Perspective Article: Multisectoral considerations to enable a circular economy for plastics

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Highlights

- Alleviate global threat from plastic pollution through intersectoral collaboration
- Target zero plastic pollution to achieve clear improvements
- Increase simplicity of plastics and associated chemicals during product design
- Precycling: Consider recyclability already in plastic material and product design
- Foster mutual understanding through cross-sectoral dialogue

Keywords

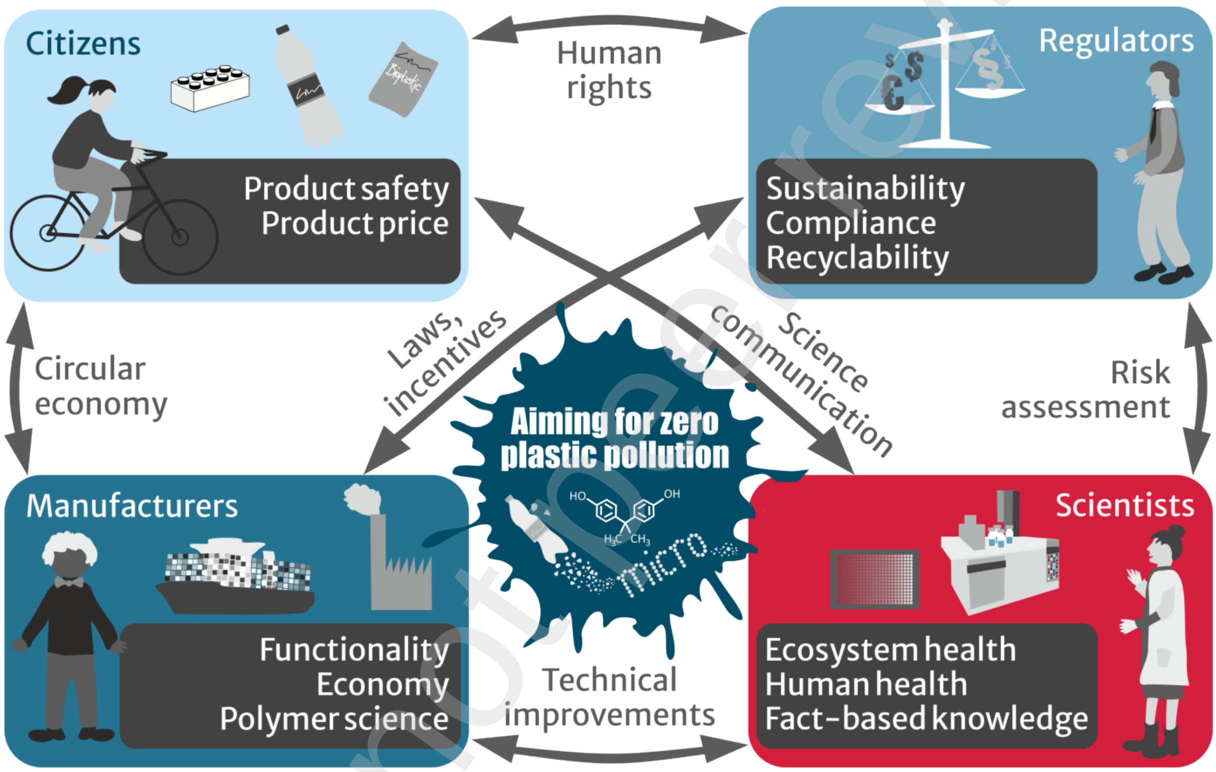
plastic-associated chemicals; leaching; complex mixtures of chemicals; micro- and nanoplastics; recyclability

Abstract

Plastics are widely used but improper disposal and release lead to increasing global pollution, threatening environmental and human health. To address this issue, we suggest intersectoral collaboration to achieve zero plastic pollution. The outcomes of the project P-LEACH demonstrated the enormous complexity and range of potential toxic effects of plastic-associated chemicals and micro-/nanoplastics released into water from UV-weathered plastics. We initiated an intersectoral dialogue amongst scientists, manufacturers, regulators and representatives of

civil society about how to alleviate the negative impacts of plastic pollution. Circular economy offers a framework for selecting against toxic chemicals, extending product (re)use, and waste reduction, which act to alleviate pollution when applied to plastics. We suggest three measures to advance a circular economy of plastics: 1.) Increase simplicity of chemicals in virgin plastics combined with transparent information on the contents; 2.) Consider recyclability already in plastic material and product design; 3.) Foster communication through intersectoral dialogue. Major cornerstones are the provision of standardized, easy-to-use tools to characterize plastic leachates chemically and (eco)toxicologically, the enhancement of citizen awareness enabling them to make informed choices, and the creation of economic incentives for manufacturers to provide products that safeguard environmental and human health.

Graphical abstract



Introduction. Plastics facilitate many aspects of human daily life. However, due to improper disposal, unintentional release or abrasion, plastics are introduced into the global environment. Hence, the ubiquity of plastic pollution and the properties of plastics and associated chemicals, some of which are considered hazardous, have resulted in a global threat to environmental and human health.

The applications of plastics range from simple packaging products with very short life spans, so-called "fast-moving consumer goods", to long-lasting items such as furniture to very specific high-tech plastics used in medical applications or the aviation and aerospace industry. Given the complexity of the material composition, its changing properties during use and in the environment, its global distribution, fate and potential impacts, it becomes clear that multi-dimensional efforts are required to quickly and effectively reduce the possible negative impacts on the environment and human health of plastics and associated chemicals. Correspondingly, we call for dialogue and collaboration across the involved sectors science, industry, regulation and civil society. We initiated cross-sectoral discussions and share the outcomes in this perspective article.

Plastics addressed in this article. The focus of the article is two-fold: First, we address short-lived single-use plastics (SUPs) that make up almost half of the plastic waste (Cowger et al., 2024). Many of these are food contact materials (FCMs) and hence highly regulated in terms of their composition, both for the base polymer and regarding plastic-associated chemicals. Keeping in mind a loss of convenience when replacing SUPs, and the potential negative impacts of their replacements, a substantial reduction is nevertheless needed. Second, we highlight necessary action regarding plastic products that are used for weeks to decades and are less strictly regulated than FCMs, implying higher and less defined chemical loads that are emitted over longer periods.

Plastic definition for this article. The term "plastics" refers to solid synthetic carbon-based polymers, which form a heterogeneous group of materials. Classical thermoplastics, such as polyethylene (PE), polypropylene (PP), poly(ethylene terephthalate) (PET) and polyvinyl chloride (PVC) are used as materials for consumer products and packaging: such polymers shed micro- and nanoplastics (MNPs) (Koelmans et al., 2022) and leach chemicals (Menger, Römerscheid et al., 2024). Our article does not specifically consider plastic materials of "essential use", such as for medical care, to be defined by an intergovernmental conference of parties during the implementation of the upcoming UNEP Global Plastics Treaty.

Plastics become plastic pollution. Polymers are widely considered to be inert materials with a low biological reactivity, but they contain a variety of plastic-associated chemicals (Groh et al., 2019; Wiesinger et al., 2021). According to the polymer and intended use, plastics are amended with chemical additives to ensure desired properties during processing, shelf-life and use, and additional chemicals occur as impurities or are added during processing (Wagner et al., 2024). Such chemicals are not covalently bound in the polymer backbone, leach out of the polymer matrix over time and may interact with either different environmental compartments (air, water, soil) or biological systems. Due to their widespread and increasing use (Borrelle et al., 2020; Lau et al., 2020), plastics and associated chemicals have been reported to enter a broad variety of environmental compartments in urban, rural and remote terrestrial, aquatic, and atmospheric environments, and they also find their way into the human body (Thompson et al., 2024).

In the environment, plastics undergo long-range transport like other pollutants and are subject to physical and/or chemical aging and weathering over time. The main aging factors include oxidation, UV irradiation, mechanical stress, temperature fluctuations, hydrolysis and biodegradation (Jahnke et al., 2017; Arp et al., 2021). These processes make the plastics brittle, foster shedding of MNPs and decrease their size, accelerating leaching of chemicals and further mechanical degradation. Plastics from macro to nano size ranges accumulate even at remote locations (MacLeod et al., 2021) where the plastics, shedding MNPs and leaching chemicals, can impact ecosystems, local communities and economies.

MNP properties and impacts. As for other particles, the physico-chemical properties of MNPs, especially the particle size but also their geometry and surface characteristics (Ramsperger et al., 2023), govern their ability to cross biological barriers. Many particles are too large for cellular uptake, but cell-particle interactions can lead to adverse effects, and particles in the low micro- or nanometer range can potentially cross membrane barriers and get into systemic circulation. This process has been suggested to apply to both, inhalative and oral uptake (Borgatta and Breider, 2024; EFSA, 2016). In theory, such particles can reach secondary organs and may accumulate there, potentially creating inflammatory response and acting as a reservoir for the release of plastic-associated chemicals.

Plastic particles can also carry environmental contaminants, but have been estimated to, e.g., increase bioaccumulation only by a minor share (Koelmans et al., 2016). Similarly, an EFSA calculation (EFSA, 2016) postulates that the contribution of MNP-bound chemicals to exposure is very low compared to the overall exposure to the chemicals from all pathways. The release of chemicals from particles depends on the polymer type, the chemical, the surrounding medium and other factors such as size and geometry. Furthermore, these partitioning processes in the human body are not yet understood. To date, no mechanisms have been proven that give a causal relationship for MNPs with harmful effects on human health. However, some adverse effects are conceivable, e.g., acute inflammatory or immunological effects (Paul et al., 2020; Thompson et al., 2024), and potential chronic effects are under evaluation.

Plastic-associated chemicals. Contrary to MNPs, the fate and potential effects of plastic-associated chemicals released to their surroundings ("plastic leachates") have so far been largely overlooked (Arp et al., 2021; Logan et al., 2024; MacLeod et al., 2021). Overall, more than 16,000 chemicals can be associated with plastics (Wagner et al., 2024), and hazard information is only available for a minor share of them. For plastic-associated chemicals with known hazards the main question is whether their leaching from the particles makes them bioavailable, potentially adding to exposure from other sources and thus, jointly trigger harmful effects. Therefore, the Helmholtz Innovation Pool Project P-LEACH (P-LEACH, 2025) focused on mixtures of chemicals leached from weathering plastics into aqueous media, their fate and potential impacts on ecosystems and human health.

Complexity beyond expectation. The outcomes of our research demonstrated that the leachates were of huge complexity (Menger, Römerscheid et al., 2024), and our comprehensive chemical analytical toolbox is still unlikely to capture all components. We also observed that organisms were severely impacted by high concentrations of leachates obtained from consumer products made for outdoor use (Bedulina et al., 2024a). This result is in accordance with a study showing that an in-depth characterization of consumer plastics such as PET bottles revealed polymer- and chemical-specific effects on a freshwater mussel (Brehm et al., 2022). These insights demonstrate that cross-sectoral dialogue is a helpful way to better understand these ubiquitous materials, to comprehensively characterize them chemically and (eco)toxicologically and to develop safe(r) alternatives.

Multisectoral collaboration. Zero plastic pollution is a very ambitious target, but needed in order to achieve comprehensive improvements quickly. It requires, among other things, multisectoral awareness, understanding structures that maintain the status quo, and addressing scientific challenges stemming from the vastly diverse compositions and physico-chemical and toxicological properties of plastics and associated chemicals. Cross-sectoral collaboration is key to better understand characteristics and hazards as a basis for improved transparency, ultimately helping to reduce the complexity of plastics and associated chemicals to a manageable level (Brander et al., 2024; Carney Almroth et al., 2025). Our team comprises scientists, regulators, manufacturers and a non-governmental organization (NGO) representing civil society to ensure diverse perspectives on the complexity of plastics and associated chemicals.

We identified three major challenges as discussed in the following subchapters together with suggested solutions. Circular economy offers a framework for selecting against toxic chemicals, extending product (re)use, and waste reduction, which all act to alleviate pollution when applied to plastics. This perspective article aims to inspire colleagues across disciplines and sectors to help shape solutions for developing a circular economy for plastics, as discussed in the following three subchapters: (1.) increasing the simplicity of plastic materials including their associated chemicals and the related testing based on P-LEACH results; (2.) the need for consideration of P-LEACH results to enable recyclability in plastic material and product design; and (3.) fostering communication across stakeholder groups to jointly find and implement solutions.

1. Increasing the simplicity of plastic materials, including their associated chemicals and the related testing based on P-LEACH results. Plastic products in many cases consist of combined materials of two or more polymers. Base polymers are mixed with chemicals such as functional additives and processing aids, which can range from <1 wt. % (e.g., stabilizers, pigments), over 1-30 wt. % (e.g., fillers, processing aids) up to >50 wt. % (e.g., plasticizers in PVC) of the product mass. With regard to proprietary formulations, more than 200,000 different polymer materials are annually produced in Europe alone (UNEP, 2023). Among the 16,000 chemicals potentially present in plastics (Wagner et al., 2024), a major share is related to non-intentionally added substances (NIAS), such as degradation products from plastic processing (e.g., un-/depolymerized monomers, residues of polymerization catalysts) or use (e.g., transformation products of additives and oxidized polymers). In P-LEACH, we developed an extensive chemical analytical toolbox to characterize the complex mixtures of chemicals and MNPs leached from consumer plastics (Menger, Römerscheid et al., 2024) and a related (eco)toxicological toolbox to assess mixture effects is being finalized. The complex composition of a plastic product is increased further if it is made from recyclates from mixed (waste) sources (Carmona et al., 2023).

Transparency on composition. We encourage the polymer-producing industry and manufacturers of plastic products to provide more transparency regarding the composition of the materials and products including intentionally added chemicals and known degradation products from the manufacturing process, as substantial product modification occurs during further processing of the base polymers to become products. Importantly, chemicals known to be hazardous should be replaced by alternatives with lower or no known hazard. Even if current exposure to single compounds may not exceed acute effect thresholds, chronic effects, mixture effects and potentially higher exposure under continuously increasing production and emissions have to be considered. Overall, such intentionally added chemicals need to be reduced in diversity and quantity, and providing safe products can be a competitive advantage. In most settings to date, trade secrets prevail, but voluntary self-commitments exist as in the CosPaTox project (Cospatox, 2024) focusing on the safe use of post-consumer plastic recyclates in cosmetic packaging. Regulators should require the disclosure of the product composition from manufacturers, possibly extending to all products entering the market, such as in the European Union (EU) Chemicals Regulation (registration, evaluation, authorization and restriction of chemicals, REACH). Within the EU, a promising tool to enhance transparency on products may be the Digital Product Passport (DPP) initiative (EU, 2024). Any provided information should be transparent, consistent, reliable, comprehensible and accessible. Scientists should provide more information, education and scientifically proven evidence with respect to consumer plastics to contribute to raising awareness on materials and products that are non-toxic for environmental and human health, hence enabling informed choices.

Recycling and waste management. Detailed knowledge of the composition of plastics is also crucial to enable recycling and proper waste handling. For certain groups of products, such as FCMs, there are strict criteria to be fulfilled, at least for regional markets such as the EU (EU, 2004). However, usually merely the identity of the polymer is indicated whereas the composition of the functional additives and other chemicals is often reported as "confidential business information" (Wiesinger et al., 2021). Due to this lack of transparency, additives are rarely included into life cycle assessments or labeling of plastics, which results in incomplete assessments of product safety, recyclability and environmental impacts (Logan et al., 2024).

Understanding leaching and toxicity. Scientists are encouraged to provide standardized, easy-to-use combined chemical and (eco)toxicological test protocols for improved characterization of leachates from plastics of unknown composition and the mixture effects of known and unknown components. The published and upcoming chemical-analytical screening (targeted, screening and non-targeted organic chemical and metal(loid) fingerprinting (Menger, Römerscheid et al., 2024), and bioanalytical profiling using cells (Rummel et al., 2019) and organisms (Bedulina, Korez Lupše et al., 2024b; Rummel et al., 2022) are promising to identify exposure and hazards more effectively and may provide suitable starting points, in particular considering aging processes (Lukas et al., 2024). Our findings highlight the need for new approach methodologies (NAMs, Sewell et al., 2024) and strategies to more accurately and comprehensively assess the potential hazards of leached plastic-associated chemicals. These new strategies could be promising to assess impacts throughout the entire life cycle on realistic conditions of plastic production, usage, and disposal. A tiered (eco)toxicological approach could cover (i) harmonized and standardized extraction or leaching (considering relevant sizes and geometries of tested materials), (ii) harmonized and standardized *in vitro* testing for baseline toxicity and specific modes of action; and (iii) acceptance of the tested batch in case of conformity vs. harmonized/standardized *in vivo* testing for batches that were problematic. It could help characterize chemicals that have leached from plastics and prioritize potential risk driver chemicals for (functional) substitution (Tickner et al., 2015).

Reference materials. The P-LEACH pilot studies gave valuable insights into custom-made plastics covering various economically important polymers with typically used additives and real-world plastics from different application areas (Bedulina, Korez Lupše et al., 2024b; Menger, Römerscheid et al., 2024). The scientific literature additionally covers testing of FCMs of unknown composition (Stevens et al., 2024; Zimmermann et al., 2021; Zimmermann et al., 2019). The use of custom-made plastics of known composition was a helpful approach in P-LEACH, and having well characterized reference materials can greatly facilitate the development of new testing protocols. Such standardized reference materials should encompass both cases; materials with effects and hazards as well as materials explicitly not showing those. Such materials are mandatory to ensure traceability and comparability of results.

Modeling enables extrapolation. While our current methodologies rely on advanced chemical and bioanalytical screening, the integration of modeling represents a critical next step for comprehensive risk assessment. Predictive models are trained by parameters such as polymer composition, additive profiles, physico-chemical properties (Nabi et al., 2024), and degradation kinetics. These models can simulate the leaching and transformation of known plastic-associated chemicals under various conditions in the environment and potentially within organisms. Other approaches for non-targeted data that enable toxicity prediction of unknowns are available (Peets et al., 2024; Rahu et al., 2024). Coupling experimental data with robust modeling frameworks helps to better predict and understand the fate and behavior of plastics and associated chemicals throughout their life cycle, thereby enhancing the overall ability to forecast properties, behaviour and potential risks to both environmental and human health. This approach could potentially reduce the testing efforts for complex recycled materials. We therefore advocate for increased interdisciplinary and transdisciplinary efforts to merge experimental findings with modeling approaches.

Recommendations. The combined insights generated from chemical analytical, bioanalytical and modeling tools can improve mechanistic understanding and pave the way for more informed decision-making in terms of plastics design and management. The P-LEACH results underline that plastic-associated chemicals must be reduced in diversity and quantity to provide safe(r) products, non-toxic recyclates and hence a better circular economy of plastics. Safety of constituents needs to be periodically revisited in collaboration between industry, regulatory bodies and science, to consider the most recent state-of-knowledge and prevent regrettable substitutions. Solutions to harmonize, simplify and increase transparency on compositions must be found, e.g., by developing customized plastics with known composition for specific applications. Moreover, these measures should be combined with a step-by-step substitution by promising new materials and alternatives as a strong measure to reduce emissions and exposure.

2. The need for consideration of P-LEACH results to enable recyclability in plastic material and product design. P-LEACH demonstrated the complexity and potentially hazardous properties of plastic leachates, underlining the importance of appropriate material and product design. At present, the majority of plastic waste in the European Union still goes to energy recovery (i.e., incineration) or landfill, whereas only 40% of the plastic packaging waste are recycled (Eurostat, 2025). Large-scale plastic recycling is currently only possible and meaningful for products that (i) are collected in highly pure waste streams (e.g., PET bottles); (ii) include mass-produced plastics (e.g., PE, PP); (iii) end in a known material quality; and (iv) have market value as recyclates. However, most of the current approaches unavoidably result in lower qualities, known as “downcycling”.

Benefits of labeling. The demand for more visually appealing, robust and functional packaging (e.g., forming better barriers) leads manufacturers to combine different plastics in one type of packaging with protected design (Trinh et al., 2023). The REACH framework requires disclosure of information on composition and hazards. Polymers are currently exempt from registration but activities are underway for them to be included (“Polymers requiring registration”, ECHA (2023)). Similarly, the Classification, Labelling and Packaging (CLP) Regulation does not extend to plastic composition. To date, plastic products rarely provide information on their composition beyond the polymer type which is shown as a permanent “Resin Identification Code” imprint or label. Our work in P-LEACH has shown limited reliability of labeling for the assessed consumer plastics, with 4 out of 8 consumer products not labelled correctly (Menger, Römerscheid et al., 2024). Standardized, comprehensive labeling and traceability has high potential to further improve plastic waste management, recyclability, and risk assessment (Burrows et al., 2022).

Barriers to recycling. Recycling plays a crucial role in paving the way to a sustainable circular economy for plastics. Hence, it is key that plastics are given a value that goes far beyond single-use. The recycling of plastics is complex and comprises several critical challenges that need to be addressed in order to substantially increase recycling rates. Specific challenges that P-LEACH results highlighted include (i) Diversity: the vast diversity of plastics and associated chemicals imply variable composition and properties, posing challenges for separation and processing; (ii) Design: many plastic products are designed in a way that they are difficult or impossible to recycle, e.g., composite materials of thin plastic films that are irreversibly fused.

Increasing recycling rates. One local success story is that of PET bottles in Germany, which are almost quantitatively recovered, shredded and submitted to recycling. Such local cases need to be extended to regional, continental and global levels, stressing the importance of agreements like the UNEP Global Plastics Treaty on measures to enable comprehensively and ambitiously solving a transboundary issue (Brander et al., 2024) which affects the triple planetary crisis involving pollution, climate change and biodiversity loss (Schmidt, Kühnel, Materić et al., 2024), the resource crisis and other major earth system processes (Villarrubia-Gómez et al., 2024).

We cannot recycle ourselves out of the problem. Recycling contributes towards achieving a circular economy of plastics, but it is only the third level of the waste hierarchy, as prevention and re-use are much more efficient in energy and resource use. As an example, the German chemical industry's direct energy requirements are immense. It uses petroleum-based raw materials, e.g. natural gas, not only to generate energy, but also as a feedstock for virgin plastics. In 2020, the chemical industry in Germany consumed a total of 383 billion kWh (1379 PJ) (BUND, 2023). This resource and energy demand is used for chemicals, in particular feedstocks for plastics production and fertilizers and is equivalent to the combined energy consumption of Denmark and Ireland. One fifth of that demand alone accounts for the production of disposable packaging. Circular economy faces many challenges, as every recycling rate comes with an irrecoverable material loss (Lehmann et al., 2022). Furthermore, renewable energy supply and storage will also be limited, therefore products should be used for as long as possible (Villarrubia-Gómez et al., 2024) which should be targeted during product design.

Plastic waste streams. Plastic waste is a commonly shipped material stream. As an example, in Europe, half of the plastic waste is transported across country borders (Baran, 2023). The transboundary waste flow poses both a challenge and an opportunity. The channeling of waste streams into larger input streams enables more specialized recycling facilities but requires high degrees of traceability and monitoring to exclude unsuitable materials. Transboundary waste treatment should be limited to cases where harmonized and enforceable regulations are in place for all participants. In the EU, existing regulations for waste shipment need to be enforced and expanded to avoid shifting the burden of hazardous waste to regions with weaker policies and inadequate waste management infrastructures (Wang et al., 2022).

Recommendations. The recyclability of plastic products can be improved through various measures that include collection practices, sorting and recycling technology and the recycling processes themselves. The P-LEACH outcomes support the potential of the following measures: Material selection: (i) high-purity raw polymers with known, fewer and less hazardous additivities for safer products; (ii) further incentives to prefer recyclable polymers with a minimum of defined, known additives; Product design: (i) design products for long-term use; (ii) simple design with few components and simple shapes enabling disassembling and recycling; (iii) favor separable components; (iv) minimized use of coatings, prints and paints; (v) orientation on existing regulation, such as the German Packaging Ordinance, may help ensure that manufacturers of poorly recyclable products share the costs of their management; Legal framework conditions: (i) fulfill the demand for good quality recyclates by improving recycling technology; (ii) apply Extended Producer and Processor Responsibility (EP&PR); (iii) define standards for the use of recyclates in various applications supported by practical procedures for testing and documentation.

3. Fostering communication across stakeholder groups to find joint solutions based on P-LEACH experience. We acknowledge that scientists have to communicate key findings more directly, in accessible language, at eye level and in an appropriate format to all other stakeholder groups. Over the course of P-LEACH, we designed custom-made plastics for our experiments together with a plastic manufacturer, to improve our understanding of the chemicals leaching into water with well-defined materials before working with complex consumer plastics of unknown composition. The cross-sectoral dialogue during a focused P-LEACH stakeholder workshop proved very helpful, and a more regular exchange across the groups of scientists from different disciplines (including analytical and environmental chemists, (eco)toxicologists, polymer scientists, process engineers), regulators, industry representatives (including engineering, legal and marketing experts) and members of civil society is strongly encouraged.

Commonalities and differences. Fundamental differences of values between the stakeholder groups exist as each group has distinct perspectives on plastic materials and products. Citizens demand safe, yet inexpensive and convenient products, industry and manufacturers focus on product performance, functionality and economic aspects, regulators aim to ensure compliance with legal frameworks, sustainability, recyclability and standardized tests whereas scientists focus on fact-based knowledge from exposure, fate and hazard assessment (Graphical abstract). These distinct values combined with different terminologies and siloed language have to date largely limited communication across stakeholder groups. The joint search for ambitious yet feasible and implementable cross-sectoral approaches and solutions is urgently needed to limit the negative impacts of plastics and associated chemicals on human health, global ecosystems and planetary processes (Li et al., 2023; Schmidt, Kühnel, Materić et al., 2024; Villarrubia-Gómez et al., 2024). However, it requires all stakeholder groups to leave their comfort zone of internal discussions, and it must be recognized that such interaction requires time, effort, future- and solution-oriented thinking and mutual interest in combatting the climate, resource, health and biodiversity crises.

Enabling informed decisions. Manufacturers should use safe materials, support long-term use, provide recyclable products with known composition to the greatest possible extent and ideally take back/reuse their own packaging or be directly involved in their recycling. Recycling processes and technologies must be improved and further developed. Regulators should facilitate such transition. Citizens should be better informed about the importance of reducing the use of plastics despite loss of convenience, due to their complex composition and the associated potential threat that liberated MNPs and leached chemicals can pose to ecosystems and human health. Re-use and unpackaged goods must be affordable and accessible, which is mostly the responsibility of companies. To allow informed choices, better education about issues such as exposure from, e.g., indoor materials like kitchenware (Yadav et al., 2023), food preparation practices (Hernandez et al., 2019; Hussain et al., 2023) and textiles (Thompson et al., 2024), considering the specific vulnerability of certain population groups is important.

Fostering behavioral changes. Combined with available, practical and economically viable alternatives including necessary information, citizens should be encouraged to change their habits to contribute to a reduction of unnecessary SUPs (e.g., packaging), to consider sustainable alternatives, and to be involved in, e.g., the presorting of plastic waste into suitable containers. Preferable alternatives suggested by circular economy principles, e.g., refill and re-use options, should be advanced, as well as information about the benefits of safe recycled materials. Certain consumers may be (and are already) willing to pay more for products that fulfill higher standards, and improved knowledge will drive demand for such materials, providing key incentives to industry.

Overarching recommendations and concluding remarks. We acknowledge that the challenges in managing plastics and plastic waste are complex and multidisciplinary. However, in P-LEACH we have identified specific solutions visualized in Figure 1 and detailed in Table 1 that may help in the transition towards a more sustainable production, use and management of plastics to safeguard environmental and human health.

Figure 1. To alleviate the global threat from plastic pollution we suggest to aim for zero plastic pollution, by focusing on: (1.) increasing simplicity of plastics and associated chemicals based on P-LEACH results; (2.) the need for consideration of P-LEACH results to enable recyclability in plastic material and product design; by (3.) fostering communication across stakeholder groups to jointly find solutions.

Table 1. According to the three main topics, we suggest solutions to facilitate a transition to a circular economy for plastics and associated chemicals, based on P-LEACH research and multisectoral dialogue. The left column gives the main actors (and supporting sectors).

Increasing the simplicity of plastic materials, including associated chemicals and related testing	
Industry (scientists, regulators)	Replacement of hazardous components with safe(r) alternatives to maintain functionality at lower exposure risk, including regular updates
Scientists, industry	Stronger focus on safe(r) functional substitutions, considering rather the required functions than the risks of a particular material
Industry	Reduced chemical complexity, e.g., by development of plastics with standardized quality for major products and applications, by fundamental reduction of the diversity and quantity of additives
Manufacturers (regulators)	Transparent labeling of the composition of plastic products (polymers and additives), as a prerequisite for recycling and waste handling; authorizing certain additives and their concentrations for specific use categories (such as PET bottles)
Scientists (regulators, manufacturers)	Establishment of harmonized and standardized chemical analytical and (eco)toxicological tests throughout the plastics life cycle to facilitate exposure and hazard assessment; facilitate compliance testing
Scientists	Expansion of the FAIR (findable, accessible, interoperable, reusable) data and knowledge base on hazards of plastic-associated chemicals towards humans, wildlife and the environment
Regulators	Define “essential use” for plastics, in particular in closed settings of fundamental importance (e.g., healthcare); demand of separate, specific recycling workflows; accounting for negative externalities, coupled with courageous interventions that correct market failures
Civil society, citizens	Increase acceptance and demand for simplified, less complex plastic products and thus incentivize producers
all	Replacement of non-essential products of plastics by alternative materials, considering their whole life cycle to avoid regrettable substitutions
Enabling recyclability in plastic material and product design	

Industry (regulators)	Reduced production of virgin, petroleum-based plastics, especially for SUPs; supported by tightening the SUP directive; increase efforts to achieve standardized recyclate qualities with performance requirements
Manufacturers	Precycling: Product design putting high priority on recyclability; transparent information on composition of plastic products and recyclates
Regulators	Providing more incentives on using recyclates for new products, including lowered costs relative to virgin plastics
Manufacturers, regulators	Life cycle analysis for new products covering ressource extraction, production, use, disposal and recycling
Fostering communication across stakeholder groups to find joint solutions	
Scientists	Making key research results available in an accessible form and language for non-scientific audiences, e.g., through social media
Scientists, manufacturers, regulators	Translation of key research results into practice going beyond mere problem description to development of solutions; promote safe(r) materials and products
Manufacturers (civil society, citizens)	Clear and consistent labeling of safe(r) products to enable informed choices
Scientists	Specific outreach to consumers to increase the overall demand for safe products
Scientists, civil society	Information on secondary costs of certain materials or products, e.g., related to (fossil) resource use, management, climate change, impacts on ecosystems and human health to enable informed choices and decisions
all	Cross-sectoral communication and binding coordination globally to overcome injustice related to plastic waste management and related impacts

Overall, closer cooperation between scientists, polymer-producing industry, manufacturers of plastic products, regulators across geographical scales and citizens could help humanity overcome the diverse challenges posed by the complexity of plastics and associated chemicals. Only together can we develop concrete overarching action plans and solutions to support the ambitious goal of zero plastic pollution. These joint efforts will help to develop sustainable solutions that enable a safe, environmentally friendly, sustainable and profitable circular economy for plastics and associated chemicals.

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CRediT authorship contribution statement

AJ, DB, OK, MR, DK: Conceptualization; AJ: Visualization; AJ, GG: Project administration; AJ, AJB, DB, LH, HJ, OK, GL, HAL, FM, MR, MSJ, KW-P, DK: Writing - Original Draft; all authors contributed to Writing - Review & Editing and approved the final manuscript before submission.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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