy making. Our work, using the EMIKE method, resulted in a more holistic understanding of the issues associated with plastics pollution, emphasising the interconnectedness of social, economic, technical and ecological systems. This work supports the cross-fertilization of understandings of complex socio-environmental challenges, strengthening synergies (*185*) and enabling progress towards the identification of more effective, sustainable, safe, and just solutions.

Under this context, scientists in all fields have a responsibility to understand and communicate the historical, social, economic, geographical, ecological, and political context within which quantitative results are situated in order to enable them to recommend effective, comprehensive, sustainable, equitable, and just responses. In grappling with the challenge of capturing this complexity, although scientific gaps remain, the experts in this process unanimously agree that existing knowledge is more than sufficient to inform decision-makers to act with urgency, and provides direction on how to do so.

Materials and Methods: Expert Multi-Issue Knowledge Elicitation (EMIKE).

EMIKE method combines structured expert elicitation with adaptive, co-productive engagement (*186*, *187*). EMIKE recognises that 'wicked' sustainability problems cannot be addressed by science alone (*31*), instead requiring the integration of ecological, chemical, socio-economic, and political dimensions through a multi-metric, context-responsive approach. This approach reflects the multiple ways research, policy, and society engage with plastics.

Originally conceived as a traditional linear expert elicitation, the method quickly evolved following experts' input, which challenged the rigid ranking models in favor of interdisciplinary dialogue attuned to dynamic uncertainties and the ongoing Plastics Treaty negotiations. EMIKE builds on established approaches - including Expert Elicitation (*188*), Horizon Scanning (*189*, *190*) and Multi-Aspect Knowledge Elicitation (MAKE) (*191*) while embedding transdisciplinary co-production, reflexivity, and adaptability.

Pre-Elicitation

Experts were selected for their dual engagement in science and policy, spanning anthropology, political ecology, environmental science, environmental engineering, chemistry, ecotoxicology, waste governance, and planetary boundaries. It also included professionals at the intersection of research and advocacy (see Supplementary Material Table 1). The expert panel consisted of 21 participants (which included the facilitator PVG, and co-facilitators BCA., and SC.). Indigenous rights and knowledge holders are also important experts (*185*, *192–194*) but despite repeated efforts to include Indigenous scholars and more underrepresented regional voices, invitations were declined due to growing demands on their expertise and limited available time from multiple sources.

A preparatory webinar established the project's social-ecological systems framing (*195*) using the impact-pathway model (*17*) and emphasizing cross-domain learning and shared principles of co-production. The process followed best pre-elicitation practices (*190*, *196*) ensuring transparency, shared expectations, and trust.

Phase 1 – Issue Identification

Experts responded to an open-ended survey to identify one biophysical and one social "issue statement" related to the plastics pollution impact-pathway. They prepared written statements explaining why these key issues require targeted attention, and indicated relevant quantifiable metrics and potential implications for policy. Experts were also encouraged to engage their professional and social networks to identify neglected, policy-relevant topics (*190*).

The survey served as an entry point to capture inter- and transdisciplinary perspectives, allowing experts to classify what they perceived as social versus ecological impacts. Experts were also encouraged to engage their professional and social networks to identify neglected, policy-relevant topics. Forty-two total issue statements (21 biophysical, 21 social), were submitted and later compiled by the facilitator (PVG) for further review.

Phase 2 – EMIKE

The issue statements were consolidated and thematically analyzed during two collaborative iterations. Two facilitated webinars explored tensions and synergies between contributory knowledge systems in the science-policy-society interface governance triangle (*197*). During the first webinar of this phase, experts moved away from rankings. Instead, they proposed an organizing principle based on the plastics lifecycle, using Villarrubia-Gómez et al.'s (*17*) impact pathway from raw material extraction and production to end-of-life-impacts. This framework supported clearer narratives for policy integration.

The first thematic analysis, aimed to identify 'biophysical' and 'social' priorities, so overlapping 'environmental' issues were merged, and 'social' issues were grouped by overarching themes, preserving disciplinary nuance. An AI large language model (ChatGPT) was used to assist the merging and synthesis of the text to avoid bias by the faciliators. The resulting 'biophysical' and 'social' issue statements (ten of each) were then returned to the experts for validation.

The expert response was that social and environmental dimensions were inseparable, particularly where economic structures drive environmental outcomes. A second round of thematic analysis yielded 21 distinct issues, within 17 thematic areas (see Table 1), in an iterative consolidation that resulted in a single integrated category 'Environmental and Socio-economic Issues'. This highlights the importance of qualitative research in critically assessing sustainability categories and re-evaluating conventional classifications.

Then, in collaborative issue development exercises, experts formed issue-specific online working groups, each led by a coordinator tasked with integrating feedback and drafting content. Participants external to each group provided "food-for-thought" comments to help surface unexamined assumptions and foster cross-disciplinary critique, as a way to address potential collective biases and disciplinary blind spots (*198*). Not all issues reflected full consensus, but the process reinforced transparency, methodological flexibility and peer learning. Facilitation emphasized mutual respect, and intellectual openness, allowing resolution of tensions through literature and experiential-informed dialogue. Non-linear, cross-disciplinary interaction beyond the conventional approaches helps to avoid unconscious biases or assumptions common across academic disciplines (*198*).

Table 1: Issues identified by experts

Code	Issue and themes
1	Problem framing: fundamental knowledge gaps related to plastics pollution
2	The colonial legacy of plastics pollution
3	From apex quantitative target to a more holistic policy making
4	Science can be weaponized to delay action
5	Plastics production, fossil fuels and climate change
5.1.	*Plastics and climate change*
5.2.	*Preventing externalities of plastics pollution through reduced and improved production*
5.3.	*The water footprint of petrochemical-based and alternative plastics production processes*
6	Plastics chemical composition: health and hazard impacts
6.1.	*Hazardous composition of plastics and toxicity impacts on the environment and humans*
6.2	*Frontline and fenceline communities' impacts by chemicals from chemical recycling of plastics*
7	Lack of transparency and corporate capture
7.1	*Lack of transparency and access to scientific information*
7.2	*Corporate capture harm on effective measures addressing plastics pollution*
8	Circular economy and the blind focus on recycling
9	Need to address challenges brought by community-level opportunistic uses of plastics waste
10	Social context, recycling and circular economy on the plastic supply chain
11	Unequal access to alternatives to single-use plastics and other non-plastic substitute products
12	Plastics hyper- and overconsumption
13	Prioritising durable materials, products, as well as supportive policies, systems, and technologies for food and water delivery
14	Cross-scale interactions of micro- and nanoplastics
15	Interconnected cumulative effects plastics pollution
16	Plastics pollution is global in scale and not reversible
17	Policy spillovers and policy leakages

Phase 3: Policy framing and collective discussion

This phase focused on identifying drivers, motivations, barriers, and challenges encountered in translating expert knowledge into actionable science-policy guidance. It moved from single-issue identification to actionable multi-issue insights, indicators and strategies relevant for fast-evolving governance such as the Plastics Treaty. Experts co-authored a discussion that contextualizes the findings in the broader literature, and identified key recommendations for science-policy integration. The goal was to enhance our ability to jointly communicate these findings to key stakeholders shaping plastics-related international policy.

EMIKE emerged as a flexible, interdisciplinary method responsive to both epistemic and political dynamics. Its value lies in prioritizing contextual sensitivity, reflexivity, and inclusive engagement, to increase effectiveness of the science-policy interface in response to global sustainability challenges. This research was possible only because the majority of experts are either attending or following very closely the evolution of the Plastics Treaty process. But this also led to a limitation of our online version of EMIKE: it was a logistical challenge to bring together experts from many different time zones for time-intensive activities during a rapidly evolving political process (the Plastics Treaty), which was external to this study and the experts' institutions.

EMIKE can be applied to other complex socio-ecological issues. An ideal format would involve intensive, in-person workshops (e.g., one week workshop), facilitating group work and final team-based synthesis. It is important that participants commit to following collectively agreed instructions, and can participate in the different sequential stages of the process.

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Competing interests:

All authors declare that they have no competing interests.

As information disclosure, with the exception of SC, MM, WC, and YA, all the authors of this paper are part of the Scientists’ Coalition for an Effective Plastics Treaty, actively engaged in the INC process of the Plastics Treaty.

Supplementary Material:

Title: Identifying and overcoming social-ecological barriers to ending plastics pollution

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Table 1: Co-authors list: with information about their field of expertise, geographical homa country and work location, and type of institution

Expert's name	**Field of Expertise**	**Geographical home country and location**	**Institution**
Patricia Villarrubia-Gómez	Natural science, social science, Science-Policy, PB, Environmental global governance, social-ecological systems	Spain, Sweden	Academic
Sarah E. Cornell	Chemistry, environmental global governance, planetary boundaries, science-policy-business interface, social-ecological systems	UK, Sweden	Academic
Bethanie Carney Almroth	Ecotoxicology, exposure chemicals, PB, Science-Policy, global environmental governance	Sweden, US	Academic
Marcus Eriksen	Abundance and distribution of plastics in global environments, national and global environmental governance, civil society	US	Research and advocacy NGO
Trisia Farrelly	Social anthropologist, political ecologist, science-policy interface, national, regional, and global environmental governance, circular economy, systems thinking	Aotearoa New Zealand.	Academic
Tridibesh Dey	Anthropologist, environmental engineer, burning, waste management, remediation and recycling, knowledge systems, cross-scale interactions	India, Netherlands	Academic
Jenna Jambeck	Environmental engineering, plastics in the ocean, waste management, data global modeling, and collectively collecting city-scale data	US	Academic
Sedat Gündoğdu	Marine biology, biodiversity monitoring, transboundary movement of plastics including imports and waste trade, civil society	Türkiye	Academic, NGOs
Yvette Arellano	petrochemical fenceline communities, grassroots environmental and racial justice advocacy, environmental legislation, local, national and global environmental governance	US	Advocacy NGO

Kristian Syberg	social and environmental science, circular economy, microplastics in the ocean, science-policy interface, global environmental governance	Denmark	Academic
Melanie Bergmann	Marine ecologist focusing in polar regions, science-policy interface, global environmental governance	Germany	Academic
Fredric Bauer	Engineer, political economy of the global chemical and plastics industry; Climate change, institution structure, and power and petrochemical industrial barriers to change	Sweden	Academic
Lisa Erdle	Biologist and ecotoxicologist, PhD focus on sources, fates, and pathways, effects and solutions of microfibers, national and global environmental governance, civil society	Canada, US	Research and advocacy NGOs
Mengjiao Wang	Ecotoxicologist, Science-Policy interface; global environmental governance, civil society	China, UK	Academic, and Research and advocacy NGO
Win Cowger	Environmental science, transport and fate of plastics, big data set, national governance, civil society	US	Research NGO
Neil Tangri	Quantitative and statistical analysis • Climate and environmental policy analysis, waste management, science-policy, global environmental governance	US	Academic, research and advocacy NGO
João Frias	Environmental Engineering, Marine biology, Science-policy, marine litter, microplastics, ecotoxicology, stakeholder engagement	Ireland	Academic
Matthew MacLeod	Environmental chemist, persistent chemicals, chemicals degradability of plastics, the chemical-particle interface of plastics.	Canada, Sweden	Academic

Issue Identification Questionnaires for Phase 1

Guidance criteria for identifying social and ecological issues related to plastics pollution:

An example issue statement is provided after this guidance. Please complete the accompanying blank templates with your own two issues, being as specific as possible. For inclusion in this exercise, an issue should meet the following criteria:

- Show evidence of impact of plastics and their chemicals of in terms of the Impact Pathway;

- Indicate impacts, whether positive or negative, of plastics as a global problem;
- Be relevant to the scope and actors of the INC process.
- Each of your statements needs to:
- Be a maximum of 250 words;
- Include a title that encapsulates your issue;
- Summarise the issue - what's causing it, what are its impacts, and what are its implications?;
- Reference as fully as possible using 'footnotes (i.e., academic journals, online news, conference proceedings, blogs, and conversations are all acceptable sources); and
- Define acronyms and use plain English where possible.

When identifying issues, we ask you to:
- Consider all stages of the life cycle of plastics and their applications;
- Consider opportunities – it's not all about risks;
- Consider how alternative approaches, policies, technologies, and societal changes could apply to plastics impacting the environment;
- Consider emerging or unseen issues, especially where the issue is seen differently by policymakers, people working in environmental science and plastics pollution, and other relevant actors.

Note that your Phase 1 issue statements are elicited in your role as an individual expert. Please do not develop statements jointly with other participants of the elicitation process. You are welcome to explore ideas with your colleagues and established networks or solicit perspectives through social media to inform your thinking. However, if you do solicit wider opinions, we ask that you keep a record of these interactions so that we can track and report transparently on the reach of the project. If appropriate, please report what individuals or forums informed your chosen issue for submission so that their specific contribution can be acknowledged if they are happy for this to be done.

To minimize potential unconscious bias, all submissions will be anonymized before circulating for scoring to other participants. The identity of the participant who identified and nominated each issue (and any members of their contributory network, as appropriate) will be revealed at the end of the process. Appropriate acknowledgment will be provided to all contributors in the final reporting and any academic journal articles arising from this process. All participants will be given the opportunity for co-authorship of any journal articles produced.

Table 2. Identification of one Environmental Issue: The definition and use of biophysically defined metrics in global plastics policy

Issue title	
Describe your biophysical issue	
Which stage(s) of the impact pathway does it target, and why?	

Can metrics show if this issue has a positive or negative impact on plastics pollution? What metrics?	
Are any current policy responses relevant to this issue? Where?	
Word count (max 250)	
Your name*	

Table 3: Identification of one social issue: Social contexts and implications of global biophysical metrics in plastics policy

Issue title	
Describe your social issue	
Which stage(s) of the impact pathway does it target, and why?	
What factors are causing this issue to arise?	
How is this social issue related to biophysical definition of planet-level boundaries, goals or targets?	
How does this issue relate to governance at the global level?	
Are any current policy responses relevant to this issue? Where?	
Word count (max 250)	
Your name*	

* All submissions will be anonymised before sharing with other participants to minimise bias. The identity of participants nominating each issue will be revealed at the end of the process.

This guidance has been adapted from the process reported in: Green, C., A. Bilyanska, M. Bradley, J. Dinsdale, L. Hutt, T. Backhaus, F. Boons, D. Bott, C. Collins, S.E. Cornell, M. Craig, M. Depledge, B. Diderich, R. Fuller, T.S. Galloway, G.R. Hutchison, N. Ingrey, A.C. Johnson, R. Kupka, P. Matthiessen, R. Oliver, S. Owen, S. Owens, J. Pickett, S. Robinson, K. Sims, P. Smith, J.P. Sumpter, S. Tretsiakova-McNally, M-J. Wang, T. Welton, K.J. Willis, I. Lynch (2023) A Horizon Scan to support chemical pollution–related policymaking for sustainable and climate-resilient economies. Environmental Toxicology and Chemistry 42, 6: 1212-1228.