

State of the **Science** on **Plastic** **Chemicals**

Identifying and addressing chemicals
and polymers of concern

www.plastchem-project.org

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EXECUTIVE SUMMARY

The chemical dimension of plastics

Chemicals are an essential feature of all plastic materials and products and are key for delivering their benefits. Yet, plastic chemicals raise significant environmental and health concerns. The diversity of plastic chemicals as well as their problematic properties necessitate a comprehensive analysis to protect human health and the environment across the life cycle of plastics. The PlastChem report “State-of-the-science on plastic chemicals” provides a thorough and comprehensive overview of the current scientific understanding of the chemical dimension of plastics, including the hazards, functionalities, uses, production volumes, and regulatory status of plastic chemicals.

Why do plastic chemicals matter?

The global plastics industry utilizes a vast array of chemicals, many of which have been shown to contaminate the environment and cause adverse impacts on wildlife, humans, and ecosystems (see [Part I](#)). Many other plastic chemicals remain inadequately studied. The known adverse impacts, combined with data gaps and fragmented scientific knowledge, present a formidable obstacle to managing the risks posed by exposure to chemicals across the life cycle of plastics. In addition, this also prevents a transition towards a non-toxic future by impeding innovation into safer and more sustainable materials and products.

What is known about plastic chemicals?

The state-of-the-science report synthesizes the evidence on more than 16 000 chemicals potentially used or present in plastic materials and products. A mere 6% of these chemicals are currently subject to international regulation, although a much higher number are produced in high volumes and possess a high potential for exposure (see [Part II](#)).

More than 4200 plastic chemicals are of concern because they are persistent, bioaccumulative, mobile, and/or toxic (PBMT). Over 1300 chemicals of concern are known to be marketed for use in plastics and 29–66% of the chemicals used or found in well-studied plastic types are of concern. This means that chemicals of concern can be present in all plastics types (see [Part III](#)).

The 4 PBMT hazard criteria

Persistence: long-term presence of a chemical in air, water, soil, or organism

Mobility: the potential of a chemical to spread in fresh- and drinking water systems

Bioaccumulation: the potential of a chemical to stay and accumulate in wildlife and humans

Toxicity: the potential of a chemical to cause harm to living organisms

The report also reveals striking data gaps: Over a quarter of known plastic chemicals lack basic information on their identity, and more than half have ambiguous or missing information on their functions and applications in the public domain. What is more, production volume data are not globally representative and restricted to certain countries (see [Part II](#)).

Importantly, hazard information is lacking for over 10 000 chemicals although such information is essential for ensuring proper assessment and management of these chemicals (see [Part III](#)). This underscores the need for more transparent information on plastic chemicals’ identities, hazards, functionalities, production volumes, and their presence in plastics.

Which plastic chemicals matter most?

The report outlines a systematic approach to identify and prioritize chemicals of concern, employing a hazard- and group-based framework centered on four critical hazard criteria (PBMT). This method enables an efficient identification of chemicals requiring further policy action. Adopting such an approach also resolves the major challenges associated with the risk assessment of 16 000+ plastic chemicals, including immense resource requirements, investments, and technical challenges for establishing robust exposure information (i.e., levels of plastic chemicals in the environment, wildlife, and humans).

Applying a stringent and comprehensive hazard- and group-based approach, the report identifies 15 priority groups and over 4200 plastic chemicals of concern, of which ca. 3600 are currently not regulated globally. It also provides additional strategies to further prioritize plastic chemicals for policy action and highlights approaches to identify polymers of concern (see [Part III](#)).

How can this evidence be translated into policy?

The 15 priority groups of concern

- | | |
|---------------------|--|
| » Aromatic amines | » Organometallics |
| » Aralkyl aldehydes | » Parabens |
| » Alkylphenols | » Azodyes |
| » Salicylate esters | » Aceto/benzophenones |
| » Aromatic ethers | » Chlorinated paraffins |
| » Bisphenols | » Per- and polyfluoroalkyl substances (PFAS) |
| » Phthalates | |
| » Benzothiazoles | |

Recommendation 1: Regulate plastic chemicals comprehensively and efficiently

The vast number and multiple known hazards require new approaches to address plastic chemicals comprehensively and efficiently. This can be achieved by implementing a hazard- and group-based approach to identify plastic chemicals of concern. Such a strategy is crucial to overcome the limitations of current assessment systems and foster innovation towards safer plastic chemicals. Accordingly, policymakers should adopt the PBMT criteria and prioritize the 15 groups and 3600 chemicals of concern for regulation, because they are currently not regulated on a global level.

Recommendation 2: Require transparency on plastic chemicals

Increased transparency on the chemical composition of plastics is essential for closing data gaps, promoting a comprehensive management of plastic chemicals, and creating accountability across plastic value chains. A unified reporting, disclosure of the chemical composition of plastic materials and products as well as a “no data, no market” approach are recommended to ensure that essential information about plastic chemicals becomes publicly available. This serves the dual purpose of facilitating safety assessments and the development of safer plastics.

Recommendation 3: Simplify plastics towards safety and sustainability

The many plastic chemicals on the market often serve similar and sometimes non-essential functions. This complexity and redundancy represent a major barrier for governance and circular economy. The concept of chemical simplification offers a means for reducing the impacts of plastics by charting a pro-innovation and evidence-based path forward. Simplification can be achieved by promoting policies that encourage the use of fewer and safer chemicals, and by adopting essential-use and safe-by-design concepts to guide innovation.

Recommendation 4: Build capacity to create safer and more sustainable plastics

To effectively manage plastic chemicals and foster innovation towards safe and sustainable plastics, technical, institutional, and communication capacity should be built in public and private sectors. This involves fostering global knowledge exchanges, providing equal access to technical capabilities, and enhancing institutional resources for an effective management of plastic chemicals. Through the

establishment of a knowledge sharing platform, international cooperation and resource allocation, the report encourages a collective effort to develop shared solutions, ensuring that knowledge, technology, and infrastructure are available in an open, fair, and equitable manner.

16 000+ known plastic chemicals
<6% currently subject to global regulation
3600+ unregulated plastic chemicals of concern

66% of plastic chemicals without hazard information
60% without information on use or presence

Chemical complexity prevents effective governance and circularity
Additional chemicals probably widespread in all plastics

Lack of technical and regulatory capacity prevents addressing chemicals of concern and innovation of safe and sustainable plastics

1

Regulate plastic chemicals comprehensively and efficiently

2

Require transparency on plastic chemicals

3

Simplify plastics towards safety and sustainability

4

Build capacity to create safer and more sustainable plastics

What are the positive impacts of addressing plastic chemicals?

Addressing plastic chemicals and polymers of concern comprehensively is expected to result in substantial benefits for the environment and human health, promote innovation into safer plastic chemicals, material, and products as well as support a transition to a non-toxic, circular economy. The proposed approaches to plastic chemicals and polymers are anticipated to reconcile the state of the science with policy and regulatory frameworks, thereby facilitating informed decision-making and responsible innovation across sectors.

Since no country has the capacity to address the transboundary issue of plastic chemicals and polymers individually, the state of the science implies that a collective global response is most appropriate to mitigate environmental and health impacts. Adopting evidence-based policies that prioritize chemical safety and sustainability will provide a pathway towards a safe and sustainable future.

The PlastChem Database. The report is accompanied by a consistent and comprehensive compilation of information on known plastic chemicals from various sources. This information is made publicly available in the [PlastChem database](#).

TABLE OF CONTENTS

7	OVERVIEW OF THE STATE-OF-THE-SCIENCE REPORT	
8	KEY TERMS AND CONCEPTS	
PART I: WHY DO PLASTIC CHEMICALS MATTER?		10
11	PURPOSE AND SCOPE OF THE STATE-OF-THE-SCIENCE REPORT	
13	BACKGROUND: THE CHEMICAL DIMENSION OF PLASTICS	
19	REGULATION OF PLASTIC CHEMICALS	
21	PREVIOUS REPORTS PERTINENT TO PLASTIC CHEMICALS	
22	IMPORTANT ASPECTS THIS REPORT ADDRESSES	
PART II: WHAT IS KNOWN ABOUT PLASTIC CHEMICALS?		23
24	KEY FINDINGS	
25	GENERAL APPROACH TO SYNTHESIZE THE STATE OF THE SCIENCE	
26	THE UNIVERSE OF PLASTIC CHEMICALS	
31	STATE OF REGULATION	
32	USE, PRESENCE, AND RELEASE OF CHEMICALS FROM PLASTICS	
35	METHODOLOGY	
PART III: WHICH PLASTIC CHEMICALS MATTER THE MOST?		37
38	KEY FINDINGS	
39	APPROACH TO IDENTIFY PLASTIC CHEMICALS OF CONCERN	
40	OVERVIEW OF PLASTIC CHEMICALS OF CONCERN	
45	PRIORITY PLASTIC CHEMICALS	
47	SCENARIOS FOR FURTHER PRIORITIZING CHEMICALS OF CONCERN	
55	PRIORITY GROUPS OF CHEMICALS	
58	LINKING CHEMICALS OF CONCERN TO POLYMER TYPES	
62	APPROACHES TO IDENTIFY POLYMERS OF CONCERN	
72	METHODOLOGY	
PART IV: HOW TO TRANSLATE EVIDENCE TO POLICY?		75
76	KEY ASPECTS	
77	POLICY PRINCIPLES	
79	POLICY RECOMMENDATIONS	
89	ABOUT THIS REPORT	
90	ABOUT THE AUTHORS	
91	ACKNOWLEDGEMENTS	
92	REFERENCES	
PART V: ANNEX		106

OVERVIEW OF THE STATE-OF-THE-SCIENCE REPORT

PART I

Why do plastic chemicals matter?
Setting the scene

Readers wanting to better understand the chemical dimension of plastics and its link to human health and the environment

PART II

What is known about plastic chemicals?
Findings from the state of the science

Readers wanting to learn about the evidence on the numbers, function, and groups of plastic chemicals, including their regulation and use in plastics

PART III

Which plastic chemicals matter most?
Assessment of chemicals and polymers of concern

Readers interested in which chemicals of concern are known and how chemicals and polymers of concern can be prioritized

PART IV

How to translate evidence to policy?
Recommendations to address plastic chemicals and polymers

Readers wanting to know which political measures can be taken to tackle the issue of plastic chemicals

PART V

Annex
Glossary, methodology, detailed findings

Readers wanting to get in-depth insights in how the evidence for the state of the science report was gathered and assessed

KEY TERMS AND CONCEPTS

Life cycle of plastics: The full life cycle of plastics begins with the extraction of fossil or bio-based feedstocks that are transformed to starting substances, including monomers, catalysts, and processing aids. These are processed into polymers to form plastic materials by mixing additives and processing aids that are further converted into plastic products. Following initial use, the life cycle continues either circularly in the case of reuse, remanufacturing, and recycling, or linearly with end-of-life options, such as energy recovery or disposal. Throughout the life cycle, chemicals are intentionally or unintentionally added to and emitted from plastics.

Plastic chemicals: All plastics consist of chemicals. Accordingly, the term encapsulates all chemicals present in plastic materials and products (Figure 1). This includes the polymer backbone forming the bulk material as well as intentionally added substances, including processing aids and additives. Importantly, non-intentionally added substances (NIAS), such as impurities, reaction by-products, and degradation products, are also plastic chemicals. Contaminants sorbing to plastics during the use and end-of-life phase are not considered plastic chemicals.

Polymers: Polymers are macromolecules made from repeating monomer units. Plastic polymers are specific types of polymers, forming the bulk plastic material, such as polypropylene, which refers to the macromolecule itself. However, in a wider context, the term is often used to encompass materials or products containing the plastic polymer as the main component, along with other plastic chemicals. The report adopts this broader interpretation.

Chemicals of concern: For the purpose of this report, the term refers to hazardous plastic chemicals, that is, chemicals with intrinsic properties that render them problematic for human health or the environment. In this report, only plastic chemicals are considered as of concern if they have been classified hazardous by an authoritative source.

Polymers of concern: These are plastic materials with specific characteristics that render them problematic for human health, the environment, and/or plastic circularity. Such characteristics might include presence of chemicals of concern, release of micro- and nanoplastics, and incompatibility with a circular economy.

Hazard properties: The hazards of a plastic chemical, material, or product refer to its intrinsic potential to cause harm. The hazards can pertain to many negative physical, chemical, or biological impacts of plastics across the life cycle. In this report, a narrower definition is used to focus on plastic chemicals: These are considered of concern if they are persistent (i.e., they stay long in nature), bioaccumulative (i.e., they accumulate in biota, including humans), mobile (i.e., they easily spread in human and natural environments), and/or toxic (i.e., they can harm human health or the environment). These hazard properties translate into the criteria of persistence, bioaccumulation, mobility, and toxicity (PBMT) used in the report.

Plastic materials and products: Plastic materials are the bulk materials used to manufacture plastic products, usually in the form of so-called preproduction pellets or powders. Plastic products are the finished articles put on the market, these can be processed further into more complex products containing other materials (e.g., automobiles, textiles). Accordingly, the term plastic products does not only refer to typical plastic consumer products but also plastic components used for other purposes.

Safety of plastics: Safety regarding plastic chemicals and polymers pertains to their lack of adverse effects on human health and the environment throughout their lifecycle. The term safety is used here in a rather narrow, toxicological context that dictates the absence of harmful effects on human health and the environment, including via the release of chemicals, micro- and nanoplastics and other relevant aspects. Ensuring safety involves rigorous testing and sound management.

Sustainability of plastics: Safety is a prerequisite for the sustainability of plastic chemicals and polymers. The latter refers to the ability to produce, use and manage these chemicals, materials, and products in ways that ensure minimal environmental impacts over their entire lifecycle. Specifically, sustainability pertains to typical parameters of environmental impacts beyond toxicological hazards, such as footprints related to carbon emissions and the use of resources typically integrated in life cycle analyses. Sustainability also encompasses the development and implementation of practices that support a sustainable circular economy, aiming to extend the lifespan of plastic materials and products and reduce waste, with minimized environmental impacts.

Circularity of plastics: The circularity of plastic chemicals, materials, and products involves creating systems where these are reduced, reused, remanufactured, refurbished, or recycled, rather than disposed of. This approach aims to minimize waste, reduce the need for new raw materials, and lower environmental impacts. Circularity ensures that plastics are designed for longevity, reusability, or recyclability, facilitating their reintegration into the use or production cycle.

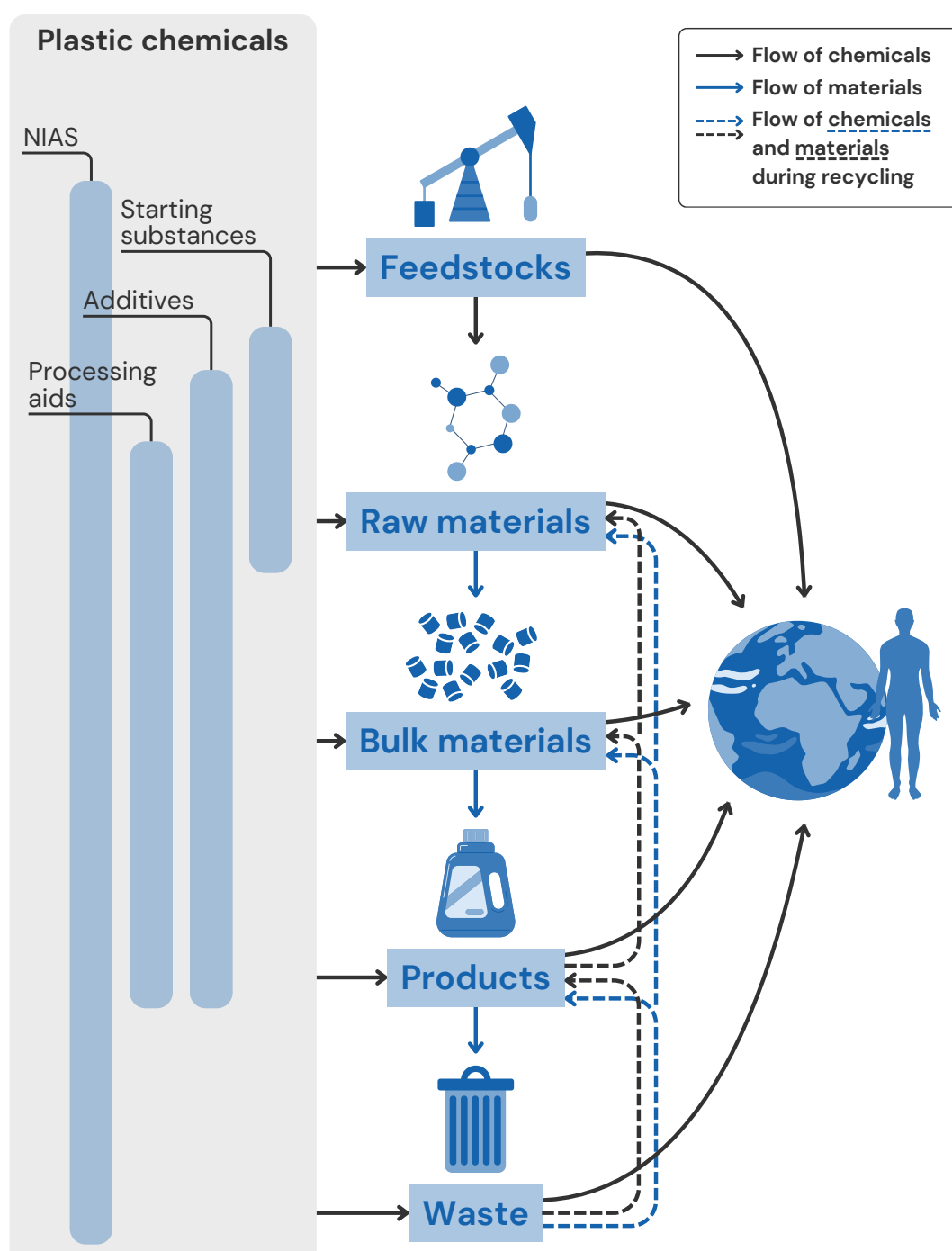


Figure 1: Overview of the life cycle of plastics, including the introduction, circulation, and release of plastic chemicals.

A person is walking away from the camera down a long, brightly lit aisle. The aisle is flanked by high, industrial-style shelving or racks on both sides. The ceiling is high and features several large, circular, recessed lights. The overall atmosphere is industrial and spacious. The image has a blueish tint.

PART I

Why do plastic chemicals matter?

Setting the scene



PURPOSE AND SCOPE OF THE STATE-OF-THE-SCIENCE REPORT

Context

This state-of-the-science report is set in the wider context of an increased public and political awareness of the problem of plastic pollution. The global momentum to act on this problem is expressed by the United Nations Environment Assembly's adoption of Resolution 5/14 "End plastic pollution: towards an international legally binding instrument" in March 2022.¹ This resolution mandates the Intergovernmental Negotiating Committee (INC) to develop an international legally binding instrument on plastic pollution, including in the marine environment, that is, a process to agree on a global plastics treaty "to prevent plastic pollution and its related risks to human health and adverse effects on human well-being and the environment".¹

All plastic polymers, materials, and products consist of chemicals, both intentionally and non-intentionally added ones. These chemicals are collectively referred to as plastic chemicals in this report. They can be released during feedstock extraction as well as the production, use, and end-of-life of plastics, causing adverse impacts on human health and the environment.^{2,3} This renders the chemical issue cutting across the whole plastic life cycle. Accordingly, plastic chemicals must be considered when tackling plastic pollution and transitioning to a more sustainable plastics economy. In turn, ignoring the chemical dimension will result in a failure to prevent and mitigate negative impacts of plastics on human health and the environment.

The rapidly growing scientific knowledge on plastic chemicals represents a valuable resource for policymakers, but much of the available evidence remains fragmented and scattered. Thus, there is a need to synthesize the state of the science on plastic chemicals to inform and support policy development, such as the INC process, and facilitate evidence-based decision-making. To address this need, the Research Council of Norway (RCN) funded the PlastChem project to produce a state-of-the-science report on plastic chemicals.

Purpose and scope

The main purpose of this report is to synthesize the state of the science of plastic chemicals as

a robust knowledge base for informed policy development in the context of the INC and other processes regarding plastics. The report also outlines a conceptual approach to promote a non-toxic future by reducing the use and spread of plastic chemicals and polymers of concern and provides policy recommendations for best achieving this aim. In particular, the report

- » provides a comprehensive overview of all known plastic chemicals, including up to date, harmonized information on their hazards, functionality, use and presence in plastics, production volumes, and regulatory status,
- » presents groups of plastic chemicals based on their structure,
- » identifies plastic chemicals of concern and priority groups of chemicals based on four hazard criteria, and links them to plastic materials,
- » proposes strategies to prioritize these for regulation,
- » suggests a conceptual approach to identify polymers of concern, and
- » identifies evidence-based policy recommendations to promote safer plastics.

The state-of-the-science report is complemented by the **PlastChem database**,⁴ a systematically compiled resource on known plastic chemicals which consolidates relevant and publicly available information. This database will enable scientists, policymakers, regulators, and stakeholders to access and trace the information used in this report and allow them to retrieve information specific to their needs.

Boundaries

The state-of-the-science report is a summary of publicly available information, including peer-reviewed scientific literature and regulatory sources. While the authors took great care to consult as many sources as possible, the report is meant to be comprehensive but not exhaustive. For instance, additional chemicals may be present in plastics that have not been listed in the consulted sources and are thus not included. Also, additional information on the hazards, production volumes, and regulatory status may be available for many chemicals in the public domain

beyond the consulted sources that is not included here. Moreover, the report contains information available at the time the report was prepared (until November 2023).

Audiences

The state-of-the-science report synthesizes the evidence on plastic chemicals for policymakers working on the issue of plastic pollution, chemicals regulation, and the interlinkages between the two. The report's key findings and recommendations are relevant for policy development on an international, regional, national, and local level. It also provides a more granular view of the evidence suitable for an expert audience in the public sector, such as regulators, as well as stakeholders from the private sector and civil society. Finally, the report can serve as useful resource for scientists investigating the sources, fate, and impacts of plastic chemicals and designing materials for safety and sustainability.

2

BACKGROUND: THE CHEMICAL DIMENSION OF PLASTICS

Plastics economy and plastic pollution

The plastics economy is one of the largest worldwide. The global plastic market was valued at 593 billion USD in 2021.⁵ In the same year, the global trade value of plastic products was 1.2 trillion USD or 369 million metric tons,¹⁶ China, the USA, and European states are the major plastic-producing countries with emerging economies experiencing a rapid expansion of local production capacities.⁷ The plastics economy is tightly embedded in the petrochemical sector, consuming 90% of its outputs to make plastics.⁸ This, in turn, creates strong linkages with the fossil industry, as 99% of plastic is derived from fossil carbon, production mostly relies on fossil energy, and the plastic and fossil industries are economically and infrastructurally integrated.^{7,9–12}

Plastic production increases exponentially. The global production of plastics has doubled from 234 million tons in 2000 to 460 million tons in 2019⁷ and its demand grows faster than cement and steel.¹⁰ On average, production grew by 8.5% per year from 1950–2019.¹³ Business-as-usual (BAU) scenarios project that plastic production will triple from 2019 to 2060 with a growth rate of 2.5–4.6% per year, reaching 1230 million tons in 2060.¹⁴ By 2060, 40 billion tons of plastic will have been produced, with about 6 billion tons currently present on Earth.³

The projected increase in plastic use is driven by economic growth and digitalization across regions and sectors. China is expected to remain the largest plastic user, but plastic demand is expected to grow stronger in fast-growing regions, such as Sub-Saharan Africa, India, and other Asian countries. Plastic use is projected to increase substantially across all sectors until 2060, and polymer types used in applications for packaging, construction and transportation make up the largest share of the projected growth.¹⁴ Importantly, the OECD predicts that petroleum-based, non-recycled plastics will continue to dominate the market in 2060. Single-use plastics, currently 35–40% of global production, are expected to grow despite regional phase-outs.

Globally, seven commodity polymers dominate the plastics market. These include

polypropylene (PP, 19% of global production), low-density polyethylene (LDPE, 14%), polyvinylchloride (PVC, 13%), high-density polyethylene (HDPE, 13%), polyethylene terephthalate (PET, 6%), polyurethane (PUR, 6%), and polystyrene (PS, 5%).¹⁵ Over 80% of Europe's total polymer demand is met by these, mostly in virgin form).¹⁵ Their usage varies by sector, with HDPE, LDPE, PET, and PP mainly being applied for packaging, and PS and PVC in construction.

The production and use of all polymers are projected to increase significantly. Predictions for Europe in 2066 forecast a 400% increase in the consumption of all polymers compared to 2016, especially for PET, PE, and PP, even when a recycling rate of 42% is achieved.¹⁶ Globally, the use of these polymers is expected to more than double by 2060, with substantial increases in PVC used in construction, PET and polyamide (PA) used in the textile sector, and PP used in the automotive sector.¹⁴ The use of alternative and bio-based materials is also predicted to grow.^{14,17}

Plastic waste largely follows the production trend. The global generation of plastic waste has more than doubled from 2000 to 2019, reaching 353 million tons in that year.¹⁴ Short-lived plastic items, including packaging, consumer products and textiles, make up almost two thirds of all plastic waste of which 9% was recycled, 19% incinerated and 50% landfilled. The remainder of plastic waste, namely 83 million tons, was disposed of in uncontrolled dumpsites, burned in open pits, or leaked to the environment.

Plastic waste generation is expected to almost triple by 2060. In line with the growth in plastic use, the future plastic waste generation is projected to almost triple, reaching 1014 million tons in 2060.⁷ Waste generated from short-lived applications, including packaging, consumer products and textiles, and plastic used in construction are expected to dominate. The latter is relevant because long-lived applications will continue to produce “locked-in” plastic waste well into the next century. Despite some improvements in waste management and recycling, the OECD projects that the amount of mismanaged plastic waste will continue to grow substantially and almost double to 153 million tons by 2060.

The scale of plastic pollution is immense. The OECD estimates that 22 million tons of plastic were emitted to the environment in 2019 alone.¹⁴ While there are uncertainties in these estimates, they illustrate the substantial leakage of plastics into nature. Accordingly, approximately 140 million tons of plastic have accumulated in aquatic ecosystems until 2019. Emissions to terrestrial systems amount to 13 million tons per year (2019), but the accumulating stocks remain unquantified due to data gaps. While mismanaged waste contributes 82% to these plastic emissions, substantial leakages originate further upstream and throughout the plastic life cycle, such as from the release of micro- and nanoplastics (MNPs). While the latter represent a relatively small share in terms of tonnage, the number of these particles outsizes that of larger plastic items emitted to nature.

Plastic pollution is projected to triple in 2060. A business-as-usual (BAU) scenario with some improvement in waste management and recycling predicts that the annual plastic emissions will double to 44 million tons in 2060.¹⁴ This is in line with other projections which estimate annual emissions of 53–90 million tons by 2030 and 34–55 million tons by 2040 to aquatic environments.^{17,18} According to the OECD, the accumulated stocks of plastics in nature would more than triple in 2060 to an estimated amount of 493 million tons, including the marine environment (145 million tons, 5-fold increase) and freshwater ecosystems (348 million tons, 3-fold increase). Since the impacts of plastic pollution are diverse and occur across the life cycle of plastics, the OECD concludes that *“plastic leakage is a major environmental problem and is getting worse over time. The urgency with which policymakers and other societal decision makers must act is high.”*¹⁴

Plastic Chemicals

All plastics consist of chemicals. Plastic monomers (e.g., ethylene, propylene, styrene) are mainly derived from fossil resources and then reacted (or, polymerized) to produce polymers (e.g., polyethylene, polypropylene, and polystyrene) that form the backbone of a plastic material (see [key terms](#), [Figure 1](#)). A mixture of starting substances (i.e., monomers, catalysts, and processing aids) is typically used in polymerization reactions. To produce plastic materials, other chemicals, such as stabilizers, are then added. This creates the so-called bulk polymer, usually in the form of pre-production

pellets or powders. The bulk polymer is then processed into plastic products by compounding and forming steps, like extrusion and blow molding. Again, other chemicals are added to achieve the desired properties of plastic products, in particular additives. Importantly, such additives were crucial to create marketable materials in the initial development of plastics, and a considerable scientific effort was needed to stabilize early plastics ([Box 1](#)). Throughout this process, processing aids are used to facilitate the production of plastics.

Organic Pollutants in 2023.²² At the dawn of the plastic age, scientists were unaware of the toxicological and environmental impacts of using additives in plastics. Their work to make plastic durable is essentially what has made plastics both highly useful, but also persistent and toxic.

The growth in additives production mirrors that of plastics. The amount of additives in plastics can significantly vary, ranging from 0.05–70% of the plastic weight.² For example, antioxidants in PE, PS, and ABS account for 0.5–3% of their weight. Light/UV stabilizers in PE, PP, and PVC constitute 0.1–10% by weight. Flame retardants can make up 2–28% of the weight, while plasticizers in PVC can be as high as 70% by weight. About 6 million tons of additives have been produced in 2016 and the annual growth rate is 4% in the additives sector.²³ Accordingly, additive production can be expected to increase by 130–280 thousand tons per year. By 2060, the joint production volume of a range of additive classes is projected to increase by a factor of five, closely mirroring the growth in overall plastic production.

Plastics also contain non-intentionally added substances. NIAS include impurities, degradation products, or compounds formed during the manufacturing process of plastics, which are not deliberately included in the material.^{24,25} Examples include degradation products of known additives (e.g., alkylphenols from antioxidants) and polymers (e.g., styrene oligomers derived from polystyrene). Unlike intentionally added substances (IAS), which are in principle known and therefore can be assessed and regulated, NIAS are often complex and unpredictable. Thus, their identity remains mostly unknown and these compounds, though present in and released from all plastics, cannot easily be analyzed, assessed, and regulated. Despite these knowledge gaps, NIAS probably represent a major fraction of plastic chemicals.

Box 1: Historic perspective - Plastics without additional chemicals are not plastic.

Plastics as we know them would not exist without the help of extra chemicals. In 1951, polymer scientists held a symposium to address the problem that most plastic materials lacked the properties for broad, practical applications.¹⁹ In addition, most plastics were unstable in the environment. Accordingly, much effort was put into research and development to make plastics both usable and durable.

The most durable plastic at that time was PVC. However, initial manufacturing did not produce a stable material, unless stabilizing chemicals were added, such as lead carbonate. Without these, PVC easily degrades and releases corrosive hydrogen chloride if heated or exposed to sunlight. Further, rigid PVC could only be made moldable and flexible by the addition of plasticizers, phthalates, used in the past to plasticize celluloid.²⁰ Thus, the dependence on additives to make plastics functional was established early in the history of plastic development.

However, experts of the 1951 symposium also noticed that the addition of phthalates and antioxidants typically used in PVC did not increase the stability of other polymers, such as polyethylene (PE). Accordingly, additional ultraviolet (UV) stabilizers were needed to prevent polyethylene from rapidly decomposing in sunlight. Research in the 1940s indicated that PE containing carbon black was the most UV resistant. Since black PE was difficult to market, more research was needed to produce UV stabilizers that were not black. Years later, the translucent chemical UV-328 was developed and used in PE plastic films for food packaging. Henceforth, polymer research was focused primarily on developing plastic additives. By 1970, the market for plastic additives exceeded half a billion USD per year, with one of the largest markets being phthalates used in PVC, and antioxidants and UV-stabilizers in polyolefins.²¹

It is now well established that many phthalates are endocrine disrupting chemicals (EDCs). Some phthalates have been banned in Europe and other regions. Further, UV-328, due to its persistent, bioaccumulative, and toxic properties has been added to the Stockholm Convention on Persistent Organic Pollutants in 2023.²² At the dawn of the plastic age, scientists were unaware of the toxicological and environmental impacts of using additives in plastics. Their work to make plastic durable is essentially what made plastics highly useful, but also persistent and toxic.

The number and diversity of known plastic chemicals is immense. A recent analysis by UNEP suggests that there are more than 13 000 known plastic chemicals, including polymers, starting substances, processing aids, additives, and NIAS.² The main reason for such chemical complexity of plastics is the highly fragmented nature of plastic value chains that market almost 100 000 plastic formulations and more than 30 000 additives, 16 000 pigments, and 8000 monomers.²⁶ While this represents the number of commercially available constituents of plastics, not necessarily the number of unique plastic chemicals, it highlights that the diversity of the plastics sector creates substantial complexity in terms of plastic chemicals.

Release of and exposure to plastic chemicals

A full overview of which chemicals are present in and released from plastics is missing, mostly due to a lack of transparency and publicly available data. Nonetheless, the available scientific evidence demonstrates that most plastic chemicals that have been studied are indeed released from plastic materials and products via migration into liquids and solids (e.g., water, food, soils) and volatilization into air. Additional chemical emissions occur during feedstock extraction and plastic production as well as at the end-of-life (e.g., during incineration). This is problematic because upon release, these chemicals can contaminate natural and human environments which, in turn, results in an exposure of biota and humans.

Most plastic chemicals can be released. The release of chemicals from plastics has been documented in a multitude of studies, especially in plastic food contact materials, that is, plastics used to store, process or package food.³ A systematic assessment of 470 scientific studies on plastic food packaging indicates that 1086 out of 1346 analyzed chemicals can migrate into food or food simulants under certain conditions.²⁷ Accordingly, 81% of the investigated plastic chemicals are highly relevant for human exposure. Newer research with advanced methods to study previously unknown plastic chemicals illustrates that this probably represents the tip of the iceberg. Studies using so-called non-targeted or suspect screening approaches show that commonly >2000 chemicals leach from a single plastic product into water.²⁸ While less information is available on non-food plastics, this highlights two important issues. Firstly, plastics can release a large number of chemicals which, secondly, then become relevant for the exposure of biota, including humans (termed “exposure potential” in this report).

Many plastic chemicals are present in the environment. Upon release, plastic chemicals can enter the environment at every stage of the plastic life cycle.^{2,3} Accordingly, plastic chemicals are ubiquitous in the environment due to the global dispersal of plastic materials, products, waste, and debris.^{29,30} For instance, a recent meta-analysis suggests that >800 plastic chemicals have been analyzed in the environment.³¹ However, this evidence is fragmented, and a systematic assessment of which compounds have been detected in the environment is lacking. Yet, the evidence on well-studied plastic chemicals indicates that these are present in various environments and biota across the globe, including remote areas far away from known sources. Examples include many phthalates,²³ organophosphate esters,³³ bisphenols,^{34,35} novel brominated flame retardants,³⁶ and benzotriazoles.^{37,38} Based on the existing evidence on well-researched compounds, it is prudent to assume that many more plastic chemicals are omnipresent in the natural and human environment, including in wildlife and humans.

Humans are exposed to plastic chemicals across the entire life cycle of plastics. This ranges from the industrial emissions during production, affecting fence line communities, to the releases during use, affecting consumers, and at the end-of-life, including waste handling

and incineration.³ These releases have resulted in extensive exposures of humans to plastic chemicals. For example, many phthalates, bisphenols, benzophenones, parabens, phenolic antioxidants as well as legacy brominated and organophosphate flame retardants have been detected in human blood, urine, and tissues in different global regions.^{35,39–47} Humans can be exposed to plastic chemicals directly, such as phthalates and other additives leaching from PVC blood bags used for transfusion or leaching into saliva in children mouthing plastic toys.^{48–50} Indirect exposure occurs through the ingestion of contaminated water and foodstuffs that have been in contact with plastics (e.g., processing, packaging). The inhalation and ingestion of plastic chemicals from air, dust and other particulate matter are other important routes of exposure. Importantly, research shows that women, children, and people in underprivileged communities often have higher levels of exposure.^{51–55}

Non-human organisms are exposed to plastic chemicals. The scientific literature provides rich information on the exposure of wildlife to plastic chemicals, in particular on bisphenols^{34,56,57} and phthalates^{58–60} in terrestrial and aquatic ecosystems as well as persistent organic pollutants, and antioxidants in marine environments.⁶¹ UNEP² highlights a global biomonitoring study which showed that seabirds from all major oceans contain significant levels of brominated flame retardants (BFRs) and UV stabilizers, indicating widespread contamination even in remote areas.⁶² Beyond seabirds, various other species are exposed to plastic chemicals according to UNEP, such as mussels and fish containing with high levels of hazardous chemicals like HBCDD, bisphenol A, and PBDEs, suggesting plastics as a probable source. Land animals, including livestock, are exposed to chemicals from plastics, such as PBDEs in poultry and cattle.^{63–65} and phthalates in insects.^{66,67} Importantly, plastic chemicals can also accumulate plants, including those for human consumption.^{68–71} This highlights a significant cross-environmental exposure that spans from marine to terrestrial ecosystems and food systems. However, while research on plastic chemical in non-human biota is abundant, it remains fragmented and has not been systematically compiled and assesses thus far.

Impacts of plastic chemicals on human health

Endocrine disrupting chemicals (EDCs) in plastics represent a major concern for human health. The plastic chemicals nonylphenol and bisphenol A were among the earliest identified compounds that interfere with the normal functioning of hormone systems.^{72,73} These findings marked the beginning of a broader recognition of the role of plastic chemicals in endocrine disruption and dozens have since been identified as EDCs. This includes several other bisphenols, phthalates (used as plasticizers), benzophenones (UV filters), and certain phenolic antioxidants, such as 2,4-ditertbutylphenol. For example, strong scientific evidence links bisphenols to cardiovascular diseases, diabetes, and obesity.³ Accordingly, there is a strong interconnection between plastic chemicals and endocrine disruption.

Additional groups of plastic chemicals emerge as health concern. The Minderoo–Monaco Commission's recent report comprehensively assesses the health effects of plastics across the life cycle, including plastic chemicals.³ In addition to phthalates and bisphenols, the report highlights per- and polyfluoroalkyl substances (PFAS) widely utilized for their non-stick and water-repellent properties. PFAS are strongly associated with an increased risk of cancer, thyroid disease, and immune system effects, including reduced vaccine efficacy in children.³ Additional concerns pertain to their persistence and their tendency to bioaccumulate in humans. In addition, brominated and organophosphate flame retardants have been linked to neurodevelopmental effects and endocrine disruption, adversely affecting cognitive function and behavior in children, as well as thyroid and reproductive health. Several other plastic chemicals are known to cause harm to human health, for example because they are mutagens (e.g., formaldehyde) or carcinogens with other modes of action, like melamine.^{74,75}

Plastic chemicals also impact human health when released from production and disposal sites. These more indirect effects include the contribution of plastic chemicals to water and air pollution across the life cycle.³ For instance, chlorofluorocarbons, previously used as blowing agents in plastic production, can deplete the stratospheric ozone layer and thereby indirectly affect human health. Other issues include the promotion of antimicrobial resistance due to the

dispersion of biocides transferring from plastics in the environment^{76,77} and the release of dioxins and PCBs from the uncontrolled burning of plastic wastes.^{78–80} The latter are especially toxic and persistent, and accumulate in the food chain, leading to increased human exposure.

The health impacts of well-researched plastic chemicals are established. Arguably, there is a large body of evidence that links certain groups of plastic chemicals to a range of adverse health effects. These include but is not limited to bisphenols, phthalates, PFAS, and brominated and organophosphate flame retardants. Research focusses particularly on their endocrine disrupting effects, include adverse impacts on reproduction, development, metabolism, and cognitive function.^{81,82} However, it should be noted that research into other groups of plastic chemicals and other types of health effects remains largely fragmented and has rarely been systematically assessed. Here, initiatives such as the Plastic Health Map⁷⁵ can support a more strategic approach.

Impacts of plastic chemicals on the environment

Plastic chemicals exert a host of adverse impacts on wildlife. This includes both acute and chronic toxicity in individual organisms and populations, as well as indirect effects across food webs. Ecotoxicological effects of heavy metals, such as cadmium and lead, as well as EDCs used in plastics, such as bisphenols, phthalates, and brominated flame retardants, have received the most research attention to date. Oftentimes, these EDCs induce environmental impacts at very low concentrations. However, due to the enormous diversity of plastic chemicals and the potentially affected species in the environment, the breadth of potential effects and mechanisms at play is probably underappreciated at present.

Novel mechanisms of the environmental impacts of plastic chemicals emerge. Several recent scientific studies have revealed novel mechanisms of adversity characterizing the interaction between certain plastic chemicals or polymers and specific organism groups (e.g., plants and insects).^{83–89} Some of these chemicals are also known to be persistent and bioaccumulative, raising further concern regarding their high exposure potential. This highlights the need to better characterize both the diversity and toxicity of plastic chemicals

that can contribute to environmental exposures. While the traditional approach typically employs toxicity tests performed with individual substances, more recent studies started incorporating the testing of plastic leachates, encompassing all chemicals in plastic materials or products.

Compared to the human health effects, the evidence for environmental impacts from plastic chemicals is more fragmented. Like human health research, environmental research focuses predominantly on well-known plastic chemicals, including bisphenols, phthalates, flame retardants, and recently PFAS. In contrast, population-wide studies, such as epidemiological ones for humans, are not easily applicable to wildlife and systematic meta-analysis are largely lacking. Hence, while there is abundant evidence for the impacts of plastic chemicals on the environment, this knowledge remains somewhat fragmented.

Impacts of plastic chemicals on circularity

Plastic chemicals can hinder technological solutions to plastic pollution. This includes but is not limited to recycling, waste-to-energy processes, and the use of biobased plastics.⁹⁰ For example, specific chemicals reduce the marketability of recycled plastics, including technical qualities and aesthetics. Here, a high-quality secondary material can only be achieved with a high degree of separation and a low degree of impurities and cross-contamination among various polymer types.⁹¹ In addition, the presence of many chlorinated substances and metals in plastics may corrode much the machinery used in the process and contaminate end-products from chemical recycling, posing technical challenges to their utilization.⁹⁰

3

REGULATION OF PLASTIC CHEMICALS

Regulatory instruments are a major tool for controlling and phasing out plastic chemicals of concern. To date, many legal instruments with relevance to plastic chemicals have been developed and implemented. They can be categorized into three types:

General instruments on the sound management of chemicals apply to some plastic chemicals. These are laws and policy frameworks that regulate chemicals in a wide range of applications, which includes their use in plastics. Examples at the global level include the Montreal Protocol on Substances that Deplete the Ozone Layer and the Stockholm Convention on Persistent Organic Pollutants. Examples at the regional and national level include the EU REACH and the US Toxic Substances Control Act (TSCA).

Instruments on the sound management of chemicals regulate some plastic-specific sectors or life cycle stages. One framework at the global level is the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal focusing on the plastic waste containing listed chemicals. Another international framework is the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade regulating the trade of listed chemicals, including plastic chemicals. Examples at the regional and national level include the European regulation for chemicals in food contact plastics (details in [Box 2](#)).

Instruments on the sound management of specific chemicals, or specific chemical applications address some plastic chemicals.

The Minamata Convention on Mercury is an international policy framework falling in this category and banning the use of mercury and mercury-containing chemicals, some of which may be used in plastics. Banning the use of bisphenol A in food contact products in France⁹² and in baby bottles in many parts of the world (see examples in ³⁰) are examples of regional and national regulations targeted to manage specific plastic chemicals.

The regulatory landscape of plastic chemicals is complex. However, several observations can be made. First, existing instruments are largely fragmented and with narrow scopes. Even with the general type of instruments, the chemical scope is limited in global-level frameworks and the geographical scope is limited in national/regional-level instruments. Second, only a few plastic chemicals are regulated globally with 128 plastic chemicals subjected to the Stockholm Convention, the Minamata Convention, or the Montreal Protocol.⁹³ Third, while many countries or regions have established specific legislations in relation to plastic chemicals, many of them may be inconsistent with each other ([Box 2](#)). That means that some chemicals are of concern and banned in many applications, but may be approved for use in other applications. For instance, while the EU requires authorization for the use of dibutyl phthalate in most applications, it is approved for use in food-contact plastics. This policy incoherence is often caused by different methodologies behind different regulations. To date, the EU has introduced the concept of “one chemical, one assessment” with the aim to address such inconsistency. The implementation of this novel approach may be watched for and potentially upscaled in other parts of the world. Meanwhile, the current fragmented, narrow-scoped, and sometimes conflicting regulatory landscape calls for global efforts in addressing plastic chemicals, such as the global plastics treaty.

Box 2. European regulation for chemicals in food contact plastics.

While chemicals used in the EU must conform with REACH, food contact materials (FCMs), including those made with plastics, have additional chemical regulations. Article 3 of the FCM Framework Regulation (EU 1935/2004) requires that chemicals from FCMs shall not migrate into food in quantities endangering human health.⁹⁴ In addition, plastic FCMs must comply with regulation (EC) No 10/2011 which includes a positive list of starting substances, additives, and polymer production aids that may be used in plastic FCMs but should not transfer to foodstuff in levels above specific migration limits.⁹⁵

However, the approach of positive lists does not guarantee safety of FCMs. Indeed, with approximately 1000 substances authorized for use in plastic FCMs in Europe, around 60% lacked a published analytical method and for 47% no analytical standards were available, the latter being a prerequisite for quantification and, thus, enforcement.⁹⁶ A compilation of data from industry and regulatory resources demonstrated that more than 12 000 chemicals may be used intentionally to produce FCMs. Of these, 608 were considered priority hazardous substances.⁹⁷ Many of these food contact chemicals are relevant for human exposure. More than 1000 have been found to migrate from plastic FCMs into food or food simulants.²⁷

In its Chemicals Strategy for Sustainability, the EU expresses the intention to reduce exposure to hazardous chemicals, including in FCMs.⁹⁸ Accordingly, consumer products should not contain the most harmful chemicals, which are defined as chemicals that are either carcinogenic, mutagenic or toxic to reproduction, or persistent, bioaccumulative and toxic, or EDCs. A recent analysis identified 388 chemicals in FCMs to fulfill at least one of these hazard criteria.⁹⁹ This demonstrates that hundreds of chemicals with well-known hazard properties of the highest concern can be used intentionally in FCMs. Through migrating into food, these chemicals become directly relevant for human exposure, and for at least 97 chemicals evidence demonstrates migration.

The current regulatory plastic FCM framework focuses on intentionally added substances while disregarding colorants, solvents, NIAS, as well as unexpected and unknown compounds present in the final product. Furthermore, many chemicals are not commercially available as reference standard and therefore can neither be quantified nor empirically assessed for their hazard properties. For these reasons, the absence of chemicals of concern from plastics cannot be ensured using current regulatory approaches.

4

PREVIOUS REPORTS PERTINENT TO PLASTIC CHEMICALS

A range of previous reports can inform on plastic chemicals. These works have been considered when preparing the present report and briefly summarized below. While building on these invaluable resources, the state-of-the-science report takes a different approach to plastic chemicals, in such that it systematically synthesized the existing knowledge to identify and prioritize groups of and individual plastic chemicals of concerns (see section below).

The UNEP/BRS Conventions' technical report on chemicals in plastics informs stakeholders about chemical-related issues in plastic pollution.² It lists 13 000 chemicals in plastics, with 7000 having hazard data and 3200 identified as chemicals of potential concern. The report identifies ten groups of chemicals of concern in plastics, such as flame retardants and phthalates, and highlights ten high-risk sectors. It advocates for regulatory instruments to phase out these compounds, prioritizing internationally restricted chemicals, and those identified as issues in other contexts. The report calls for increased transparency, improved risk assessments, updated regulatory testing guidelines, and robust waste management frameworks. It also points out the lack of comprehensive data on plastic chemicals and the need to address NIAS.

The Minderoo–Monaco Commission's report on plastics and human health examines the impact of plastic chemical on health, environment, and economy across the life cycle.³ It also assesses the impacts of specific groups of plastic chemicals as well as of micro- and nanoplastics (MNPs). The report reveals how chemicals leach from plastics, causing health issues like neurodevelopmental disorders and impacting aquatic life through bioaccumulation. It estimates that in 2015, health costs related to plastic-associated chemicals in the USA exceeded 920 billion USD. The Commission proposes the plastics treaty should regulate all chemicals in plastics, reduce complexity, set health standards, and mandate full disclosure of the chemical composition. It also recommends treating certain polymers as persistent organic pollutants and forming an advisory

body to guide treaty implementation, urging national governments to invest in safer plastic alternatives.

The BRS Conventions' report reviews global governance of plastics and associated chemicals.⁹³ It identifies gaps in existing multilateral environmental agreements (MEAs), with only a small fraction of chemical of concern regulated (<1%). The report recommends a new global instrument to complement existing MEAs, focusing on reducing plastics production and use, and establishing safety and sustainability criteria for plastic chemicals. It emphasizes control measures to phase out or regulate harmful materials and the need for global regulation of plastic chemical trade. The report also highlights the absence of measurable targets and indicators to track progress towards safer, environmentally friendly plastic use.

The OECD report on sustainable plastics design focuses on designing sustainable plastics from a chemical perspective.¹⁰⁰ It highlights the importance of sustainable chemistry in the design process, emphasizing the complexity and variability of sustainable design requirements. The report advises designers and engineers to consider life cycle impacts and chemical trade-offs, and underscores the role of policymakers in supporting systemic changes for sustainable practices. The goal is to guide the creation of sustainable plastics through informed decision-making and collaboration, facilitating the transition to safe and sustainable plastic use.

The OECD Workshop Report on flexible food-grade plastic packaging discusses the transition to sustainable food packaging and other plastic products.¹⁰¹ It provides an overview of the status of plastic chemicals and industry barriers in sustainable packaging, without highlighting specific chemicals. The report suggests recycling-focused solutions, such as making plastic recycling economically valuable and improving waste sorting. It emphasizes the need for regulation of chemicals in plastics and cross-regional policy alignment, noting the lack of transparency in plastic composition and concerns over contaminants in recycled plastics.



IMPORTANT ASPECTS THIS REPORT ADDRESSES

When considering the state of the science, there is abundant evidence on the existence, exposure, and effects of plastic chemicals. However, this evidence is fragmented and scattered across sources, resulting in the lack of comprehensive, consistent, and up-to-date public information on

- » an overview of all known plastic chemicals,
- » a grouping of plastic chemicals based on their structure,
- » the hazards for plastic chemicals in terms of human health and the environment,
- » the use and presence of plastic chemicals in specific materials and products, and
- » the regulatory status of plastic chemicals on an international, regional, and national level.

The state-of-the-science report collects and synthesizes this information from a variety of public sources to provide

- » a comprehensive and consistent assessment of all known plastic chemicals based on the information listed above,
- » a database that makes this information publicly available,
- » a unified framework to identify plastic chemicals of concern,
- » a conceptual approach to identify polymers of concern, and
- » policy recommendations to address the issue of plastic chemicals and polymers.

Accordingly, the report addresses three key questions:

1. What do we know about plastic chemicals? > Findings in **Part II**
2. Which are the most concerning plastic chemicals? > Findings in **Part III**
3. How can policymakers address these chemicals? > Recommendations in **Part IV**



PART II

What is known about plastic chemicals?

State of the science overview

1

KEY FINDINGS

- » **There are at least 16 000 known plastic chemicals.** The report identifies 16 325 compounds that are potentially used or unintentionally present in plastics.
- » **There is a global governance gap on plastic chemicals.** 6% of all compounds are regulated internationally and there is no specific policy instrument for chemicals in plastics.
- » **Plastic chemicals are produced in volumes of over 9 billion tons per year.** Almost 4000 compounds are high-production volume chemicals, each produced at ≥ 1000 tons per year.
- » **At least 6300 plastic chemicals have a high exposure potential.** These compounds have evidence for their use or presence in plastics, including over 1500 compounds that are known to be released from plastic materials and products.
- » **Plastic chemicals are very diverse and serve multiple functions.** In addition to well-known additives, such as plasticizers and antioxidants, many plastic chemicals often serve multiple functions, for instance, as colorants, processing aids, and fillers.
- » **Grouping of plastic chemicals based on their structures is feasible.** Over 10 000 plastic chemicals are assigned to groups, including large groups of polymers, halogenated compounds, and organophosphates.

Key knowledge gaps and blind spots

Based on the finding of this report, many plastic chemicals cannot be adequately assessed and controlled because they lack publicly available and verifiable information on

- » **Chemical identities and structures:** More than 25% of plastic chemicals lack basic information on their chemical identity.
- » **Functions and applications:** More than half of plastic chemicals lack information regarding their function, and available information on their functionality is often ambiguous.
- » **Production volumes:** Data are not globally representative because they are restricted to certain OECD countries, and the fractions allocated to plastic uses are often unclear.
- » **Presence in plastics:** Over 9000 plastic chemicals do not have publicly available information on their origins or uses in plastics in the public domain.

2

GENERAL APPROACH TO SYNTHESIZE THE STATE OF THE SCIENCE

The state-of-the-science report consolidates information on all known plastic chemicals.

By compiling, harmonizing, and updating information from previous databases, scientific literature, and regulatory sources, the report and the accompanying PlastChem database provide a synthesis of the knowledge on plastic chemicals (Figure 2, Part II). Building on this, the report adopts an evidence-based framework for identifying and prioritizing chemicals of concern, resulting in a set of lists of plastic chemicals with different hazard and priority levels that can inform policy development (Part III). Besides individual chemicals, the report also highlights groups of chemicals of concern and

proposes a conceptual approach for identifying polymers of concern. Considering the state of the science, the report provides concrete policy recommendations to address the issue of plastic chemicals of concern (Part IV). Throughout the project, two rounds of expert consultations were held to align the report with the needs of policymakers and regulators, as well as to gather feedback on the overall approach, the prioritization of chemicals of concern, and the reporting of the findings. Seven experts on chemicals assessment and management from diverse institutions, genders, and regions were consulted and their input integrated in the report (details in Annex A3).

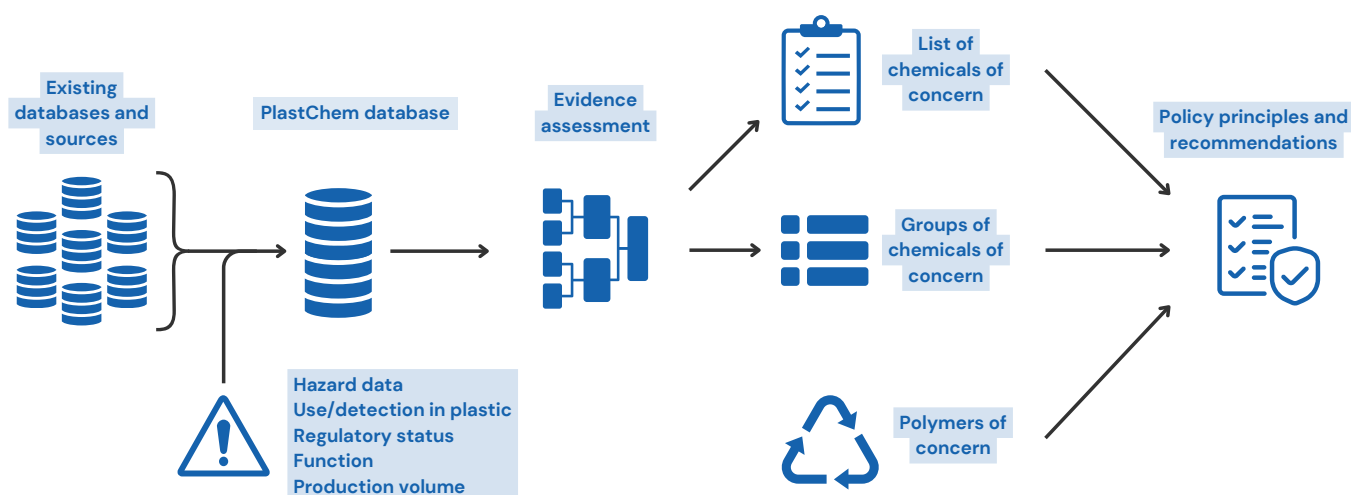


Figure 2: General approach to produce the state-of-the-science report.

Chemical landscape

More than 16 000 chemicals are potentially used or unintentionally present in plastics.

This represents the number of compounds which could be assigned a Chemical Abstract Service Registry Number (CASRN) as identifier (Table 1). CASRNs enable tracking a chemical substance across data sources and, therefore, are a prerequisite for collecting the hazard and other information of any given chemical. Only this “core collection” of 16 325 chemicals is further considered in this report. Among them, 12 990 chemical substances have structural identifiers, such as SMILES or InChI codes. Another 4706 compound were identified, resulting in a total of 17 933 entries. However, those chemicals do not have identifiers or unique structures, rendering these inaccessible for assessment. Hence, they are not further considered in this analysis. There is a considerable overlap in the chemicals collected from the seven sources used to construct the PlastChem database but most of the sources contained chemicals not covered by others (details in Annex A3).

The landscape of plastic chemicals is dominated by organic chemicals.

About three fourths of plastic chemicals are organic (11 950, Figure 3), and another 926 (6%) are inorganics, while the remaining 3449 chemicals miss information on their elemental composition. The organic plastic chemicals include many halogenated compounds (2180) that are predominantly chlorinated (1175), brominated (525), and fluorinated (532, of which 440 are PFAS). 465 plastic chemicals are organophosphates, commonly known for being used as flame retardants.

Poorly defined chemicals and mixtures make up one fourth of plastic chemicals. Mixtures of multiple chemicals or compounds with a complex structure make up 23% of all plastic chemicals. This included 1103 substances of unknown or variable composition, complex reaction products or biological materials (UVCBs) and 628 other mixtures. With some overlap to the former, the chemical landscape of plastics also consists of 2329 polymers used as polymer backbone or

Table 1: Overview of chemical entries in the PlastChem database and its sources..

Database	Source	Entries	Unique CASRNs	Unique structures
CPPdb v1	Groh et al., 2019 ¹⁰²	4227	4220	3612
FCCdb v5	Groh et al., 2021 ⁹⁷	3543	3535	2543
FCCmigex	Geueke et al., 2022 ²⁷	4257	3196	3201
ECHA PMFCdb	EU List of Authorized Substances ^{95, a}	1046	788	724
PlasticMAP	Wiesinger et al., 2021 ¹⁰³	10 547	10 547	8455
LitChem	Wiesinger et al., 2024 ¹⁰⁴	3467	3467	3076
Aurisano	Aurisano et al., 2021 ¹⁰⁵	5983	5684	4319
PlastChem	This report	17 933	16 325	12 990

Note: ^a Annex I, Plastics Food Contact Regulation 10/2011/EU

for other functions. Accordingly, 3667 plastic chemicals are complex mixtures that are difficult to assess.

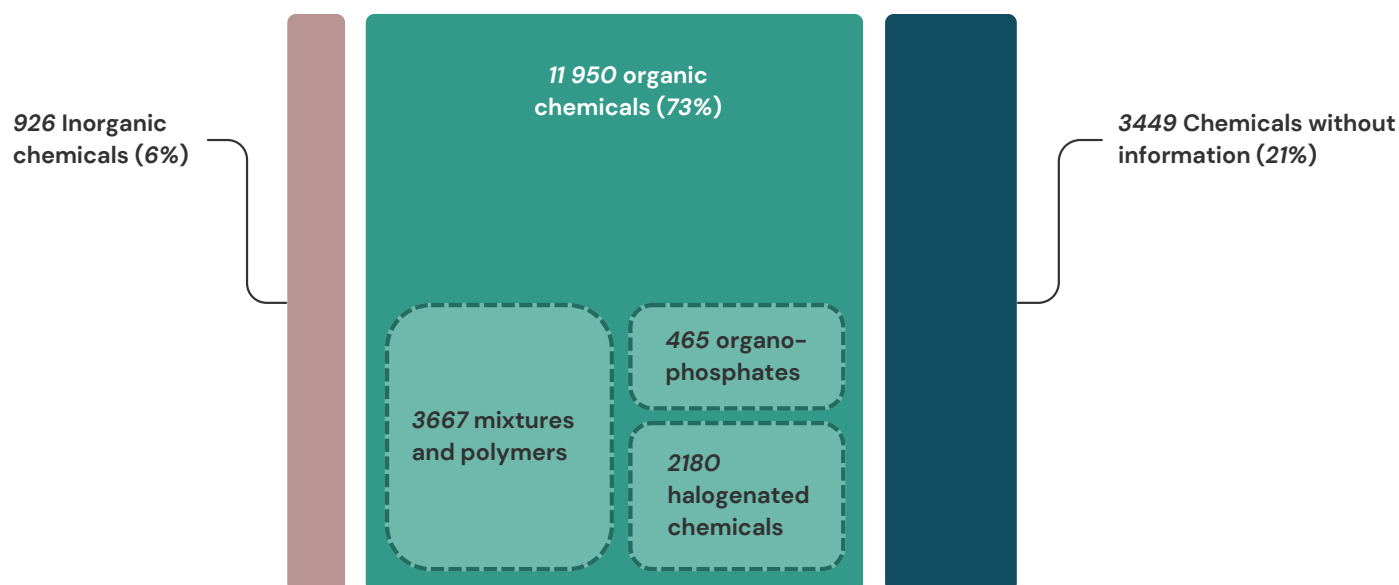


Figure 3: Landscape of plastic chemicals. The mixtures and polymers include 1103 substances of unknown or variable composition, complex reaction products or biological materials (UVCBs).

Functional landscape

Only half of the plastic chemicals have information on their functions. Data on the functionalities of 7585 chemicals, or 47% of all plastic chemicals with CASRNs, are available from the consulted sources. Since the sources use divergent terminologies, the chemical functions were collated into 34 categories covering plastic additives, starting substances, processing aids, and NIAS (Figure 4, Annex A3). Since the sources used here are very comprehensive, the lack of functional information for more than half of the plastic chemicals highlights the lack of transparency regarding the chemicals' functionality in plastic materials and products.

Most plastic chemicals have a multitude of functions. Noticeably, 4054 chemicals are reported to have more than one function in plastics (Annex A3). For instance, bisphenol A, mostly known as monomer of polycarbonates and epoxy resins, has in total 14 reported functions, including as an antioxidant, antistatic agent, blowing agent, catalyst, colorant, crosslinking agent, filler, flame retardant, intermediate, light stabilizer, lubricant, and plasticizer, among others. This demonstrates that many chemicals may fulfill more than one function in plastics and often cover multiple stages of the plastic life cycle. Meanwhile, inconsistencies in reporting the functional information across sources exist that could be overcome by harmonizing the terminology.

Colorants, processing aids, fillers, intermediates, and lubricants dominate the functional landscape of plastic chemicals.

Each of these functional classes is associated with >1500 plastic chemicals (Figure 4). Notably, the well-known classes of plasticizers (883 chemicals), antioxidants (478), and flame retardants (389) rank much lower and represent >12% of the compounds with functional information, each.

Information on NIAS is lacking. While not fulfilling a function in plastics, NIAS, which include degradation products and impurities, can be relevant in terms of their impacts on health and the environment. Despite their importance and prevalence, only 56 NIAS have been explicitly identified across sources. These often include degradation products of bisphenols and phenolic antioxidants. Since thousands of NIAS are suspected in plastics, their low number in the PlastChem database strongly suggests that information on this group of chemicals is scarce and fragmentary at best. The reason for this is that many NIAS remain either truly unknown or are known but not annotated as such. Taken together, the NIAS included here merely represent the tip of the iceberg, and more effort is needed to elucidate these compounds.

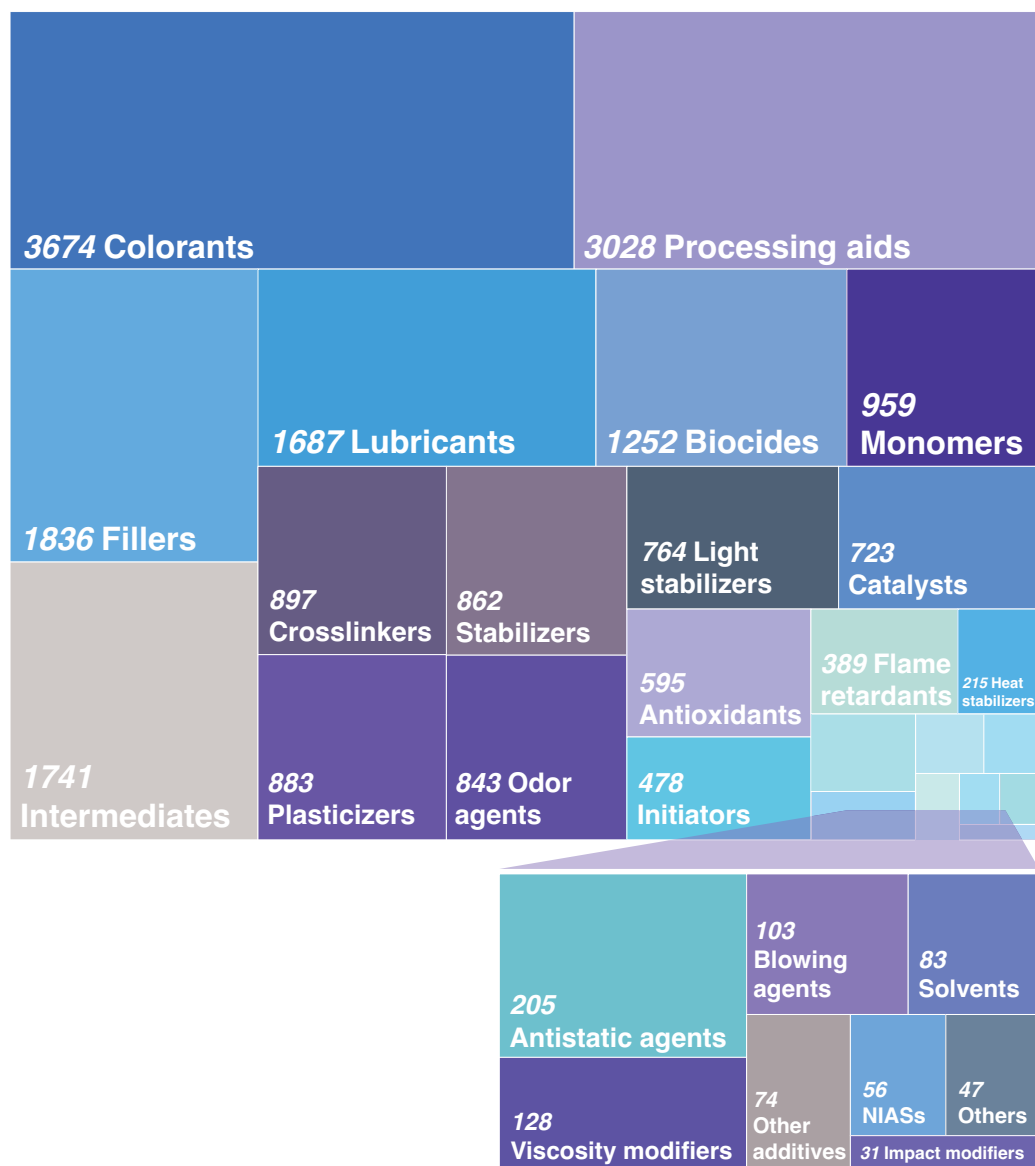


Figure 4: Overview of the functions of plastic chemicals. Note that many compounds have more than one function.

Production landscape

More than 9 billion tons of plastic chemicals are produced annually. 6120 plastic chemicals have information on their production volumes from the EU, the Nordic Countries, and the USA, or have been included in the OECD high production volume chemical list. Since the information is limited to the EU (information for 4298 chemicals) and the USA (2525 chemicals), the production volumes of plastic chemicals are probably underestimated here. However, it is important to emphasize that many of these chemicals may also be used in processes, materials, and products unrelated to plastics. Due to the lack of specific information on the application of these chemicals in plastics, the production volumes allocated for specific use in plastics remain unknown.

Almost 4000 plastic chemicals are high production volumes chemicals. 3976 chemicals are produced at ≥ 1000 tons per year, including more than 1100 chemicals with production volumes of $\geq 100\,000$ tons, and 501 chemicals with ≥ 1 million tons per year (Figure 5). The 43 chemicals with the highest production volumes (≥ 100 million tons annually) mainly comprise plastic feedstocks (e.g., ethane, propane), raw materials (e.g., ethene, propene), as well as petroleum distillates and naphtha fractions.

Groups of plastic chemicals

More than 10 000 plastic chemicals can be grouped based on their structure. The groups include large and heterogeneous groups of substances, such as 1103 UVCBs, 2329 polymers, and 1521 mixtures as well as 926 inorganics and 365 organometallics. These diverse groups can be further broken down by expert eyeballing (e.g., for PFAS), cross-referencing existing lists (e.g.,

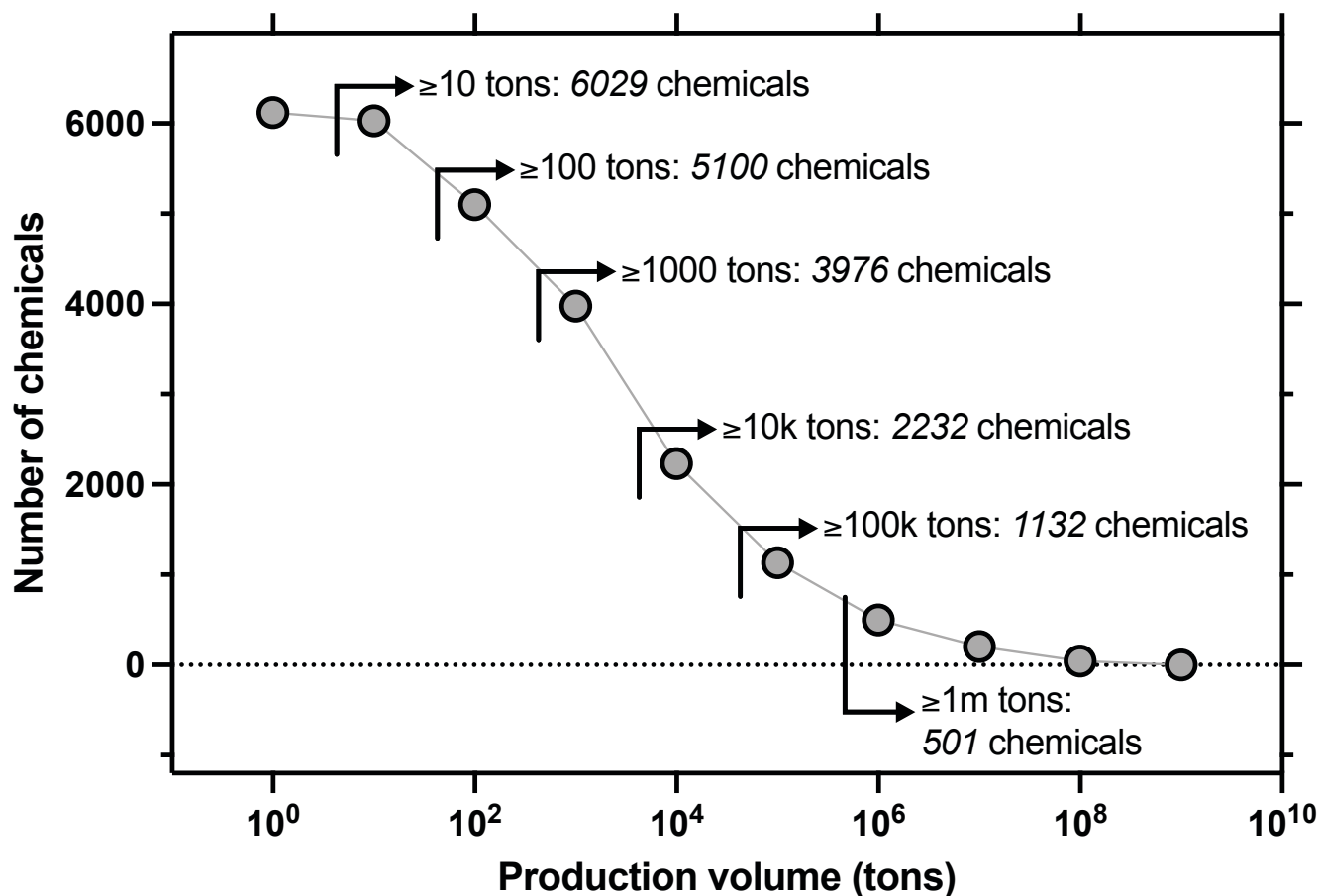


Figure 5: Number of plastic chemicals according to their annual production volume. The numbers are shown cumulatively, that is, the number of chemicals with ≥10 tons include all chemicals with a higher production volume.

chlorinated paraffins), or the identification of toxic metals, metalloids and their derivatives through keyword search (see Appendix A4 for details). In other cases, more information on the chemical identities is needed to allow for grouping.

Grouping results in many groups of chemicals with clear structural similarities. These include groups with simple structures, such as simple alkanes and alkenes, for which the hazards have been rather well-established for the entire groups (Table 2). Groups with more complex structures can be further divided into groups with common (e.g., PFAS) or similar substructures (e.g., bisphenols). Additional grouping would be possible but requires either increased expert scrutiny or the refinement of automated methods. Some overlap exists between the groups where 4099 chemicals (40%) are members of more than one group. Most of them, 2989 chemicals, are grouped in two groups, and 10% in more than two groups.

Table 2: Groups of chemicals with clear structural similarities. Only groups containing more than ten members are presented here.

Group	Number of chemicals	Group	Number of chemicals
Alkenes	802	Bisphenols	34
Silanes, siloxanes, silicones	443	Iso/terephthalates and trimellitates	29
PFAS	440	Benzotriazoles	28
Alkanes	376	Ketones simple	25
Carboxylic acids salts	202	Benzothiazole	24
PCBs	140	Aromatic amines	22
Aldehydes simple	124	Alkynes	20
Azodyes	89	Alkane ethers	20
Dioxines and furans	75	Chlorinated paraffins combined	18
Alkylphenols	66	Aliphatic ketones	15
Ortho-phthalates	61	Aliphatic primary amides	14
Aceto- and benzophenones	52	Salicylate esters	11
Phenolic antioxidants	50	Parabens	10
PAHs	45	Aromatic ethers	10

Note: PFAS = per- and polyfluoroalkyl substances, PCBs = polychlorinated biphenyls, PAHs = polycyclic aromatic hydrocarbons

4

STATE OF REGULATION

Six per cent of all plastic chemicals are regulated under MEAs. The MEA list compiled in PlastChem contains 980 chemicals that are regulated under existing multilateral environmental agreements, including 462 under the Stockholm Convention, 487 under the Basel Convention, 26 under the Minamata Convention and ten under the Montreal Protocol. A previous assessment identified 128 plastic chemicals regulated by existing MEAs in 2021.⁹³ The discrepancy of the numbers is mainly due to the fact that the previous assessment did not cover the individual chemicals included in regulated groups, whereas the present report does.

National and regional regulations address 1021 additional plastic chemicals. California addresses 293, the EU 258, the Republic of Korea 653, and Japan 70 chemicals. The Rotterdam Convention, which regulates 151 chemicals, is included here since its primary mechanism refers to the exchange of information between specific exporting and importing countries. The Republic of Korea has the broadest jurisdiction, incorporating 320 chemicals that are not regulated in any other regulations (Figure 6). This demonstrates that additional plastic chemicals are regulated in particular countries or regions.

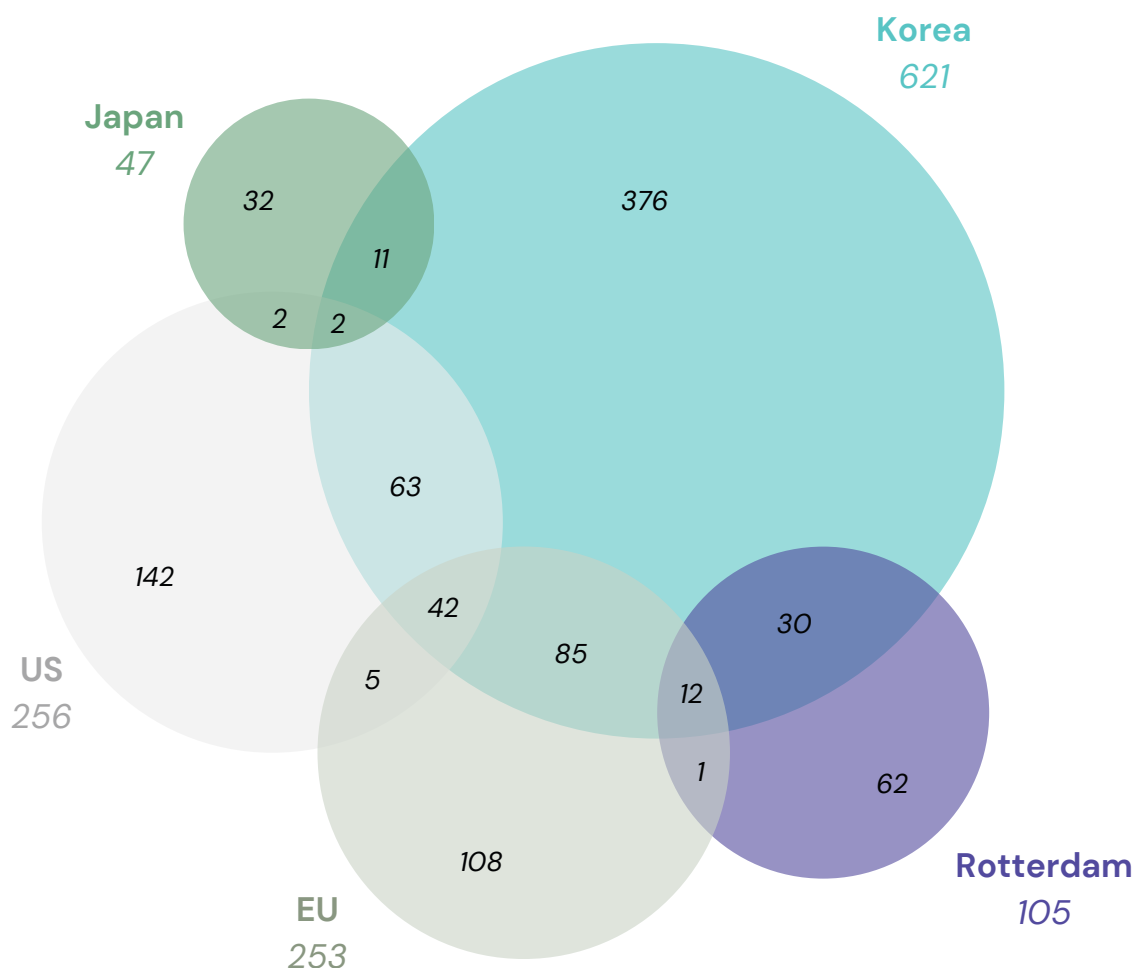


Figure 6: Overlap of the number of plastic chemicals regulated in regional and national jurisdiction. Minor overlaps are not shown here to improve clarity.

5

USE, PRESENCE, AND RELEASE OF CHEMICALS FROM PLASTICS

More than 6200 chemicals have evidence for their use, presence, or release from plastics. The evidence indicates that 6276 plastic chemicals are either used, or present in or released from plastics. This represents almost 90% of the chemicals that have relevant information and 40% of all plastic chemicals (Figure 7). 2148 compounds (13% of all plastic chemicals) have only use information, that is, they are marketed for being added to plastic materials and products. Empirical evidence demonstrates that 2557 chemicals (16%) are present in plastics. These compounds have been detected in plastics in scientific studies, mostly by chemical analyses of extracted plastic materials or products. Additional scientific evidence shows that 1571 chemicals (10%) are released from plastics. This means that these compounds leach from plastic materials or products into liquid or solid matrices, such as water or foodstuffs, thus representing the strongest evidence for the exposure potential of these plastic chemicals. 132 chemicals have been analyzed for in scientific studies but not detected in plastics.

Specific information on use, presence and release of plastic chemicals is limited. Out of all plastic chemicals, almost 60% (9245 compounds) lack specific information on their use or have not been analyzed in plastics, based on industry or scientific sources. The reasons for this are manifold and include the lack of public use information, as well as a bias in the scientific literature towards well-studied chemicals. Moreover, information is incomplete in terms of the chemicals that have evidence for their use or detection in plastics. Out of all 9245 chemicals, 1104 compounds have evidence for at least two criteria, that is, their use, presence, or release (Figure 8). Importantly, only 267 chemicals have evidence for their use and their presence and their release from plastics. Taken together, this highlights the lack of use information and of a consistent monitoring of chemicals in plastic materials and products.

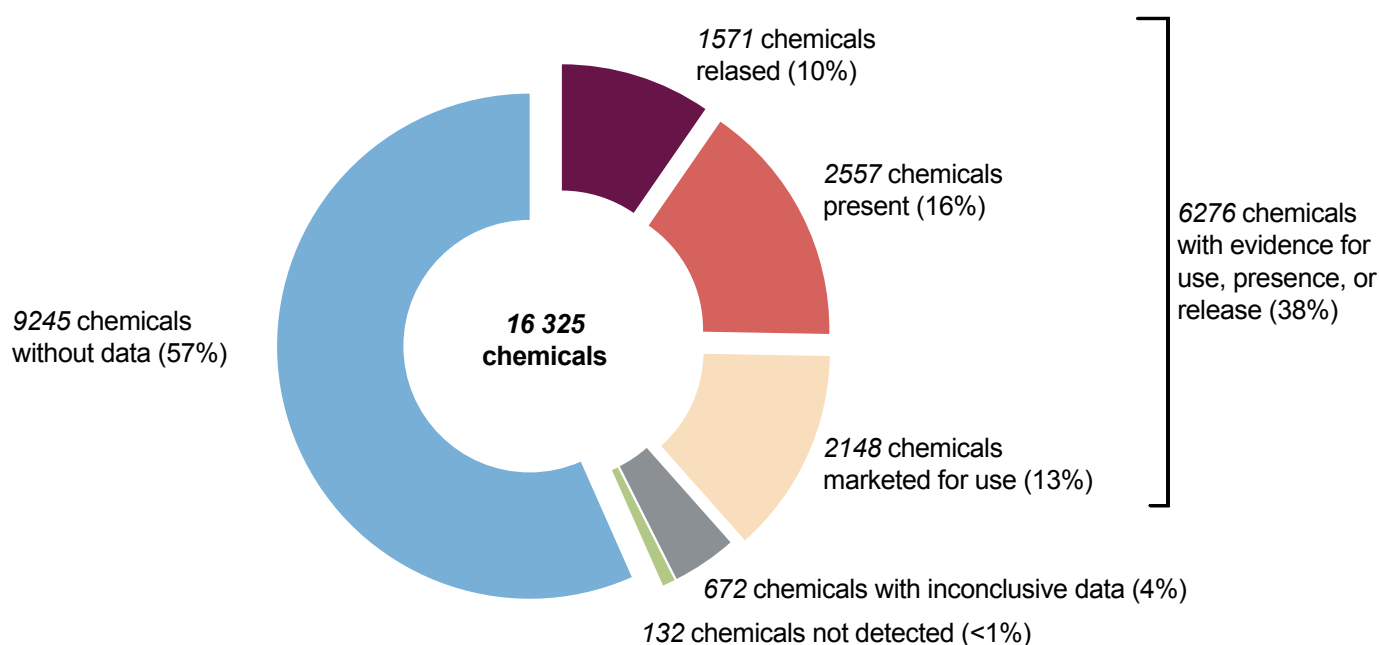


Figure 7: Number of chemicals with evidence for their use, presence, or release from plastics. Chemicals that have been analyzed but have not been detected or had inconclusive results are also included. There is a considerable overlap in use, presence, and release information and the highest level of evidence per chemical is presented here.

Many of the chemicals used in plastics have not been analyzed for their presence and release. Analyzing the chemicals with use information (2899 chemicals) further highlights that only 750 have evidence for their presence or release (Figure 8). This means that only about one fourth of the chemicals that are marketed for use in plastics have been assessed in scientific studies. This results in a striking data gap for >2100 chemicals that are probably present in some plastic materials and products but lack additional information on their presence or absence. Conversely, 3379 chemicals have been detected in plastics but lack public use information. Importantly, this also illustrates that many chemicals detected in plastics might not be intentionally used, that is, they are NIAS.

covers 1759 chemicals with use information, 2202 chemicals that are present in, and 1056 chemicals that are released from plastics (Figure 9). The second largest group are unspecified plastics, that includes all sources that did not further specify which polymer type a chemical is used or detected in. While the utility of this evidence is limited, it nonetheless indicates that 2533 chemicals are used or detected in plastics. Much less evidence is available for the remaining major groups, including specialty plastics (all petroleum-based polymer types not included in commodity plastics), elastomers (rubbers and silicones), and bioplastics (all bio-based and/or biodegradable polymers). Importantly, the availability of less information on chemicals in these polymer groups does not imply that fewer

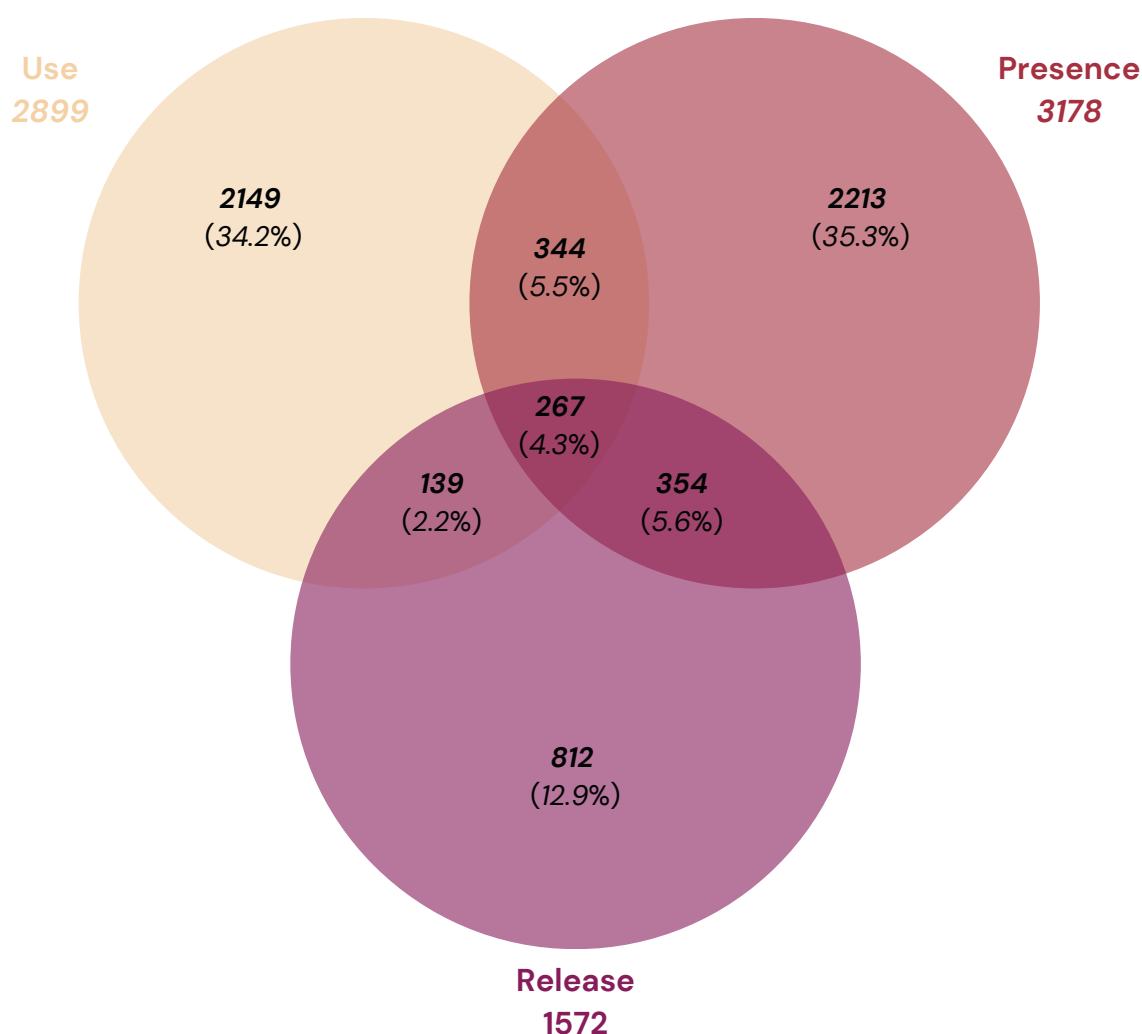


Figure 8: Overlap of plastic chemicals that have information on use, presence, or release.

More than 5000 chemicals are used or present in or released from commodity plastic. Concerning the major groups of polymers, most plastic chemicals (5017 compounds) are used or detected in commodity plastics, including PE, PP, PVC, PET, PUR, PS, and PA.³ This

chemicals are used or may be detected in them. For instance, only 619 chemicals have information regarding their presence or use in bioplastics, compared to 5681 in commodity plastics. This highlights the lack of information on chemicals in other polymer types than commodity plastics.

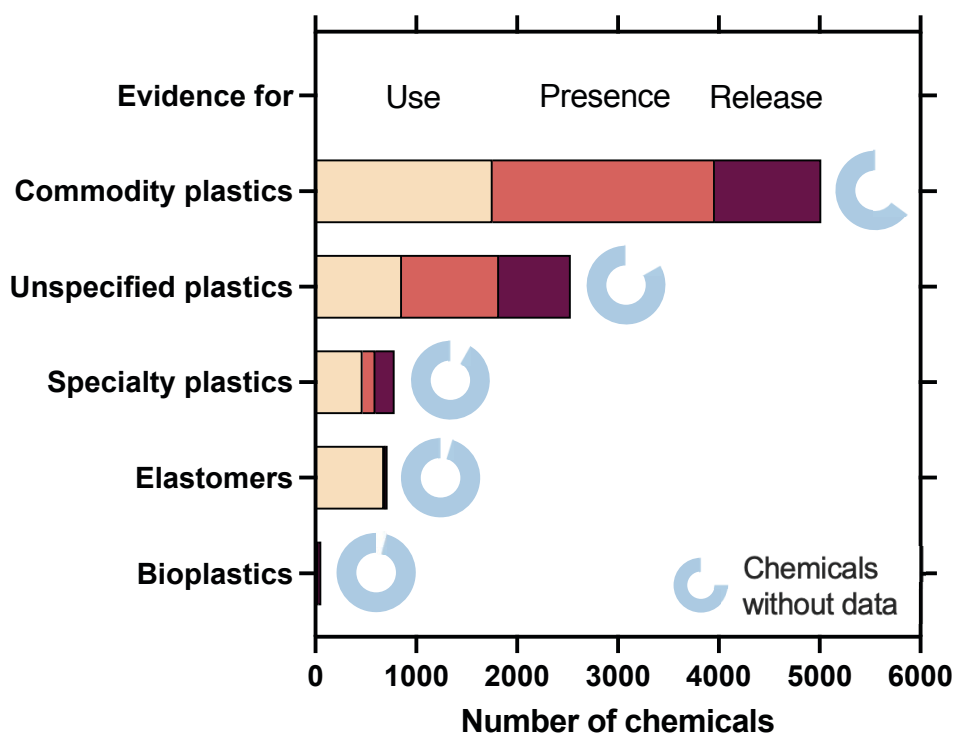


Figure 9: Number of chemicals with evidence for their use, presence, or release from major groups of plastics. Chemicals that have been analyzed but not detected, or with inconclusive detection data, are not shown. The blue pie charts indicate the proportion of chemicals out of all plastic chemicals that do not have respective data.

Many chemicals are used, present or released across all polymer types. Further increasing the granularity allows for investigating how many chemicals are used or present in or released from specific polymer types. Focusing on information-rich polymer types resulted in ten polymer types that have information for >550 chemicals each (Figure 10). Here, 2565 chemicals are used or detected in PET, 1919 in PE, 1393 in PP, 1290 in PVC,

and 1150 in PS. Most of these chemicals (43–72%) have empirical evidence for their presence or release from these polymer types. While the use information is relatively consistent across all polymer types, much less empirical evidence is available for PA, rubber, PUR, ABS and PC, with >60% of evidence on use information stemming from industry sources.

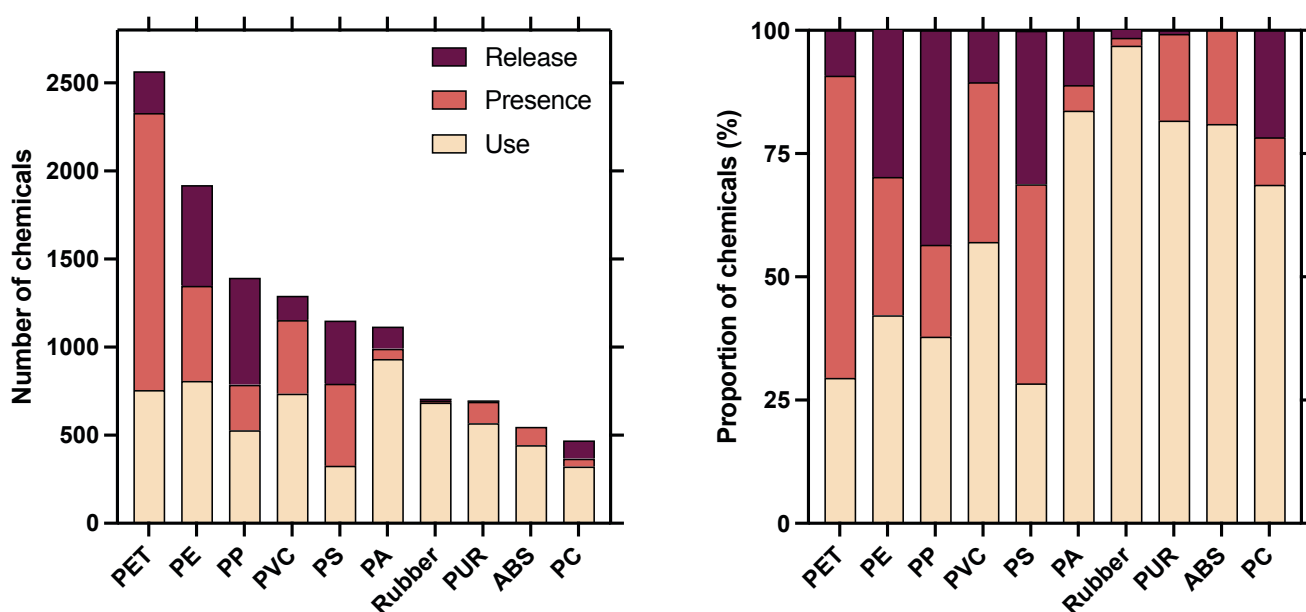


Figure 10: Number of chemicals with evidence for their use, presence, or release from polymer types. Polymer types with data on <400 chemicals are not shown here. Chemicals that have been analyzed but were not detected, or with inconclusive detection data, are also not shown here.

Expert consultations

Throughout the PlastChem project, two rounds of expert consultations were conducted to ensure the research aligned with policy needs and to gather feedback on methods and findings, particularly regarding the prioritization of chemicals of concern. Diverse experts from academia, national regulatory agencies, and international organizations contributed insights in guided interviews that were integrated to ensure the report's policy relevance (details in Annex A4).

Building the PlastChem database

The PlastChem database was built in three steps. Firstly, information from seven previous databases of plastic chemicals was compiled and harmonized in a backbone database. Secondly, hazard information on the chemicals in the backbone database was updated using regulatory sources and integrated (latest update in August 2023). At the same time, information on the use and detection of chemicals in certain polymers and their regulatory status was integrated. In this step, chemicals were also grouped based on their chemical structure. Finally, a framework was developed and applied to identify and prioritize plastic chemicals of concern based on their hazard classification (details in [Part III](#)).

The seven sources for creating the PlastChem database were (1) the dataset of Aurisano et al., 2021,¹⁰⁵ (2) the database of Chemicals associated with Plastic Packaging (CPPdb, version 1),¹⁰² (3) the EU list of Authorized Substances Annex I, Plastic Food Regulation 10/2011/EU (PFCRdb),⁹⁵ (4) the Food Contact Chemicals database (FCCdb, version 5),⁹⁷ (5) the PlasticMAP dataset from Wiesinger et al., 2021,¹⁰³ (6) the dataset on Migrating and Extractable Food Contact Chemicals (FCCmigex, version Feb. 2023),²⁷ and (7) the LitChem dataset.¹⁰⁴ To identify chemical structures in the sources, CASRN or chemical names (when CASRNs were invalid or missing) were used with the automatic API services of PubChem.¹⁰⁶ The PlastChem database was assembled using unique chemical structures and inventory identifiers as basic information. Because of the nature of the data at hand, the PlastChem database content may contain some de facto duplicates. However, extensive quality

control procedures have been applied, together with manual curation to ensure the highest degree of quality possible (details in Annex A4).

Grouping of plastic chemicals

Plastic chemicals were grouped based on their structures by (1) searching a pre-defined set of keys in the chemical names to identify inorganic compounds, organometallics and metalorganics, UVCBs, polymers, and mixtures, (2) searching the name and chemical symbol of respective elements in the chemical names and SMILES to identify chemicals including organohalogen, organophosphate and organosilicon chemicals, as well as various chemicals containing certain metal/metalloid elements, and (3) matching chemicals in the PlastChem databases with existing lists of chemical groups compiled by the US EPA CompTox Chemicals Dashboard, the European Chemicals Agency, the Australia Industrial Chemicals Introduction Scheme, and others. In addition, expert judgement was applied to identify PFAS from all the organofluorine chemicals, as well as those PFAS and short-chain chlorinated paraffins that are regulated under the Stockholm Convention.

Inclusion of hazard information

Hazard information included in the PlastChem database is aligned with those mentioned in the EU Chemicals Strategy for Sustainability (CSS)⁹⁸ and the updated version of the Regulation on Classification, Labelling and Packaging of chemicals (CLP).⁴ Information on these hazard traits was retrieved from 15 regulatory and other sources that are mostly aligned with the UN Globally Harmonized System of Classification and Labelling (GHS), and integrated in the PlastChem database (details in [Part III](#) and Annex A4). Accordingly, hazard criteria for persistence, bioaccumulation, mobility, and toxicity (PBMT) were considered. Persistence and bioaccumulation information is based on persistent, bioaccumulative and toxic chemicals (PBT) and very persistent and very bioaccumulative chemicals (vPvB). Persistence and mobility related hazard information is based on persistent, mobile, and toxic chemicals (PMT) and very persistent and very mobile chemicals (vPvM). Toxicity is based on the hazard traits comprising carcinogens, mutagens,

and reproductive toxicants (CMR), endocrine disrupting chemicals (EDC), and specific target organ toxicity (STOT). In addition, following previous studies,^{97,102,105} aquatic toxicity is included as hazard trait for environmental toxicity following the EU's REACH regulation.¹⁰⁷

Inclusion of additional information

Functions

Information on the known functions of plastic chemicals were gathered from Aurisano et al., 2021,¹⁰⁵ CPPdb,¹⁰² and PlasticMAP.¹⁰³ The latter was used as a starting point given that it provides the most consistent terminology on functions. Information on chemicals not included there was retrieved from the other sources and aligned with that terminology.

Production volume

Production volumes were retrieved from PlasticMAP¹⁰³ which includes data from the OECD list of high-production-volume (HPV) chemicals,¹⁰⁸ the US EPA Chemical Data Reporting Program (CDR),¹⁰⁹ the EU REACH registration dossiers,¹¹⁰ and the Substances in Preparations in the Nordic countries (SPIN) database.¹¹¹ Total global production volumes in PlasticMAP were calculated by combining the tonnages reported in the CDR and EU REACH registration dossiers. The SPIN database was used when no data were available in the EU REACH registration dossiers. In addition, for chemicals without quantitative tonnage information but with listing on the OECD HPV list, tonnages were considered as >1000 tons per year.

Regulatory status

To integrate the regulatory status of plastic chemicals, two lists were created: the MEA list, comprising information from the Basel, Rotterdam, Stockholm and Minamata conventions, and the Montreal Protocol, and the Precedent List, aggregating updated information from various regulatory lists in the EU, Japan, Republic of Korea, and the USA, as well as those substances regulated under the Rotterdam Convention (details in Annex A4). For some chemical groups, such as PFAS regulated under the Stockholm Convention, chemicals were manually annotated.

Information on the use, presence, and release of chemicals in plastic polymers

Data on the use, presence, and release of chemicals from plastics were retrieved from the FCCmigex,²⁷ LitChem,¹⁰⁴ and PlasticMAP¹⁰³ databases. The FCCmigex and LitChem datasets list chemicals with scientific evidence for presence in plastics (e.g., detected in extraction experiments) and for release from plastics (i.e., detected in migration experiments), used as food contact materials (FCCmigex) and other applications (LitChem). PlasticMAP includes use information from industry sources (details in Annex A4).



PART III

Which plastic chemicals matter most?

Assessment of chemicals and
polymers of concern

1

KEY FINDINGS

- » **Scientific criteria can be used to identify and prioritize plastic chemicals of concern.** Hazard criteria address persistence, bioaccumulation, mobility, and toxicity.
- » **Over 4200 or 25% of plastic chemicals are of concern because they are hazardous to human health and the environment.** Half of the chemicals marketed for use in plastics are classified as of concern.
- » **Less than 1% of plastic chemicals may be classified as non-hazardous.** However, a complete hazard assessment is lacking, implying that their safety cannot be determined conclusively.
- » **3651 plastic chemicals of concern are not regulated globally.** These chemicals require most attention, and further granularity may be added by considering information on use, production, and regulatory status.
- » **Fifteen groups of plastic chemicals have been identified as major concern.** These groups contain a high number of chemicals of concern.
- » **Over 1800 chemicals of concern are known to be present in plastics.** This includes more than 500 chemicals of concern that are released from plastic materials and products, indicating potential for human and environmental exposure.
- » **Each major polymer type can contain at least 400 chemicals of concern.** Rubber, polyurethanes, polycarbonates, and PVC are most likely to contain such compounds.

Key knowledge gaps and blind spots

Based on the finding of this report, many plastic chemicals cannot be adequately assessed and controlled because of the:

- » **Absence of hazard information:** Most plastic chemicals, that is, over 10 000 compounds, lack information on their hazard properties.
- » **Paucity of comprehensive hazard assessments:** Only one compound has been fully assessed for all hazard properties, and information on persistence, bioaccumulation, and mobility of most plastic chemicals is lacking.
- » **Incomplete knowledge of presence in plastics:** Information that links plastic chemicals to specific polymer types remains scarce.
- » **Lack of systematic approach in chemical evaluation:** The current assessment of plastic chemicals is fragmented and lacks a systematic approach, leading to inconsistencies and gaps in hazard identification.

2

APPROACH TO IDENTIFY PLASTIC CHEMICALS OF CONCERN

The report identifies and prioritizes plastic chemicals of concern. An evidence-based framework was adopted, integrating information on the harmonized hazard classification and global regulation of plastic chemicals. This approach enables classifying all known plastic chemicals into five priority lists, including a list of chemicals of concern. Furthermore, additional information is provided to effectively manage plastic chemicals not regulated under existing global mechanisms. The same approach is applied to identify groups of chemicals of concern, resulting in the prioritization of groups with a higher level of evidence regarding their hazards. Finally, a conceptual approach is suggested to identify polymers of concern.

Plastic chemicals of concern are identified using a hazard-based approach in this report. The rationale is that such an approach is sufficient and much more efficient for protecting human health and the environment than the common risk-based approach. This follows two lines of arguments: Firstly, information on the exposure of biota, including humans, is required for performing risk assessments, but largely lacking. Generating and assessing such data for the plethora of plastic chemicals is impractical if not unfeasible. Secondly, since widespread exposure must be assumed for many plastic chemicals, requiring exposure assessments for all scenarios introduces unnecessary complexity and risks creating more scientific uncertainty. Additionally confirming and quantifying exposure for every single plastic chemical and exposure scenario would cause substantial delays in policy decisions. Apart from the overwhelming number of chemicals to assess, practical and technical constraints, such as limited resources, data gaps, analytical challenges, and difficulties in establishing exposure-effect causality, prevent comprehensive assessment of the exposure and risks for all plastic chemicals within a reasonable time frame. Using a hazard-based approach as a first step in the management of plastic chemicals allows for effective and most efficient identification of chemicals of concern that require further action. In this framework, four hazard criteria based on persistence, bioaccumulation, mobility, and toxicity were adopted to identify and prioritize plastic chemicals of concern.

3

OVERVIEW OF PLASTIC CHEMICALS OF CONCERN

More than 4200 plastic chemicals are of concern. Looking at the hazard classifications of individual chemicals alone, of the 16 325 plastic chemicals with CASRNs in the PlastChem database, 4219 chemicals (26%) are of concern due to their hazard properties, meeting one or more criteria of PBMT (Figure 11). An additional 1191 compounds (8%) are considered “less hazardous” here since they possess a hazard trait that is one level lower than the hazard criteria used in this study (e.g., mutagenicity 2, or PM only with unknown T), or are present on proposal lists, that is, they are awaiting regulatory assessment or harmonized classification.

The chemicals of concern include well-known and less obvious compounds. Many chemicals of concern are established POPs, such as decaBDE, endosulfane, lindane, PFOA, and UV-328. The list is also topped by organochlorines, such as chloroaniline dyes, vinyl chloride used as monomer in PVC, and vinylidene chloride used as monomer in polyvinylidene chloride

coatings, and by organophosphates used as flame retardants (e.g., dibutyl phosphate, tris(2-chloroethyl) phosphate, triethyl phosphate). However, amongst the chemicals of concern, there are also compounds that have received less scientific and regulatory attention (Table 3). For instance, melamine used as plastic monomer and flame retardant is highly toxic, persistent, and mobile but is nonetheless widely used across sectors, with an annual production volume of at least 2 million tons. This compound, along with other chemicals of concern, such as ammonium 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy) propanoate (GenX chemical) and 2,4,6-tri-tert-butylphenol, have been identified as Substances of Very High Concern (SVHC) under the EU REACH regulation.¹¹²

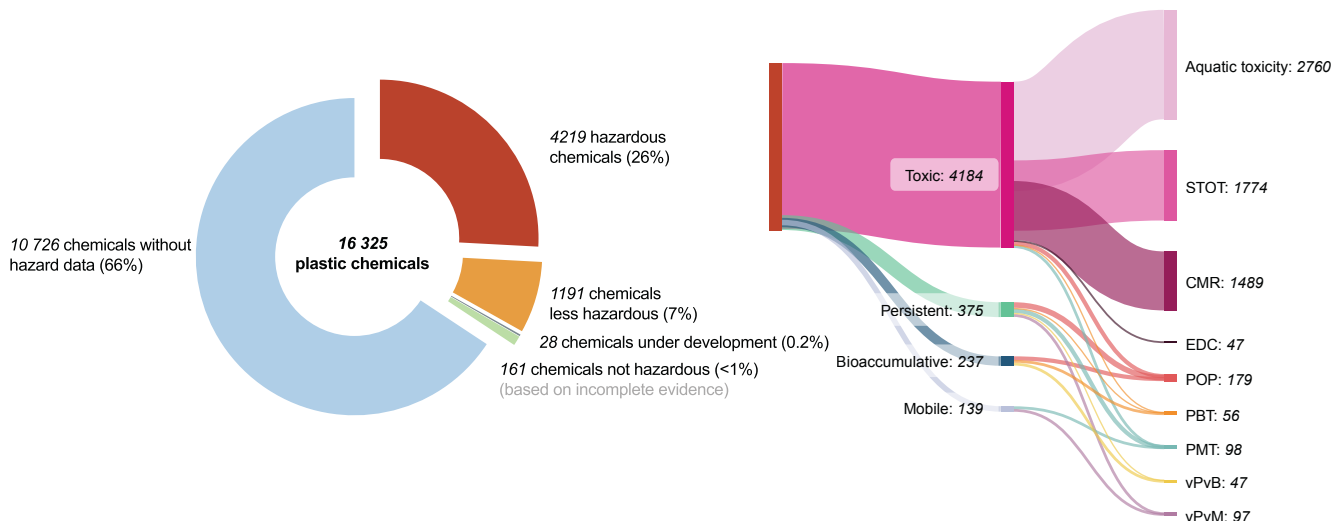


Figure 11: Overview of chemicals classified as hazardous, less hazardous, not hazardous, and with no hazard data. The right-hand side shows which hazard criteria (PBMT) and traits the chemicals of concern fulfil.

Table 3: Examples of 20 relevant chemicals with high hazard score (HS) and evidence score (ES).

CASRN	Chemical name	HS	ES	Chemical group	Hazard traits							
					CMR	EDC	STOT	Aquat. tox.	PBT	vPvB	PMT	vPvM
108-78-1	Melamine	6.25	6	-	X		X	X			X	X
62037-80-3	Ammonium 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoate (Gen X)	6.25	3	PFAS			X				X	X
101-80-4	4,4'-Oxydianiline	6	25	Aromatic amines	X		X	X			X	X
111-96-6	Diglyme	6	9	-	X						X	X
3846-71-7	2-(2H-Benzo[d][1,2,3]triazol-2-yl)-4,6-di-tert-butylphenol	6	9	Alkylphenol, Benzotriazoles			X			X	X	
732-26-3	2,4,6-Tri-tert-butylphenol	6	6	Alkylphenol			X	X		X	X	
36437-37-3	2-(2H-Benzotriazol-2-yl)-4-(tert-butyl)-6-(sec-butyl)phenol	6	7	Benzotriazoles			X			X		
307-55-1	Perfluorododecanoic acid	6	3	PFAS				X		X		
29385-43-1	4-(p-Tolyl)-1H-1,2,3-triazole	5	3	Benzotriazoles	X			X				X
79-94-7	Tetrabromobisphenol A	4	10	Bisphenol	X			X		X		
27955-94-8	1,1,1-Tris(4-hydroxyphenyl)ethane	3	5	Bisphenol				X			X	
84-61-7	Dicyclohexyl phthalate	2.5	8	Phthalates	X	X		X				
84-69-5	Diisobutyl phthalate	2.5	10	Phthalates	X	X		X				
4979-32-2	N,N-Dicyclohexyl-2-benzothiazolesulfenamide	4.5	2	Benzothiazoles				X		X		
120-78-5	2,2'-Dithiobisbenzothiazole	2	3	Benzothiazoles				X				
103-95-7	3-(4-Isopropylphenyl)-2-methylpropanal	2	4	Aralkyldehydes	X			X				
80-54-6	Lilial	2	7	Aralkyldehydes	X		X	X				
103-50-4	Dibenzyl ether	2	3	Aromatic ethers				X				
93-04-9	2-Methoxynaphthalene	2	2	Aromatic ethers	X		X	X				
119-36-8	Methyl salicylate	2	4	Salicylate esters	X		X	X				

Note: CMR = carcinogenic, mutagenic, reproductive toxicant, EDC = Endocrine disrupting chemical, STOT = Specific Organ Toxicity, PBT = persistent, bioaccumulative and toxic, vPvB = very persistent, very bioaccumulative, PMT = persistent, mobile, toxic, vPvM = very persistent, very mobile

Data gaps prevent identifying non-hazardous plastic chemicals. While 161 plastic chemicals (<1%) are considered as not hazardous in this analysis, none of them has been fully assessed for all relevant hazard properties. In other words, these chemicals are not hazardous based on an incomplete hazard assessment, and thus, should not necessarily be considered safe. For example, only 12 chemicals have been evaluated for their PBT properties and are considered not persistent, not bioaccumulative, and not toxic (Table 4) but have not been evaluated for mobility. Further data collection and hazard assessment are still relevant for these 161 chemicals as most of them have been assessed for toxicity exclusively.

Table 4: List of the 12 plastic chemicals that are not persistent, not bioaccumulative, and not toxic based on the hazard information in the consulted sources.

CASRN	Chemical name
1103-38-4	Pigment Red 49:1
26401-35-4	Diisotridecyl adipate
28182-81-2	Hexamethylene diisocyanate homopolymer
3520-72-7	Benzidine orange
5333-42-6	2-octyl-1-dodecanol
61790-51-0	Resin acids and rosin acids
632-79-1	Tetrabromophthalic anhydride
6683-19-8	Pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate)
75-78-5	Dichlorodimethylsilane
8027-33-6	Lanolin alcohols
85507-79-5	Diundecyl phthalate, branched and linear
91082-17-6	Phenyl 1-pentadecanesulfonate

Two thirds of plastic chemicals lack hazard information. Around 66% (10 726) of all plastic chemicals have no hazard information available in the consulted sources and thus have not been evaluated in this study (Figure 11). Accordingly, it

remains unknown whether two thirds of plastic chemicals are of concern or not, highlighting the remarkable lack of (accessible) information on the hazards of many plastic chemicals and the order of magnitude of efforts that remain to understand and manage plastic chemicals.

Combining multiple sources reveals more chemicals of concern in plastic. Combining, harmonizing, and updating the different hazard classifications results in >1100 additional chemicals being considered as “of concern”, compared to the latest UNEP assessment on chemicals in plastics.² PlastChem, thus, significantly expands the knowledge on the presence of hazardous chemicals in plastics. When comparing the results of this report with previous work (Table 5), the following aspects need to be noted. First, while 4554 chemicals are present in various hazard lists, the sources do not provide actual hazard data for these chemicals. Thus, previous studies overestimated the number of chemicals with actual hazard information, whereas the present report captures this aspect. Second, in accordance with UNEP’s Technical Report² and previous literature,^{103,105} PlastChem also differentiates between recognized (harmonized regulatory sources) and identified (self-classified by the industry under REACH) chemicals of concern.

340 chemicals of concern fulfill at least three hazard criteria. Out of these chemicals of concern, one is persistent, bioaccumulative, mobile and toxic (1,2,3-trichlorobenzene, CASRN 87-61-6), 224 are persistent, bioaccumulative and toxic (PBT), and 115 persistent, mobile and toxic (PMT). This means that 8% of the chemicals of concern in plastics fulfill at least three hazard criteria. 23 additional chemicals are persistent and mobile, and 12 chemicals are persistent and bioaccumulative. Importantly, the vast majority of chemicals of concern, namely 3844 chemicals, are toxic but have not been evaluated for other hazard criteria (Figure 12). These toxic compounds have mostly been classified as toxic to the aquatic environment (Aquatic toxicity), to specific organs (STOT), and are carcinogenic, mutagenic, or toxic to reproduction (CMR), with considerable overlap between the toxicity traits. In addition, the toxic chemicals comprise 47 endocrine disrupting chemicals.

Table 5: Comparison of the number of chemicals listed, evaluated, and identified as hazardous in PlastChem and the previous databases.

Source	All chemicals with CASRN	Chemicals on hazard lists ^a	Chemicals with hazard data	Hazardous chemicals
Wiesinger et al. (2021) ¹⁰³	10 547	6400	Not analyzed	2486
UNEP Technical Report (2023) ²	>13 000	7000	Not analyzed	>3200
Aurisano et al. (2021) ¹⁰⁵	>6000	1463	Not analyzed	590
PlastChem	16 325	10 153	5599	4332
		3437 (recognized)	2669 (recognized)	2131 (recognized)
		6715 (identified)	930 (identified)	2201 (identified)

Note: ^a This means that some chemicals present on a list of hazardous chemicals do not have associated hazard data. Consequently, some of the sources overestimate the number of chemicals that have been assessed for their hazards.

More than half of the chemicals of concern are classified as hazardous by at least two sources. 2388 plastic chemicals (57%) have been classified as hazardous by two or more regulatory sources and 20%, or 829 chemicals, have at least five sources showing their hazard classifications (Figure 13). 221 chemicals are particularly well assessed with ten or more sources classifying them as hazardous. This leaves 1831 chemicals

of concern for which the hazard classification is derived from a single source.

Most chemicals of concern are toxic to human health or the environment. More than 4500 chemicals have been evaluated for aquatic toxicity, and >60% (2760) are classified as toxic for the aquatic environment (Figure 12). The second most frequently assessed hazard trait

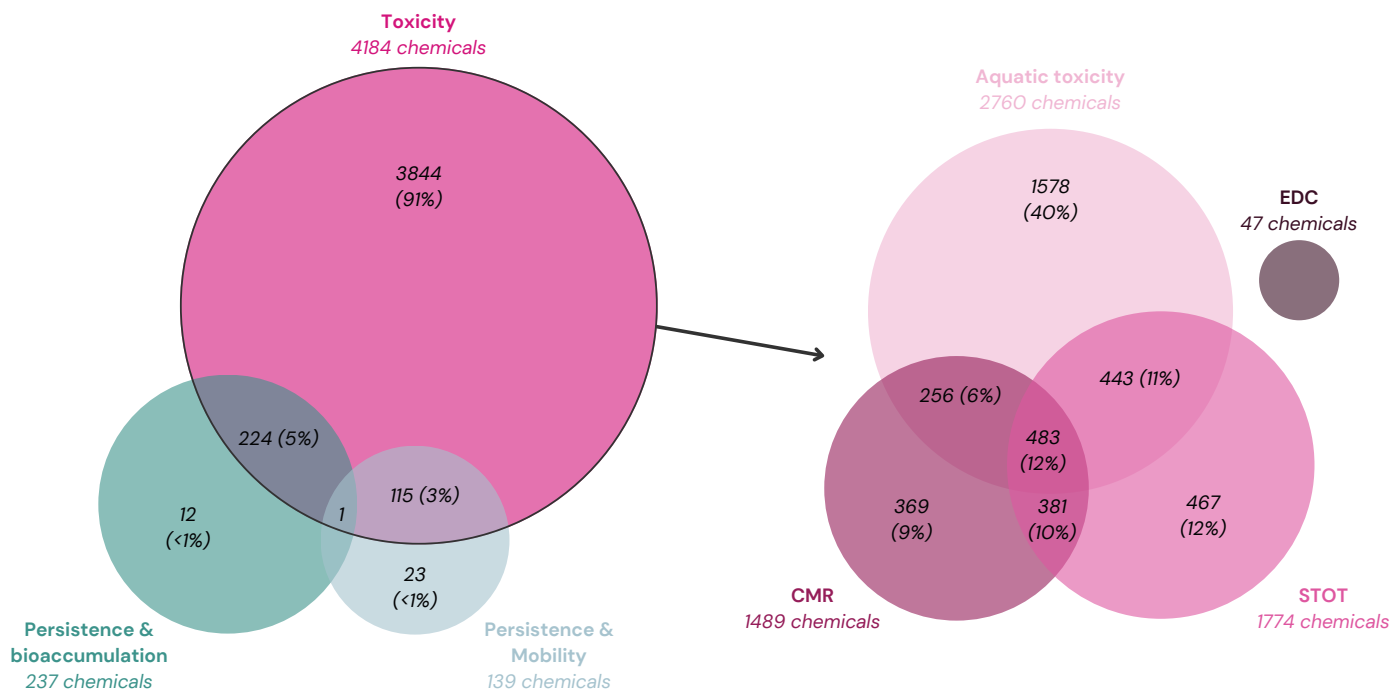


Figure 12: Overview of the hazards posed by plastic chemicals of concern. The figure presents the overlaps between the hazard criteria (left) and overlaps between toxicity traits (right). The endocrine disrupting chemicals (EDCs) overlap with other toxicity traits but are shown separately for the sake of simplicity.

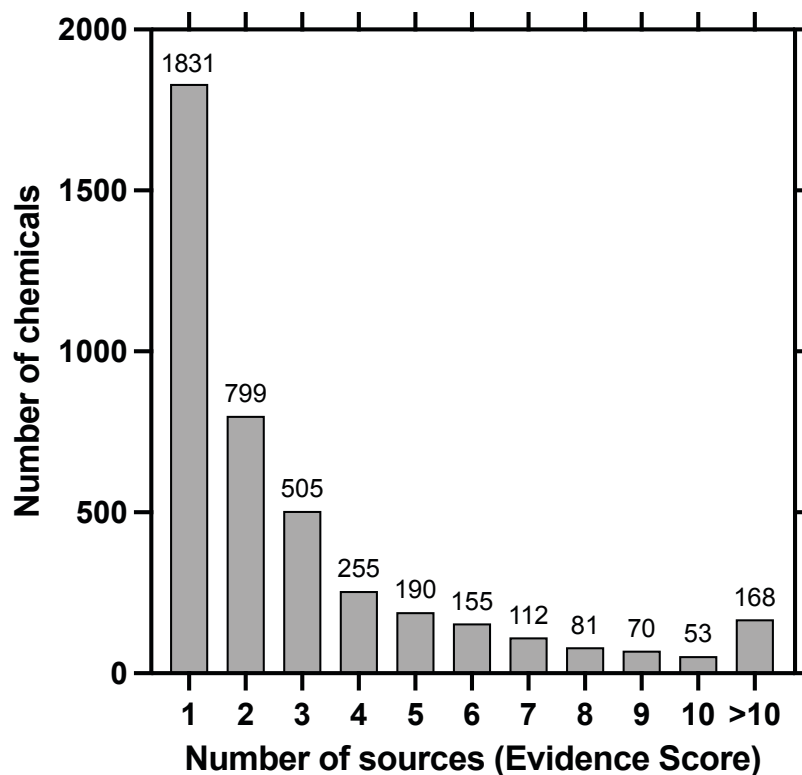


Figure 13: Number of chemicals of concern according to their respective number of sources that classify them as hazardous (Evidence Score).

is CMR, aggregating carcinogens, mutagens, and reproductive toxicants, with more than 2200 chemicals evaluated and 67% (1489) classified as CMRs. 1801 compounds have been evaluated for Specific Target Organ Toxicity (STOT), with almost all of them (1774 compound, 99%) being classified as hazardous. Endocrine disruption has recently been included in the CLP regulation¹¹³ but is a less frequently evaluated toxicity trait (121 chemicals), with 47 identified EDCs.

Persistence, bioaccumulation, and mobility are less assessed hazard criteria. In contrast to toxicity, hazard criteria related to persistence, bioaccumulation, and mobility are less frequently assessed and classified, with 732 chemicals evaluated in total and 64% of them being considered persistent, bioaccumulative, or mobile. Mobility is still rarely assessed, with 187 compounds evaluated and 74% of them being classified as such. Persistence and mobility (PMT, vPvM) have been recently added under the EU CLP as a new criterion for hazardous substances.¹¹⁴

Considerations and limitations. Importantly, the absence of a plastic chemical from a hazard list or the lack of hazard information do not imply that this chemical is not hazardous. Only chemicals that have been assessed and classified as not hazardous are considered as

such in PlastChem. Regarding the data gaps, >10 000 chemicals have no associated hazard information, and thus have not been assessed by the regulatory sources consulted here. This represents a substantial knowledge gap that hampers a comprehensive assessment of the known plastic chemicals. Therefore, it is important to note that the PlastChem list of chemicals of concern represents the state of the science at the time of this synthesis (2023) and may change once updated with new information (e.g., more chemicals of concern will be discovered as knowledge and assessments evolve). This highlights that a regular update of the list of chemicals in plastics and their hazards is crucial to reflect the evolving state of science and regulation.

4

PRIORITY PLASTIC CHEMICALS

A tiered approach can be applied to regulate plastic chemicals. The PlastChem report provides six lists for prioritization of plastic chemicals for regulatory action (Figure 14).

- » The MEA List includes 980 chemicals that are currently regulated under existing MEAs, namely the Basel, Stockholm, and Minamata Conventions as well as the Montreal Protocol. Noting that the Basel Convention may regulate these chemicals at a specific life-cycle stage (i.e., waste), more comprehensive regulation of some of these chemicals may be needed.
- » The Red List contains the 3651 chemicals of concern that are currently not regulated internationally. These chemicals are hazardous according to well-established criteria (one or more hazard criteria) and should be regulated.
- » The Orange List covers 1168 chemicals that have been classified as less hazardous (e.g., carcinogenic, mutagenic category 2). They may be further watched, as additional hazard traits may be identified.
- » For the 28 chemicals on the Watch List, a hazard evaluation is currently under development or inconclusive. Similar to the Orange List, it includes chemicals that have potential to become chemicals of concern once fully assessed.
- » The chemicals on the White List are classified as not hazardous but their hazard profiles are incomplete. While there is some level of evidence that White List chemicals are not of concern, the incomplete hazard assessment warrants prioritization for further evaluation to provide a complete hazard profile.
- » The largest list, the Grey List, includes 10 345 plastic chemicals without hazard information. Those chemicals constitute the biggest knowledge gap as their hazard properties are unknown based on the authoritative sources consulted. In the absence of this information, no regulatory action is possible at this point. However, three strategies can help fill these knowledge gaps. Firstly, compounds can be assessed based on the chemical groups they belong to. Secondly, additional regulatory, scientific, and industry sources can be consulted to collect additional hazard information. Given that these sources are scattered over the public domain, additional efforts may be time- and resource-intensive. Lastly, chemicals on the Grey List could be prioritized for research into their hazards and for assessments.

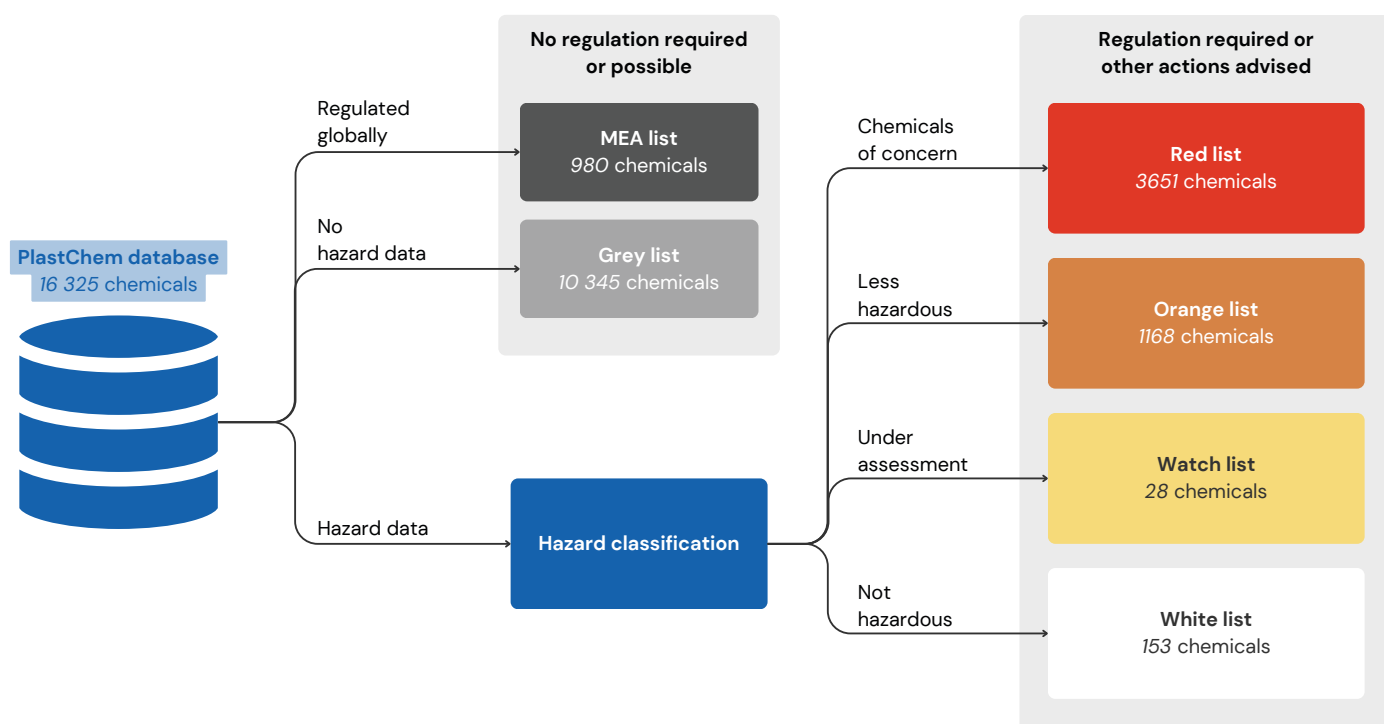


Figure 14: Overview of the six PlastChem lists.

The Grey List chemicals require a prioritization for assessment. The PlastChem database contains information on the use and detection, as well as on the production volumes, of 7047 chemicals that can aid prioritization. Both types of information on use/detection and production volume represent a proxy for the exposure potential of a chemical. 6531 chemicals without hazard data have evidence for their use or detection in plastics, and 2350 chemicals are produced at quantities of ≥ 1 ton per year, with both types of information being available for 1856 chemicals. When combining the information, 341 chemicals that are used or have been detected in plastics are high-production-volume chemicals (≥ 1000 tons per year), and thus, could be prioritized for hazard assessment. This selection could be further refined by filtering for chemicals with high exposure potential, such as chemicals with evidence for their release from plastics (85 chemicals in this report). Using such a prioritization approach could ensure that some plastic chemicals are fast-tracked for assessment based on the relevant scientific evidence. Nonetheless, this approach may overlook other important plastic chemicals for which any additional data is unavailable in the public domain.

5

SCENARIOS FOR FURTHER PRIORITIZING CHEMICALS OF CONCERN

Additional information can be used to further prioritize plastic chemicals of concern. The Red List chemicals should be regulated with high priority. However, should policymakers identify the need to further prioritize these plastic chemicals for official assessment, additional scientific, market, and regulatory criteria can be used to do so. This includes the degree of hazard (Hazard Score) in combination with the level of evidence for hazardousness (Evidence Score), use and detection data, production volumes, and the status of national or regional regulation (Figure 15). Importantly, it should be noted that such prioritization is based on political decisions rather than scientific evidence. Accordingly, the report provides scenarios for further ranking plastic chemicals of concern (Table 6).

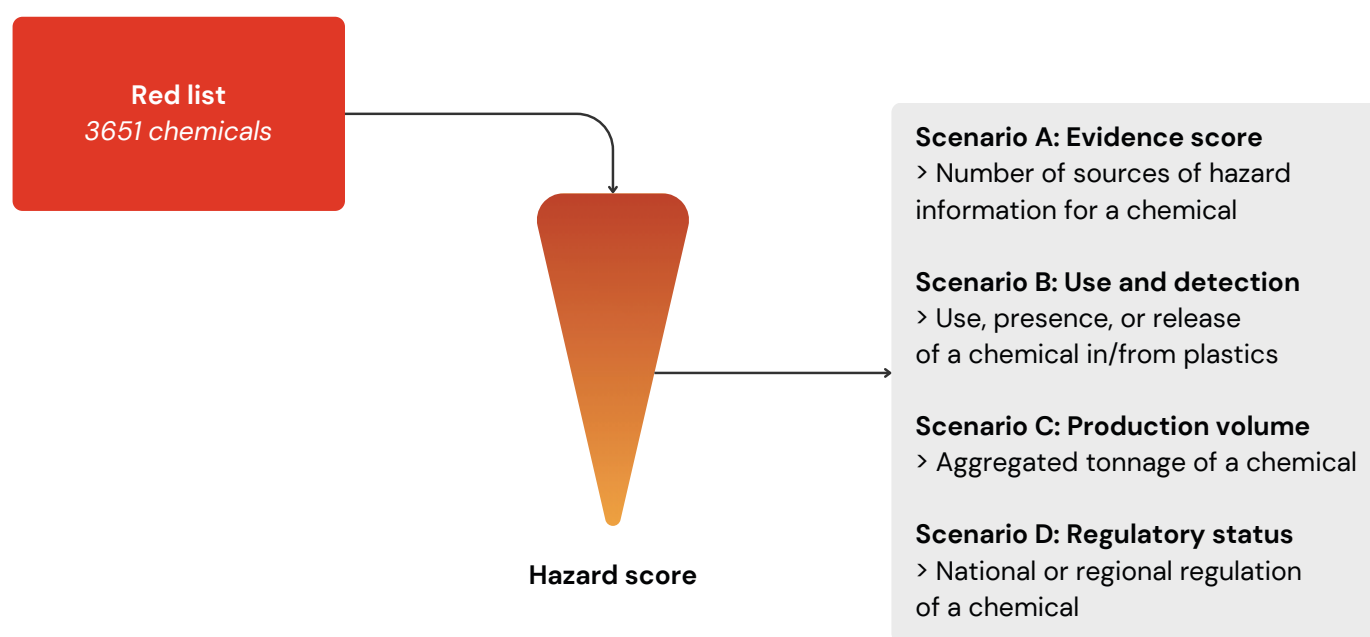


Figure 15: A conceptual approach for prioritizing chemicals of concern in plastics.

Table 6: Comparison of the different scenarios for further prioritization of the Red List chemicals. The different parameters used for building the scenarios, the arguments, the resulting chemicals to prioritize, as well as the limitations are shown.

Scenario	Base	Scenario A	Scenario B	Scenario C	Scenario D
Based on	Sum of Hazard Scores	Evidence Score	Use and detection	Production volume	Regulatory status (Precedent list)
Arguments	Higher confidence in regulatory action for chemicals with more hazard traits.	Higher confidence in regulatory action for chemicals with more information on hazards.	Higher exposure potential for chemicals that are used or detected in plastics.	Chemicals with high production volumes have higher a higher exposure potential.	Chemicals already regulated in some regions or countries provide more confidence in regulatory action.
Priority chemicals	Scenario Base – Hazard Score ≥ 2 : 2672 chemicals	Scenario A1 – evidence score ≥ 2 : 1929 chemicals	Scenario B1 – for use and detection: 1506 chemicals	Scenario C1 – high production: 1903 chemicals	Scenario D1 – regulated nationally or regionally: 861 chemicals
	Scenario 2 – Hazard Score ≥ 3 : 184 chemicals	Scenario A2 – evidence score ≥ 10 : 208 chemicals	Scenario B2 – for detection: 787 chemicals	Scenario C2 – very high production: 324 chemicals	
Limitations	Data limited and incomplete for all red list chemicals and may be biased towards well-known chemicals.	Data limited and incomplete for all red list chemicals and may be biased towards well-known chemicals.	Data incomplete and not feasible to obtain for all red list chemicals and may be biased towards well-known chemicals.	Data incomplete and limited to few countries, data may include non-plastic uses.	Data limited to few countries. Mapping national legislations comprehensively is resourc intensive and requires continuous updates.

Base scenario: Hazard Score

Ranking according to the Hazard Score is the base scenario for prioritization. This score represents the sum of classifications across all hazard traits. The rationale for taking such an approach is that a chemical that possesses more than one hazard trait (e.g., it is persistent, bioaccumulative, and carcinogenic) may be considered more problematic than a chemical that has only one hazard trait. Importantly, this approach is limited by the fact that the assessment of hazard traits is incomplete for all Red List chemicals and skewed towards toxicity data and towards well-known chemicals. Another consideration is that oftentimes, fulfilling one hazard criterion (e.g., carcinogenicity) is sufficient to warrant regulatory action.

Under Scenario Hazard 1, 2672 chemicals would be considered as of priority for action. Setting the cut-off for prioritization at a Hazard Score of ≥ 2 results in 2672 plastic chemicals that would be subjected to an official assessment (Figure 16). This represents 73% of the Red List chemicals and includes 184 compounds with a Hazard Score ≥ 3 that fulfill at least two hazard criteria, namely 1 PBMT chemical, 34 PBT chemicals, and 112 PMT chemicals. The 2488 remaining chemicals consist mostly of chemicals that are very toxic (e.g., 457 chemicals classified as carcinogenic 1A or 1B). Accordingly, the most concerning chemicals with high toxicity alone or in combination with other hazards would be first regulated under Scenario Hazard 1.

Scenario Hazard 2 is less ambitious and would prioritize 184 chemicals. The cutoff for regulation is set at a Hazard Score of ≥ 3 , resulting in 184 regulated plastic chemicals (5% of all the Red List chemicals). Among them, 94 chemicals have a Hazard Score of >5 and fulfill at least three hazard criteria, including 1 PBMT, 22 PBT, and 71 PMT compounds. The next 90 chemicals have a Hazard Score of 3 to 5, with 51 compounds fulfilling at least three hazard criteria, being classified as PBT or PMT.

Scenario A: Evidence Score

The Evidence Score can be used to rank chemicals based on the number of regulatory sources that classify a chemical as concerning. It reflects the level of evidence available for the hazard of a chemical and can be used to further prioritize chemicals. The rationale for applying the Evidence Score is that the more evidence is available for a hazard criterion, the more likely it is to reach consensus in the hazard assessment. However, it should be noted that for the identification of chemicals of concern, additional testing of chemicals for all possible hazard traits should not be requested if robust evidence on one adverse effect (e.g., carcinogenicity) exists. For instance, some highly hazardous chemicals have only been evaluated for one hazard trait (i.e., low Evidence Scores). Thus, many chemicals of concern would be missed, should the Evidence Score be applied as the only criterion for prioritization. In addition, the Evidence Score is

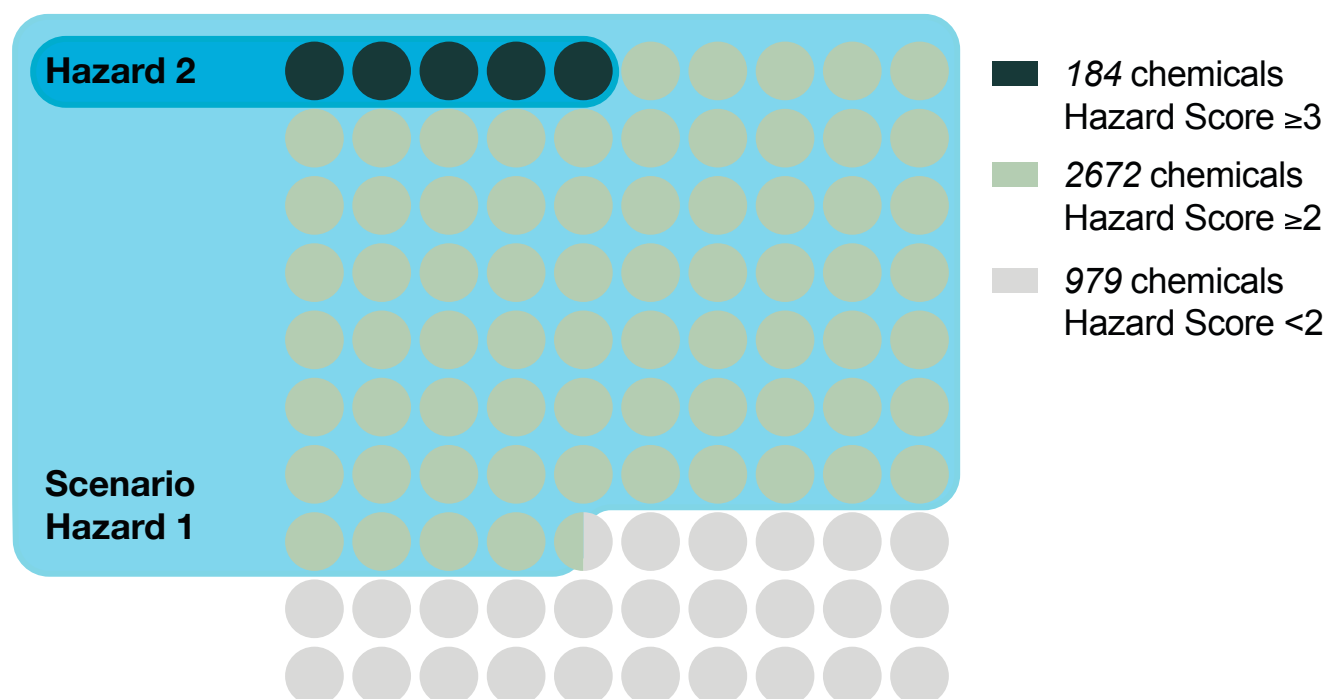


Figure 16: Scenarios for prioritizing the Red List chemicals based on their Hazard Score.

susceptible to bias since regulators often do not perform another hazard assessment once one institution has classified a compound. As a result, a low Evidence Score might simply imply that an existing classification suffices for regulators to move towards the management of a chemical.

Scenario Evidence A1 prioritizes chemicals with at least two sources of hazard classification.

Setting a cut-off at 2, that is, filtering for chemicals that have been classified as hazardous by least two sources, results in the prioritization of 1929 compounds (Figure 17). The other 1689 Red List chemicals have an Evidence Score of 1, meaning that their hazard classification originates from a single regulatory source.

Scenario Evidence A2 requires a very high level of evidence and results in 208 priority chemicals. Setting the threshold for the Evidence Score at 10 prioritized 208 plastic chemicals that are included in at least ten sources for their hazard classification. This would be very restrictive and prioritize only chemicals with overwhelming information on their hazard properties. Importantly, a high Evidence Score does not necessarily correspond to chemicals that match multiple hazard criteria since almost three fourths of the chemicals included in this scenario (106 chemicals) have abundant evidence for their toxicity but have not been assessed for other hazards. Accordingly, Scenario Evidence A2 would regulate those chemicals with the highest evidence for their toxicity and

cannot capture emerging chemicals for which an assessment is limited.

Scenario B: Use and detection in plastics

Use and detection data can be used to prioritize chemicals of concern with high potential for exposure to humans and the environment. Approximately 40% of the Red List chemicals have additional evidence for their use or detection in plastics. This means that these chemicals are marketed for use in plastics or have empirical evidence for their presence in or release from plastic materials and products based on scientific studies. A major benefit of applying this approach is that it filters for chemicals that are indeed known to be used or present in plastics. However, a critical limitation is that the detection information is biased towards well-studied plastic chemicals. Likewise, the use information is fragmentary. Accordingly, using this information for prioritizing chemicals of concern risks missing other relevant chemicals that are used in plastics but that have limited public information on their use and presence.

Scenario Use and Detection B1 prioritizes 1519 Red List chemicals with evidence for their use or detection in plastics. This represents 42% of all plastic chemicals of concern (Figure 18). This scenario covers both, chemicals that are marketed for use as well as compounds that have been detected in or are released from plastics.

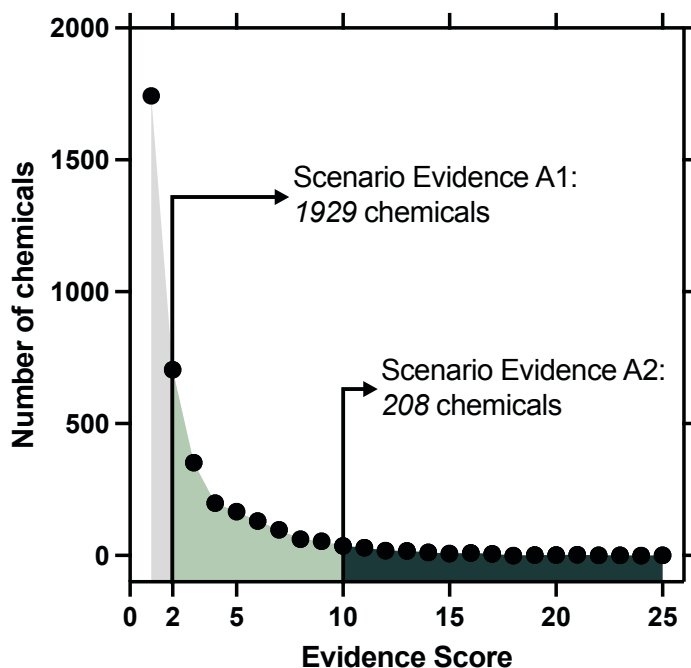


Figure 17: Scenarios for prioritizing the Red List chemicals based on their Evidence Score.

Accordingly, there is a high level of evidence that these 1509 priority chemicals are indeed present in plastic materials or products.

Scenario Use and Detection B2 covers 882 chemicals with scientific evidence for their presence in or release from plastics. This represents roughly 25% of the Red List chemicals. Among them, 696 have been detected in and 473 are released from plastic materials or products, with 287 compounds fulfilling both. More than 90% of the detected chemicals are identified as toxic, with aquatic toxicity, STOT and CMR being the most frequent hazard traits. The remaining 10% of chemicals are PBT (5%) or PMT (5%). Since this scenario exclusively relies on empirical evidence, it is more restrictive.

low quantities might still represent a health issue if it is very hazardous and causes severe impacts at low concentrations or if it is used in high quantities in specific plastic products. Meanwhile, the production volumes used here reflect all uses, including those that are unrelated to plastics. As elaborated above, this lack of more granular information renders it impossible to resolve the production volumes dedicated to plastics and might result in selection of high production volume chemicals of which only a small share is actually used in plastics.

Under Scenario Production C1, 1903 chemicals would be regulated. These Red List chemicals have an annual production volume of ≥ 1000 tons per year and are considered high production

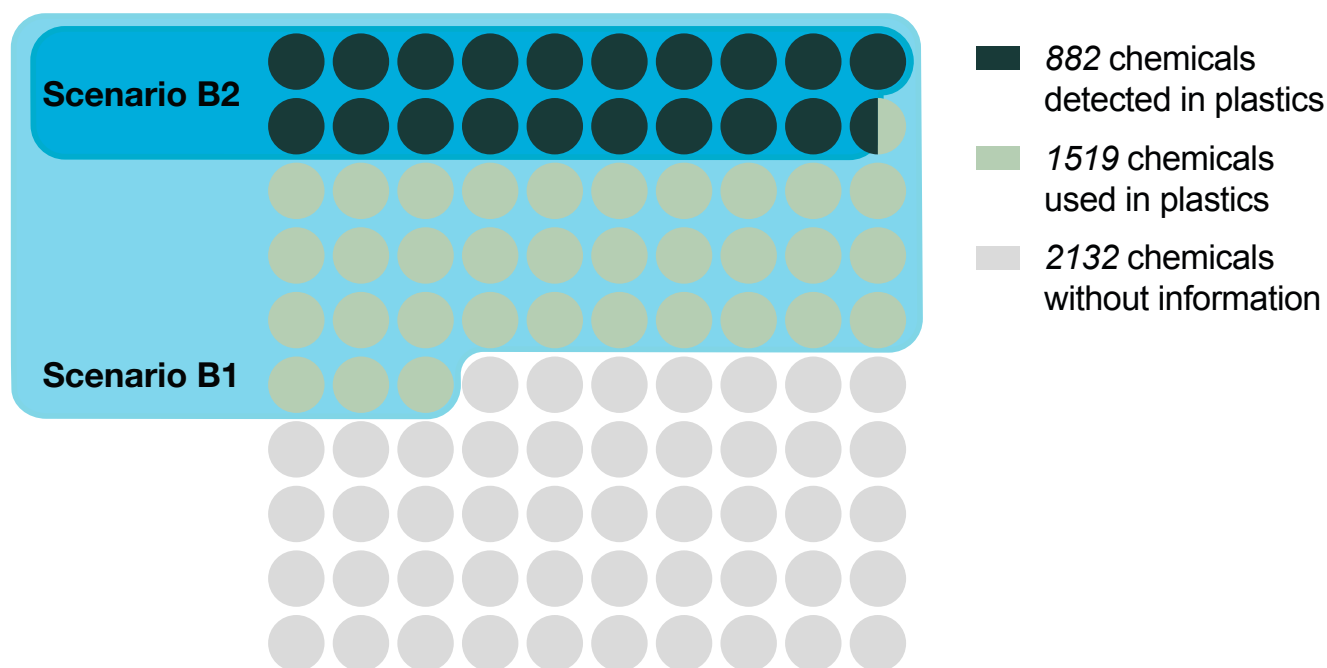


Figure 18: Scenario for prioritizing the Red List chemicals based on their use or detection in plastics.

Scenario C: Production volume

A prioritization based on production volumes assumes chemicals have a higher exposure potential when manufactured at higher quantities. However, this information is only available for 2785 out of the 3651 Red List chemicals (76%). This means that the remaining chemicals could be produced in large quantities with a correspondingly high exposure potential but are not prioritized due to data gaps. In addition, the production volumes used here are based only on information from the EU, USA, and other OECD countries. Thus, the production volumes used here are likely underestimated. Furthermore, production volumes might be a poor proxy for the exposure potential of a chemical. For example, a chemical produced in

volume chemicals (Figure 19). Regulating these compounds would cover about half of all plastic chemicals of concern.

Scenario Production C2 would regulate a few chemicals with very high production volumes. Increasing the production volume cut-off to at least 1 million tons per year results in prioritizing 324 chemicals of concern for regulation. These chemicals include many plastic feedstocks used to produce starting substances (e.g., butane, ethane, petroleum distillates), starting substances including many monomers (e.g., ethylene, propylene) and reactants (acids, solvents, catalysts), and additives used as fillers (e.g., titanium dioxide, carbon black, kaolin). The ubiquitous use of these chemicals in processes,

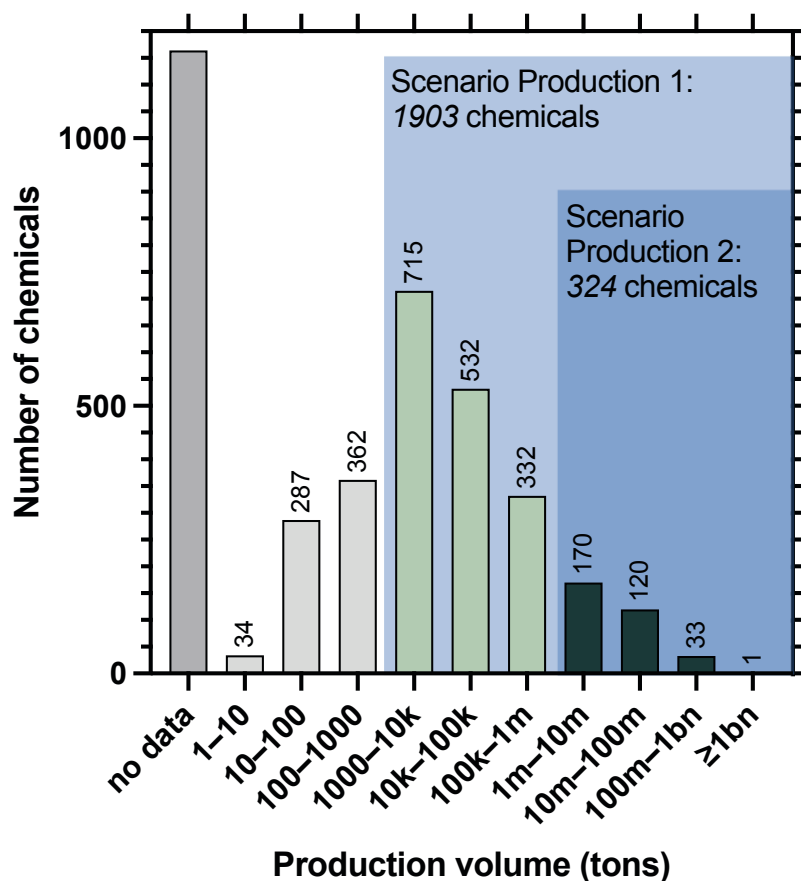


Figure 19: Scenarios for prioritizing the Red List chemicals based on their production volumes.

materials, and products unrelated to plastics might make it difficult to enforce regulations on their use in plastics. While higher resolution data are unavailable to refine the share of production volumes relevant to plastics, policymakers may have to refine the filtering approach when using production volume as a criterion.

Production volume can also be used to prioritize chemicals that lack other information. Despite its limitation, production volume data can be used to select chemicals for assessment or prioritize them for gathering additional information (Figure 20). For instance, policymakers could decide to prioritize the testing and assessment of the 496 chemicals that have been classified as less hazardous but have a high production volume. The same is true for the 1334 high production volume chemicals that lack hazard data. Conversely, the 1165 Red List chemicals that do not have information on their production volumes may be fast-tracked to gather missing data. Such an approach would enable a strategic prioritization of plastic chemicals for assessment.

Scenario D: National or regional regulatory status

The national or regional regulatory status provides additional arguments to prioritize plastic chemicals of concern. The Precedent List includes chemicals that are currently regulated in the EU (212 chemicals), California (286 chemicals), Japan (37 chemicals), and the Republic of Korea (570 chemicals). They also include 151 chemicals regulated under the Rotterdam Convention. The reason for prioritizing chemicals already regulated by certain countries or regions is that the existing precedent provides additional confidence in that concerns over these compounds warrants regulatory action. It is important to note that the information collected on the regulatory status of plastic chemicals originates almost exclusively from Global North countries and regions. This creates a bias in the precedent list as it misses plastic chemicals regulated in other countries or regions. The main reason for such bias is that gathering and harmonizing regulatory data from multiple jurisdictions is resource-demanding and outside the scope of this report.

Under the Regulatory Scenario, 861 chemicals currently regulated regionally or nationally

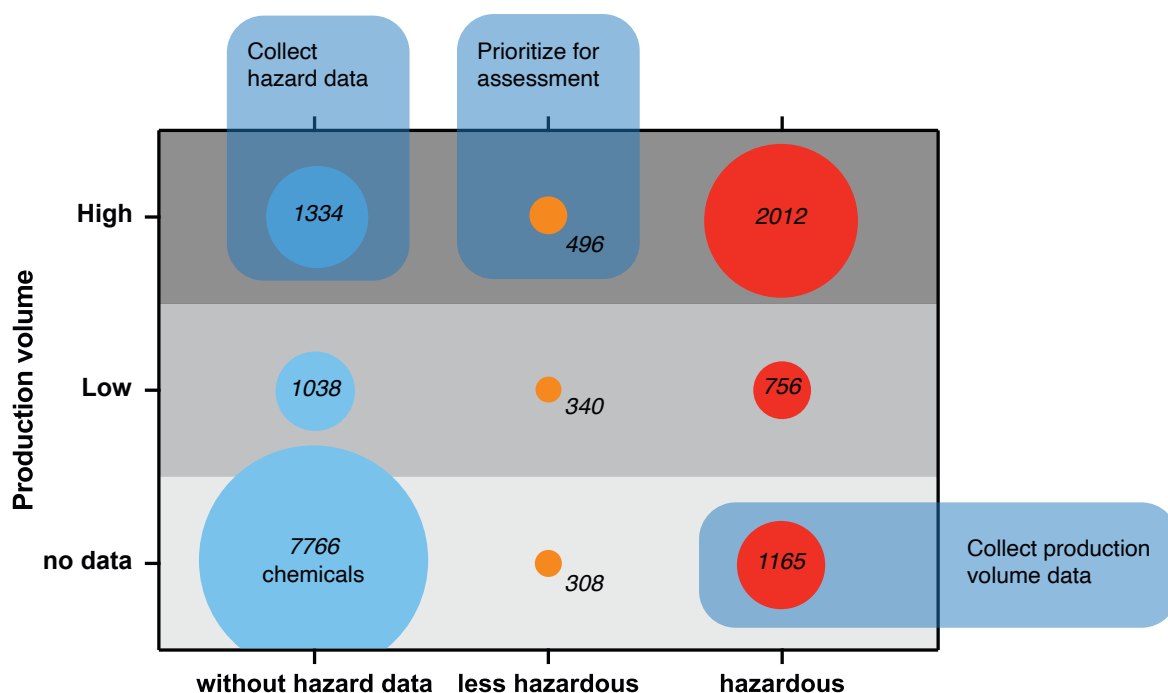


Figure 20: Number of chemicals in the PlastChem database with and without hazard data according to production volume. The highlighted chemicals could be prioritized for gathering additional information or assessment. Production volume bands correspond to 1–1000 (low) and ≥1000 (high) tons per year.

would be prioritized. This represents approximately one quarter of all plastic chemicals of concern (Figure 21). The average Hazard Score is 2, with 854 compounds (99%) being identified as toxic, 51 as PMT (6%) and 25 as PBT (3%). 489 chemicals are CMRs, 517 induce specific target organ toxicity (STOT), 513 are toxic to the aquatic environment, and 42 are endocrine disrupting chemicals. In addition, more than 55% of these compounds have evidence for their presence in or release from plastics (205 and 149 chemicals, respectively).

Combined scenarios

The additional information can be combined to tailor regulatory measures. For example, the scenarios outlined above can be merged to filter for Red List chemicals with an Evidence Score of ≥2, that are used or have been detected in plastics, and are produced in quantities ≥1000 tons. Such a selection results in a set of 638 Red List chemicals that could be prioritized (Figure 22). In another combination, 499 chemicals already regulated in some countries and regions and with a high production volume could be prioritized.

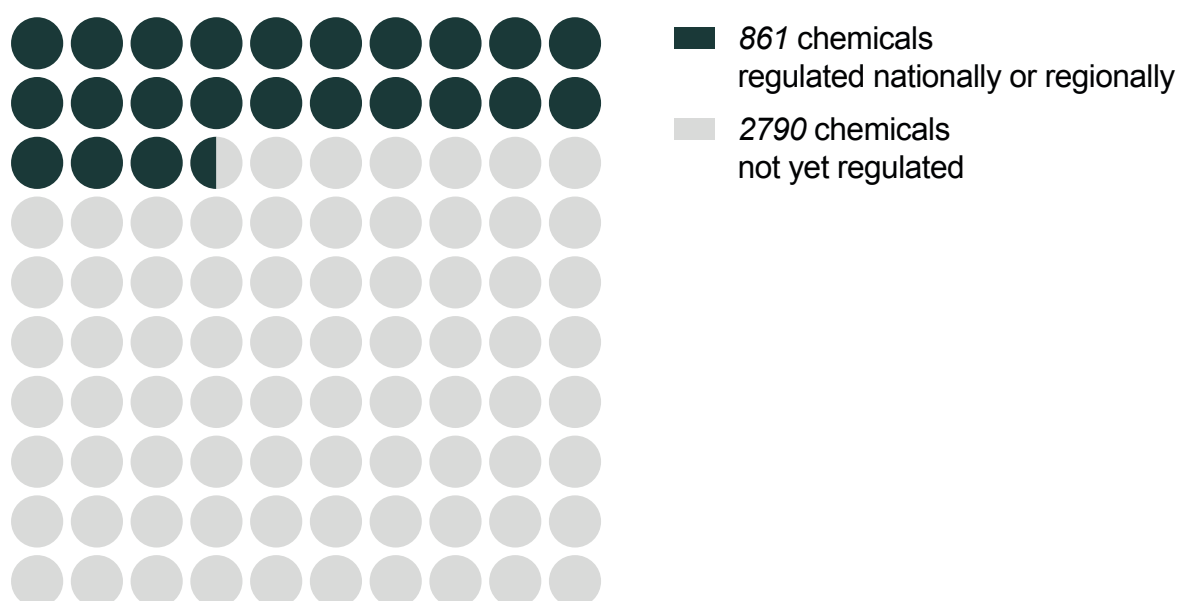


Figure 21: Scenario for prioritizing the Red List chemicals based on their regulatory status.

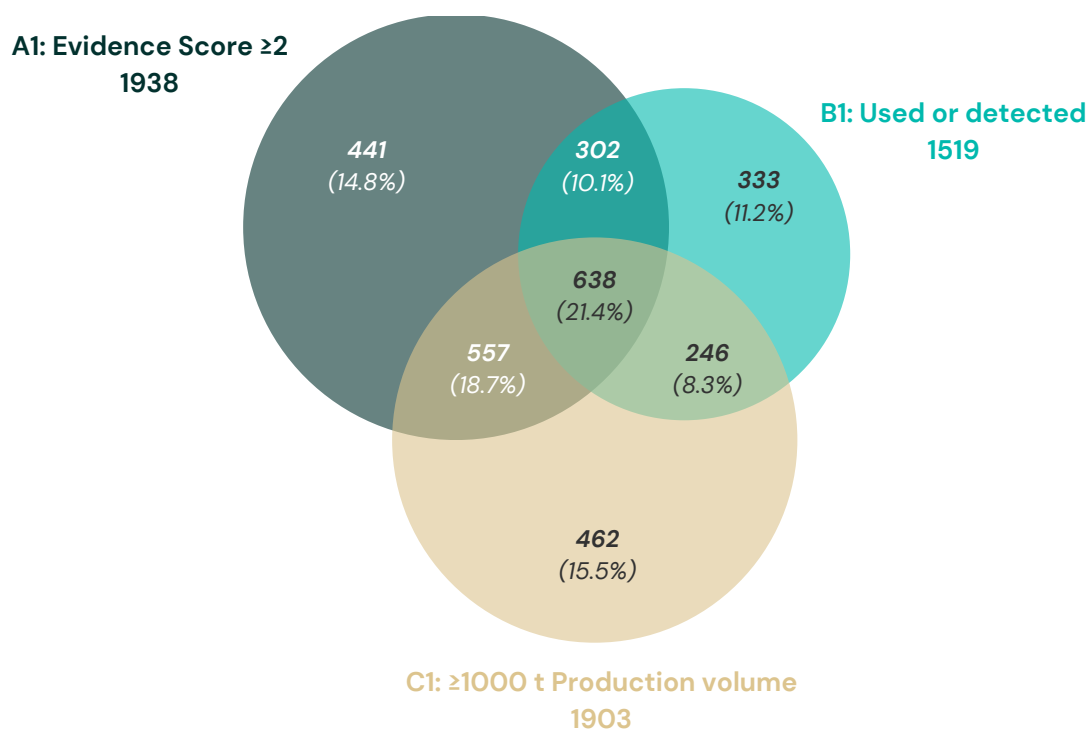


Figure 22: Overlap of the Red List chemicals covered by the prioritization scenarios A1 (Evidence Score ≥ 2), B1 (used or detected in plastics), and C1 (produced at ≥ 1000 tons).

Combining the additional information adds granularity to prioritization decisions.

Merging the scenarios outlined above creates multiple lines of additional evidence for prioritizing chemicals of concern. For example, octamethylcyclotetrasiloxane, an SVHC present on the EU candidate list for authorization¹¹² and the Korea intensive control list,¹¹⁵ is not regulated under any existing MEA but is identified by several sources as highly hazardous, has a high

production volume, and is released from PP and multilayer plastics (Table 7). Another example, perfluorononanoic acid, is very hazardous with a robust level of evidence, is included in two regional regulatory lists, and has been found to be released from PP. However, its production volume is unknown. This highlights that prioritizing chemicals of concern solely based on production volumes omits compounds with robust evidence for their hazards that lack this information.

Table 7: Plastic chemicals that are already nationally or regionally regulated, have high Hazard and Evidence Scores, and have evidence for release from plastics.

CASRN	Chemical name	Already regulated in	HS	ES	Release from	Production volume
101-80-4	4,4'-Oxydianiline	California P65, Korea hazardous chemicals, Korea intensive control, REACH SVHC	6	25	PS, PA, multilayer plastic	10 100 tons
556-67-2	Octamethylcyclotetrasiloxane	Korea intensive control, REACH restriction, REACH SVHC	6	15	PP, multilayer plastic	2 000 000 tons
106-47-8	4-Chloroaniline	California P65	6	13	PVC, PA	1000 tons
375-95-1	Perfluorononanoic acid (PFNA)	Korea intensive control, REACH SVHC	6	13	PP	NA
108-45-2	m-Phenylene-diamine	Korea hazardous chemicals	6	9	PA, multilayer plastic	110 000 tons

6

PRIORITY GROUPS OF CHEMICALS

Regulating groups of plastic chemicals has many advantages. Addressing chemicals of concern following a group-based approach represents a pragmatic way to tackle the large number of plastic chemicals and in light of the prevailing data gaps. As such, it will greatly improve the efficiency and effectiveness of managing chemicals of concern in plastics. A regulation of groups of chemicals may also pre-empt the problem of so-called regrettable substitutions, that is, the replacement of a regulated compound with another structurally similar, but unregulated chemical. Such structural similarity makes it very probable that the replacement possesses similar hazard and exposure properties like the compound it replaces. Regulating groups of chemicals that are structurally similar removes the regrettable substitution problem and incentivizes developing safe-by-design chemicals. Thus, a grouping approach should be the default for regulating plastic chemicals.

Existing MEAs already regulate some chemical groups relevant to plastics. Recognizing the advantages of a group-based approach, existing MEAs increasingly regulate groups of chemicals. Some of these are very relevant for plastics, such as polychlorinated biphenyls (PCBs), polychlorinated dioxins and furans (PCDD/Fs), and polycyclic aromatic hydrocarbons (PAHs, [Table 8](#)). These three groups contain 38–140 plastic chemicals. PFAS represent another large group of chemicals with 166 long-chain PFAS covered by the Stockholm Convention and other MEAs, while many more PFAS remain to be regulated globally (see [Box 3](#)). Taken together, there is much precedence for taking a group-based approach to regulate chemicals internationally. It is noteworthy that these decisions have generally been taken without requiring that all group members have been fully assessed for their hazards, as exemplified by PCBs, chlorinated paraffins, PFAS, and mercury-containing chemicals ([Table 8](#)).

Table 8: Groups of plastic chemicals regulated under existing MEAs. Note that the numbers presented here refer to the plastic chemicals included in the PlastChem database, not the total number of group members.

Groups	Regulation	Number of plastic chemicals...			
		hazardous	without data	sum	per cent hazardous
Chlorinated paraffins (short-chain)	Stockholm	6	12	18	33.3
Dichlorodiphenyltrichloroethane (DDT) and metabolites	Stockholm	5	0	5	100
Dioxins ^a	Stockholm	25	0	25	100
Mercury and chemicals containing mercury	Minamata	18	8	26	69.2
PFAS (long-chain) ^b	Stockholm	128	38	166	77.1
Polybrominated diphenyl ethers (PBDEs)	Stockholm	3	3	6	50.0
Polychlorinated biphenyls (PCBs)	Stockholm	60	80	140	42.9
Polychlorinated dioxins and furans (PBDD/F)	Stockholm	18	32	50	36.0
Polycyclic Aromatic Hydrocarbons (PAHs) ^c	Basel	35	3	38	92.1

Note: ^a nomination pending, ^b few members regulated in the Basel Convention and the Montreal Protocol, ^c only regulated in waste, not during production and use.

Fifteen groups of plastic chemicals are of major concern. Implementing a quantitative grouping approach in this report results in eleven priority groups of plastic chemicals that consist of at least 40% of hazardous chemicals, each (Table 9). Four additional groups are included because of their high group hazard scores and existing knowledge on their hazards (see Box 3). For instance, all chemicals in the groups of aromatic amines, aralkyl aldehydes, and aromatic ethers are classified as hazardous. Alkylphenols, bisphenols, and phthalates are other prominent groups of plastic chemicals for which 63–83% of members are of concern, often due to their endocrine disrupting properties. Taken together, these three groups contain 160 chemicals, out of which 116 are hazardous. This is a good example for the usefulness of the group-based approach. Instead of assessing the remaining 44 alkylphenols, bisphenols, and phthalates individually, these should be considered “guilty by association” until more information is available, given their structural similarities, and regulated together with the other groups members.

Regulating priority groups would overcome knowledge gaps and incentivize safer design.

A total of 785 chemicals would be subject to regulation when taking a group-based approach for the 15 priority groups identified here. Since this also covers chemicals without hazard data, 294 compounds would be regulated that are not included in the Red List. This approach

is conservative because only groups were considered that contain $\geq 40\%$ of chemicals of concern. As this cut-off is arbitrary, policymakers could decide to set different thresholds for regulating a certain group. For instance, siloxanes would be included as priority groups if the cut-off would be lowered to 30% of chemicals of concern per group. The inclusion of groups with $< 40\%$ hazardous members under existing MEAs (Table 8) supports such an approach. This would also increase the coverage of chemicals without hazard data and avoid the need to fill the many data gaps. Importantly, taking a group-based approach would incentivize abandoning chemical structures known to be of concern and promote designing out hazard properties for new plastic chemicals.

Many relevant chemical groups are data deficient. UVCBs, other mixtures, and polymers form the largest group of plastic chemicals and cover almost one fourth of all plastic chemicals (4161). Out of the 1206 UVCBs, 292 have data to show that they are hazardous (24%). The 1831 mixtures include 392 known hazardous ones (21%). The 2477 polymeric substances contain 255 known hazardous polymers (10%). Taken together, only 897 compounds in the three groups, or 22%, have information regarding their hazards, highlighting major knowledge gaps regarding these complex mixtures and poorly defined chemicals.

Box 3. Considerations for including chlorinated paraffins and PFAS as priority groups.

Four additional groups are included because of their high group hazard scores, indicating that individual group members are very hazardous, and because additional information provides convincing links between their chemical structure and hazard properties.

The POPs Review Committee of the Stockholm Convention has concluded that medium-chain chlorinated paraffins “are likely, as a result of long-range environmental transport, to lead to significant adverse human health and environmental effects, such that global action is warranted.”¹¹⁶ For the remaining long-chain chlorinated paraffins in the group, while they might not meet the bioaccumulation criterion, existing scientific evidence shows that they are (very) persistent in the environment and are at least toxic to organisms in sediment.¹¹⁷

PFAS with a chain length of 9–21 carbon atoms have been added to the Stockholm Convention in 2019.¹¹⁸ Those that have not been regulated at the international level have diverse physicochemical properties (e.g., as gas, liquid, or solids) but share some similar hazard properties: they are highly persistent or can degrade into highly persistent chemicals that are still PFAS, with some being bioaccumulative, some others mobile, and some may be both. Importantly, all of them can harm the environment and/or humans throughout their life cycle, possibly through different mechanisms of action. Scientists have repeatedly called for their regulation as a class.^{119–121} Such regulation has been put in place in some parts of the world, including California, Canada, and the EU.^{122–124}

Table 9: Priority groups of plastic chemicals, with ranking based on the proportion of chemicals of concern. The Group Hazard Score represents the aggregated Hazard Score (HS) of all chemicals in a group. The relative Group Hazard Score has been normalized to the number of all hazardous plastic chemicals, to account for dissimilar group sizes and data availability.

Groups	Group HS	Relative HS	Number of chemicals...				Total	per cent hazardous
			hazardous	less hazardous	not hazardous	without data		
Aromatic amines	52.5	2.39	22	0	0	0	22	100
Aralkyl aldehydes	12.5	1.79	7	1	0	0	8	87.5
Alkylphenols	101.5	2.03	50	5	0	11	66	75.8
Salicylate esters	15	1.88	8	2	0	1	11	72.7
Aromatic ethers	12	1.71	7	3	0	0	10	70
Bisphenols	39.5	1.98	20	3	0	11	34	58.8
Phthalates	57.8	1.75	33	5	1	23	62	53.2
Benzothiazoles	25.5	2.13	12	0	0	13	25	48
Benzotriazoles	45	3.46	13	4	0	13	30	43.3
Organometallics ^a	305.3	1.90	161	39	0	173	373	43.2
Parabens	7.5	1.88	4	1	0	5	10	40
Azodyes	81	2.31	35	26	1	27	89	39.3
Aceto- and benzophenones	43	2.05	21	5	0	28	54	38.9
Chlorinated paraffins ^b	10.5	2.63	3	1	0	5	9	30
PFAS ^b	210.8	2.37	76	9	3	186	274	27.7
Sum	-	-	472	104	5	496	1077	43.8

Note: ^a the organometallics include subgroups of chemicals containing lead, chromium, antimony, tin, cadmium, and nickel; ^b includes only group members currently not regulated under existing MEAs.

7

LINKING CHEMICALS OF CONCERN TO POLYMER TYPES

Chemicals of concern used or detected in plastics

More than 1800 chemicals of concern are used or detected in plastics. 1875 chemicals that have been classified as hazardous are either marketed for their use in plastics, or have scientific evidence for their presence in, or release from plastics (Figure 23). This represents about one third of the chemicals that have relevant information in the PlastChem database. Accordingly, strong evidence suggests that many chemicals of concern are indeed present in plastic materials and products. Furthermore, the data show that another 394 chemicals (6% of compounds with data) are classified as less hazardous. Only 90 chemicals that are used or have been detected in plastics are classified as not hazardous. However, the hazard profiles of most of the latter compounds are incomplete (see White List and Annex A5 for details).

Almost 4000 chemicals used or detected in plastics have no hazard data. Representing >60% of all chemicals with relevant data, 3904 compounds have not been assessed for their hazards based on the sources consulted for this report. This demonstrates that most chemicals used or detected in plastics have not been assessed for their hazards. Such assessments are under development for only 15 compounds (0.2%). Conversely, this is supported by the fact

that only 44% of the known chemicals of concern (1875 out of 4219 compounds) have evidence for their use, presence, or release from plastics. This means that hazard data for most chemicals present in plastics, as well as use and detection data for chemicals of concern, are lacking. Taken together, these data provide a striking example of the limited capacity of regulatory systems to evaluate chemicals that are used or detected in plastics.

Half of the chemicals used in plastics are of concern. Out of the 2899 chemicals marketed for use in plastics, 46% (1322 compounds) have been classified as hazardous. Accordingly, >1300 chemicals of concern can be intentionally added to plastic materials or products. This calls attention to the fact that many producers do not take into account the hazard properties of their chemicals. In addition, this further highlights the governance gap regarding a regulation of plastic chemicals put on the market.

More than 500 chemicals of concern are released from plastics. The available scientific evidence shows that 508 hazardous chemicals are released from plastic materials or products. These compounds represent one third of the chemicals that have been found to leach or volatilize from plastics in scientific studies, demonstrating that a substantial number of chemicals of concern have a high exposure

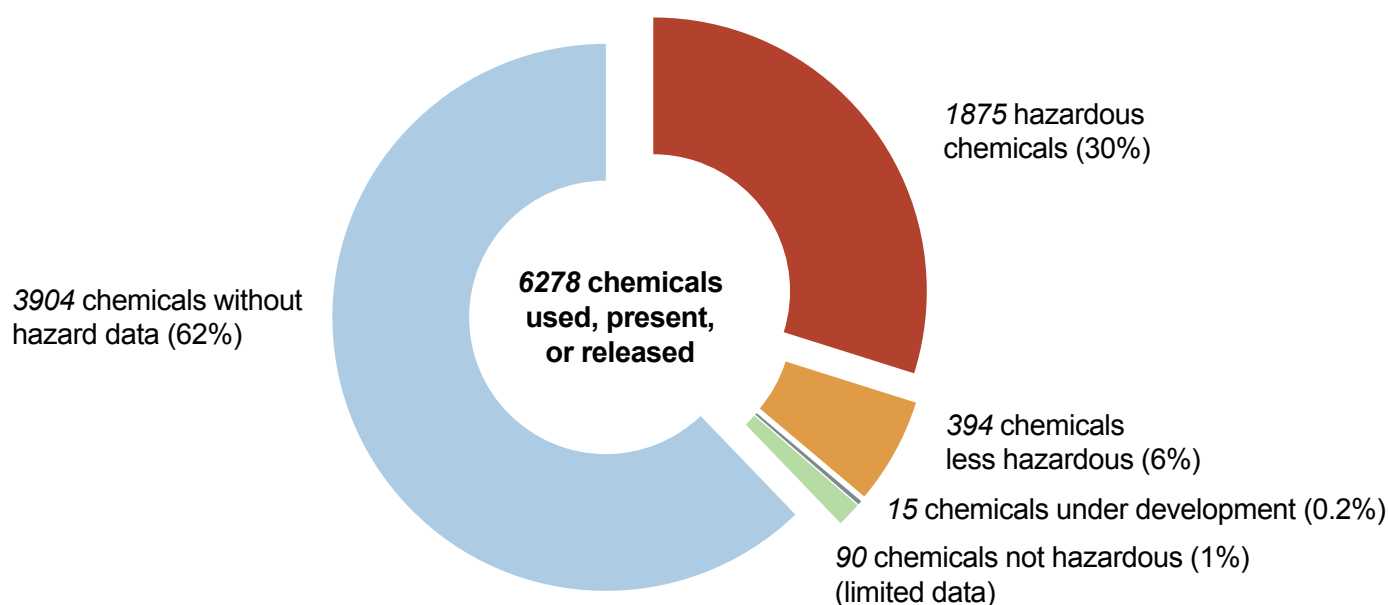


Figure 23: Overview of chemicals of concern with evidence for use, presence in, or release from plastics.

potential. Additional empirical evidence suggests that a similar proportion of chemicals of concern (27% or 850 out of 3178 compounds) has been detected in plastics. The use, presence, and release information overlap somewhat, and 627 chemicals have evidence for at least two criteria (Figure 24). Out of these, 178 chemicals of concern have very robust evidence because they are marketed for use and have been shown to be present in and released from plastic in scientific studies.

show a high proportion of chemicals of concern (details in Annex A5).

Each major polymer type contains at least 400 chemicals of concern. Amongst the polymer types with sufficient information, the commodity polymers PET, PE, PP, PVC, PS, PA, and PUR as well as rubber can contain >400 hazardous chemicals, each (Figure 25, Table 10). This represents between 31% (PET) and 66% (rubber) of all

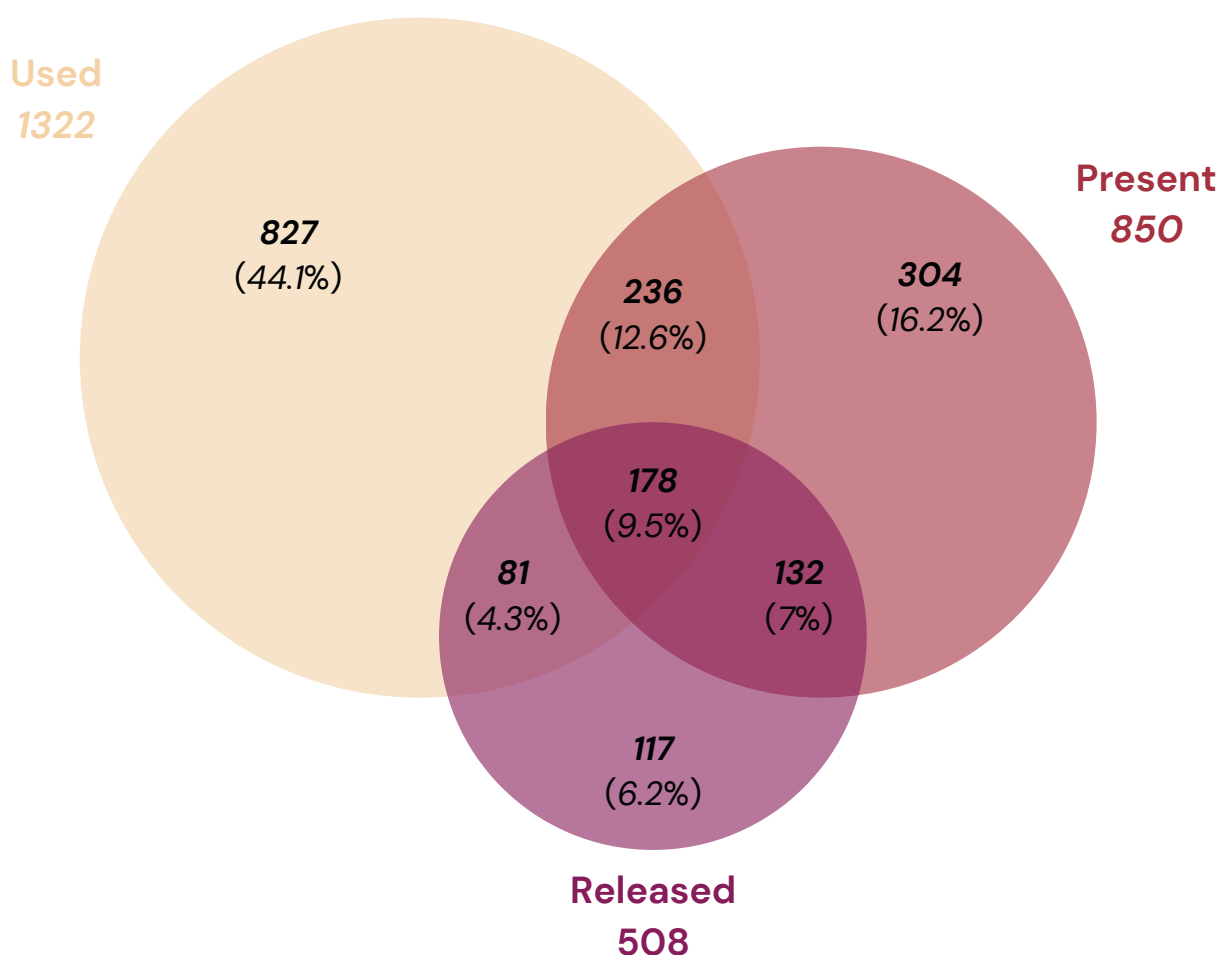


Figure 24: Overlap of chemicals of concern in plastics that have evidence for their use, presence, or release.

Chemicals of concern used or detected in specific polymer types

Commodity plastics contain or are associated with 1483 chemicals of concern, nearly 80% of all such plastic chemicals. This reflects the depth of information available for the polymers representing the bulk of the market. Their extensive production volume increases exposure risks, particularly in the use, disposal, and recycling phase. This situation is compounded by the challenge in tracing specific chemicals to particular polymer types, especially in multilayer packaging. Moreover, specialty plastics, elastomers, and bioplastics, despite limited data,

compounds used or detected in these polymer types. Most information is available for chemicals used or detected in PET and PE. These polymer types contain most chemicals of concern, namely 806 and 722 hazardous compounds, as well as the highest number of chemicals without hazard data (Table 10). 633 and 618 chemicals of concern have evidence for their use or detection in PP and PVC. The number of hazardous compounds is similar in rubber and PUR. Accordingly, there is good evidence for the presence of numerous chemicals of concern in well-studied polymer types.

More than 100 chemicals of concern are released from PET, PP, and PE. In PET, 292 chemicals of concern are known to be used, 329 have been detected, and another 143 compounds are released. In PP, 253 hazardous chemicals are used, and scientific studies have demonstrated that another 107 and 197 chemicals are either detected in or leach from the polymer. For PE, 399 hazardous compounds have market information for their use, and 136 and 187 chemicals have scientific evidence for their presence and release, respectively. Interestingly, only 42 (PET), 76 (PP), and 56 (PE) chemicals of concern have been analyzed in these polymers but were not detected. Taken together, this provides strong evidence that many chemicals in these polymer types can be released and have, thus, a high exposure potential.

Rubber, PUR, ABS, PC, and PVC are most likely to contain chemicals of concern. Due to the skewed data availability, it makes sense to compare the proportion of chemicals of concern between polymers. Such analysis shows that a large fraction of hazardous chemicals is used or detected in rubber, PUR, ABS, PC, and PVC, namely between 48 and 66% of all compounds with such information (Figure 25, Table 10). This demonstrates that it is more likely than not that chemicals of concern are present in these polymer types.

Information for chemicals of concern in other polymer types is largely lacking. Notably, the evidence compiled for this report is biased towards polymers with high production volumes. This leaves many relevant polymer types with little information on whether they contain chemicals of concern or not. This is particularly problematic for elastomers other than rubbers, such as widely used silicones, but also for bio-based and biodegradable polymers. Here, 22 and 5 chemicals of concern are used or present in polylactic acid (PLA) and starch-based plastics. This implies that these polymer types also contain hazardous chemicals. However, such evidence is limited by the fact that market information is unavailable and scientific studies focus largely on petroleum-based polymers.

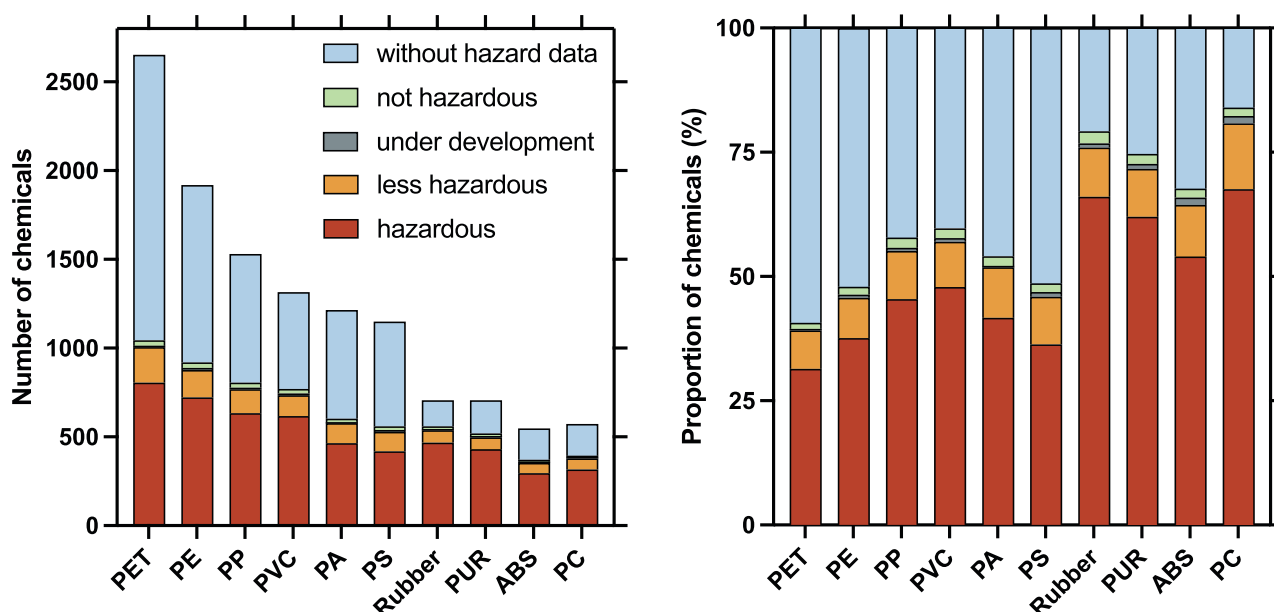


Figure 25: Hazard information for chemicals used or detected in plastics according to polymer type. The left graph presents the number of chemicals, the right graph shows the proportion of chemicals normalized to the number of chemicals used or detected in each group. Only polymer types with information for more than 550 chemicals were considered here.

Table 10: Overview of the ten polymer types in which most chemicals are used or detected. Only polymer types with information for >550 chemicals were considered here.

Polymer	Use	Number of plastic chemicals...				Sum ^a	Thereof...		
		analyzed	used	present	released		not hazardous	without hazard data	hazardous
PET	Packaging, food/household, textiles	2914	757 (26%)	1573 (54%)	236 (8%)	2566 (88%)	31 (1%)	1609 (63%)	806 (31%)
PE	Packaging, consumer goods, textiles	2529	809 (32%)	539 (21%)	571 (23%)	1919 (76%)	31 (2%)	999 (52%)	722 (38%)
PP	Packaging, consumer goods, transport	1835	528 (29%)	259 (14%)	606 (33%)	1393 (76%)	29 (2%)	725 (52%)	633 (45%)
PVC	Construction, health care, electronics, transport	1370	736 (54%)	418 (31%)	136 (10%)	1290 (94%)	25 (2%)	546 (42%)	618 (48%)
PS	Packaging, food/household, construction	1347	327 (24%)	465 (35%)	358 (27%)	1150 (85%)	20 (2%)	591 (51%)	418 (36%)
PA	Textiles, transport, kitchen utensils, textiles	1259	933 (74%)	58 (5%)	124 (10%)	1115 (89%)	22 (2%)	611 (55%)	465 (42%)
PUR	Construction, furniture, transport	900	568 (63%)	122 (14%)	5 (1%)	695 (77%)	14 (2%)	187 (27%)	431 (62%)
Rubber	Transport, health care, electronics	711	685 (96%)	11 (2%)	11 (2%)	707 (99%)	17 (2%)	147 (21%)	467 (66%)
ABS	Household, consumer goods, transport, health care	621	444 (71%)	104 (17%)	0 (0%)	548 (88%)	10 (2%)	177 (32%)	296 (54%)
PC	Electronics, health care, construction, transport	590	322 (55%)	45 (8%)	102 (17%)	469 (79%)	8 (2%)	179 (38%)	317 (68%)

Note: ^a sum of chemicals used, present, or released

8

APPROACHES TO IDENTIFY POLYMERS OF CONCERN

Hazard and circularity criteria can be applied to identify polymers of concern. The identification of polymers of concern (see [Box 4](#) for terminology) is strongly connected to plastic chemicals but requires additional considerations. Accordingly, the report outlines some key aspects for identifying polymers of concern, following two lines of evidence, namely their intrinsic hazards and their compatibility with circularity ([Figure 26](#)). The hazard criteria for polymers relate to

their content of chemicals of concern, their leachate toxicity, and their propensity to release micro- and nanoplastics (MNPs). These safety aspects can be combined with sustainability aspects related to the compatibility of a polymer with a circular economy. Since these criteria are non-exhaustive, additional aspects may also warrant consideration, such as ecological, economical, and societal impacts from plastic pollution.

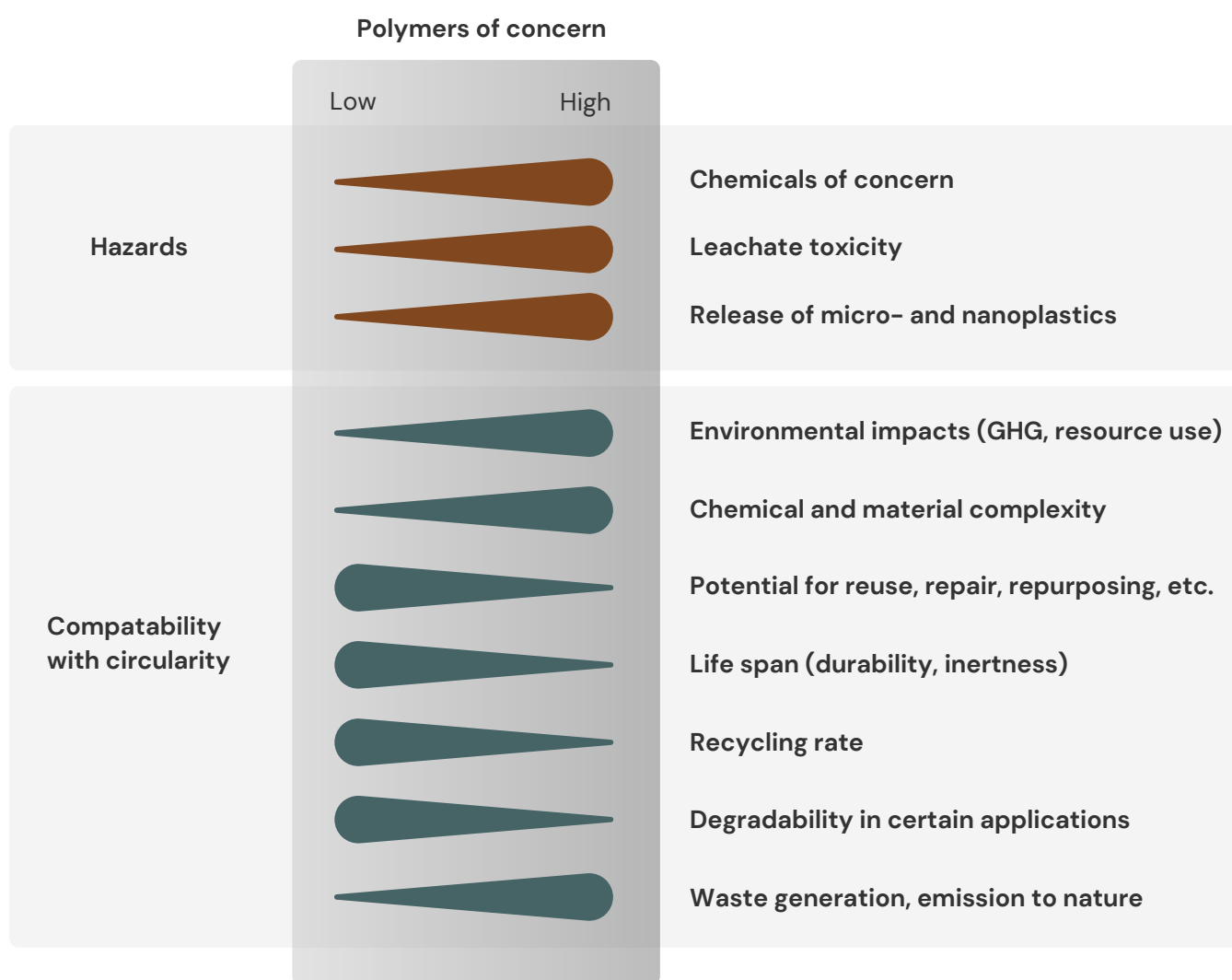


Figure 26: Conceptual framework to identify polymers of concern based on their hazards and circularity criteria.

Box 4. What are polymers of concern?

In addition to chemicals of concern, the INC decided to discuss “polymers of concern” in the context of the global plastics treaty. Since this term might be used with different meanings, it is worthwhile clarifying.

Technically speaking, polymers are large macromolecules consisting of repeated units of monomers.² As such, they are simply specific types of chemicals. For instance, the term polypropylene – in a strictly scientific sense – refers to the macromolecule, that is an individual chemical, used in whichever form.

In a policy context, the term polymer typically refers to the polymer type or plastic type. For instance, the term polypropylene is used to talk about materials or products consisting of polypropylene as polymer backbone. Accordingly, polymers in such contexts are plastic materials or products that contain the polymer as bulk material but also contain other plastic chemicals.

In the PlastChem report, the term polymer is used in the latter context. This means that polymers of concern here refer to materials and products made from a certain polymer type. Other polymers can be used as additives or processing aids in plastics and are included in the chemicals of concern sections.

Identifying polymers of concern based on hazard considerations

Presence of chemicals of concern

Origin of plastic chemicals of concern. It may seem intuitive to consider plastic polymers that contain high numbers of chemicals of concern as polymers of concern. However, before doing so, the origins of chemicals of concern in plastic materials and products should be considered. In general, chemicals of concern either originate from their intentional use as plastic additives and processing aids (origin 1) or are unreacted monomers and NIAS from the production and processing of plastics (origin 2), such as reaction intermediates (e.g., oligomers), reaction byproducts, contaminants, degradation products, and reaction products of intentionally and non-intentionally added chemicals. The third origin, namely adsorption of contaminants from the environment, is not considered here.

Addressing chemicals of concern would remove the concern for certain polymers.

Groups of chemicals of concern from origins 1 and 2 can be addressed by using the model of POPs (Annex A and B) and unintentional POPs (Annex C) under the Stockholm Convention, respectively. For example, origin 1 chemicals may be eliminated from plastic materials and products by banning or restricting them, whereas origin 2 compounds may be eliminated from plastics

by implementing cleaner (post-)production processes. Thus, should a comprehensive, effective mechanism eliminating chemicals of concern be in place, using the number of chemicals of concern as a criterion for identifying polymers of concern may be less conducive.

The abundance of chemicals of concern can be used to identify polymers of concern in specific cases. There are also good reasons for using the number of chemicals of concern as a criterion for identifying and prioritizing polymers of concern. For example, thousands of chemicals of concern may be present in plastics, and it may take a long time until all chemicals of concern are listed and controlled under a regulatory framework, such as the global plastics treaty. In addition, specific chemicals of concern may not be readily removed from plastic materials and products due to technical or other reasons, particularly when their origins are challenging to discern, such as reaction byproducts of commonly used chemicals in plastic production. In such cases, prioritizing polymers for regulation based on their content of chemicals of concern, for instance through leachate toxicity, provides an effective solution.

Leachate toxicity

Leachate toxicity information addresses the issue of unknown chemicals in plastics. The presence of unknown compounds is the major impediment to assessing the safety of plastics. This is particularly true for NIAS, most of which are unknown. These chemicals can neither be easily detected in plastics, nor can they be assessed for their hazards using conventional approaches. An analysis of the joint toxic effects of all chemicals present in or leaching from a plastic material or product (i.e., leachate toxicity) can address this challenge.^{125,126} Testing the leachates of plastics using biological test systems (bioassays) relevant for human health or the environment has many advantages, foremost the fact that the observed toxicity integrates the effects of all chemicals present in or leaching from a material or product, including the unknown compounds and mixture effects. Such bioassays, also known as new approach methods for toxicity testing, include diverse in vitro assays and are predominantly used in research, but their adoption by major brand owners to test the safety of their products^{127,128} showcases the potential of this hazard identification approach.

Polymers of concern can be identified based on leachate toxicity. Information on the leachate toxicity of a polymer type can address important challenges, such as the dearth of information on the exact chemical composition and on the hazards of known plastic chemicals, as well as the potential presence or release of unknown chemicals. Accordingly, leachate toxicity information can be used to compare the toxicity of plastic materials and products and thus contribute to prioritizing these for regulatory actions. The basic rationale is that if a specific material or product induces more leachate toxicity, it contains and releases more hazardous chemicals, which can be characterized as such, independent of whether these chemicals are known or not. Since this approach also covers chemicals not included in the lists of known chemicals of concern, it can help closing an important regulatory gap in terms of the many plastic chemicals that are currently unknown or have not yet been assessed for their hazards.

Information on the leachate toxicity of plastics is available but fragmented. Based on the evidence map of bioassay-based research on plastics (details in Annex A6), 201 studies have investigated leachate toxicity, providing 6364 datapoints. Scientific studies have analyzed all major polymers, but mainly focus on the

commodity polymers PE, PVC, PP, PS, and PET. The available research covers preproduction pellets as well as plastic products, in particular food contact materials, medical and dental products, and durable household items. Information is available on a range of adverse effects of plastic leachates, including cytotoxicity, endocrine disruption, growth, survival, reproduction, as well as genotoxicity (e.g., mutagenic, carcinogenic) and developmental effects (details in Annex A5). Accordingly, there is abundant evidence from the scientific literature that bioassay-based testing can provide an efficient assessment of potential toxicity hazards of plastics, covering both human health and the environment. However, the dearth of systematic studies that investigate plastic materials and products comprehensively, as well as numerous data gaps, highlight that a more strategic approach is needed to fully unfold the potential of bioassay-based testing in the assessment of plastic materials and products.

Leachate toxicity can help identify polymers of concern but must be fit for purpose. An analysis of the leachate toxicity evidence map shows that plastic materials and products made of all major polymer types frequently exert substantial leachate toxicity in diverse bioassays relevant to human health or the environment (Figure 27). The leachates of PC, rubber, PUR, and PVC materials and products induce most toxicity across studies and affected groups of organisms. The evidence also suggests that leachates of PA and PP induce less toxicity, but the available data are limited for many polymer types. Both PET and PLA are also found to frequently induce leachate toxicity. These observations underscore the findings in this report that all major polymer types contain many known chemicals of concern. In addition, the available studies show that virgin polymers (i.e., preproduction pellets) are almost always less toxic than their compounded, additive-containing counterparts (i.e., final products).¹²⁹ This demonstrates that a higher additive content and resulting higher chemical complexity almost invariably correlates with higher toxicity. In addition, a degradation of plastics, in particular by UV irradiation as it occurs in the environment, can result in the generation of degradation products which often exert higher toxicity upon release^{130–133} but can also result in the reduction of toxicity.¹³⁴ Taken together, these findings suggest that an assessment of virgin polymers based on their leachate toxicity may be rather pointless, since both the additives content and the degradation processes typically bear a strong contribution to the overall toxicity. Accordingly, a

bioassay-based assessment of plastic materials and products should be performed, considering the specific applications and end-of-life expectations in the selection of testing strategies, such as the choice of a method used to produce the test leachates.

important aspect in the discussions of polymer registration under the European REACH. MNPs are ubiquitous in natural and human environments (e.g., food, indoor air) with most particles originating from abrasion during plastic use (e.g., tire wear, handling of food packaging, wear

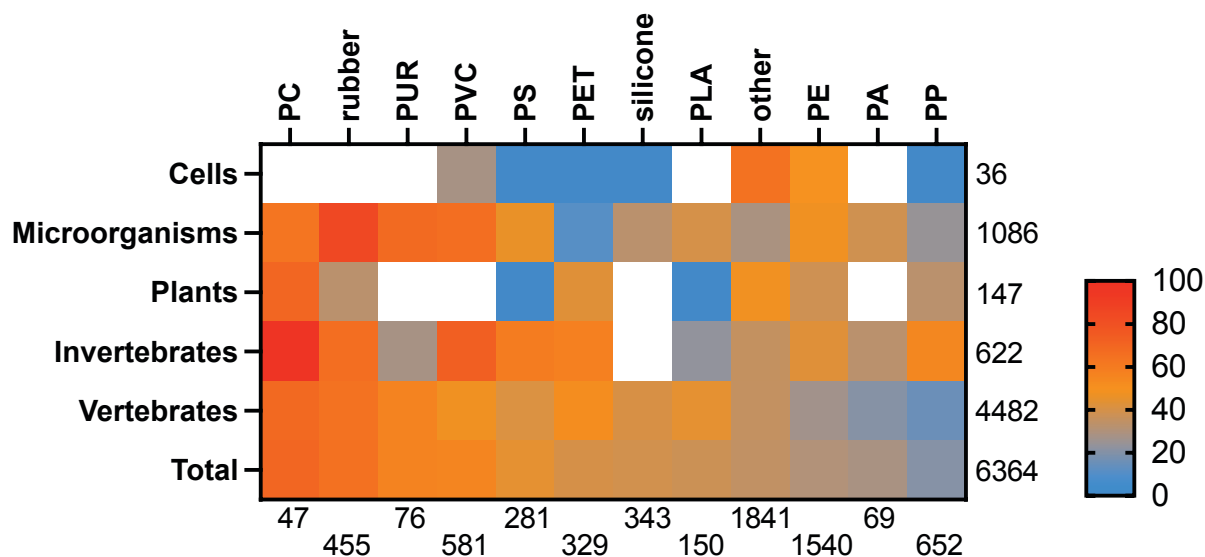


Figure 27: Heatmap of leachate toxicity across polymer types and affected taxa. The color of the heatmap represents the proportion of datapoints that indicate an adverse effect. White squares refer to a lack of data. The category "other" aggregates data for other polymer types not shown here. The numbers next to the heatmap refer to the number of datapoints per category. Note that most cell-based effects are allocated to the taxa they are linked to.

Facilitating the use of leachate toxicity information for identifying polymers of concern. In order to facilitate a broader application of bioassay-based testing for assessment and prioritization of plastic materials and products, the following measures are recommended: (1) establish guidance for selecting test samples that ensures systematic representation of various polymers, materials, and products, (2) develop standardized methods for obtaining relevant leachates, (3) establish a panel of robust and relevant bioassays that cover typical and relevant toxicity hazards and exposure routes, and (4) agree on approaches to interpret leachate toxicity results and translate these into subsequent regulatory actions.

Release of micro- and nanoplastics

Micro- and nanoplastics release is highly relevant for prioritizing polymers of concern. The propensity of plastic materials and products to release plastic particles in the nano- and millimeter size range, MNPs,¹³⁵ is another important aspect to consider in the prioritization of polymers.¹³⁶ For example, MNP formation is an

and tear of textiles) or from the degradation of plastics in the environment.¹³⁷ Depending on their size, MNPs readily available for inhalation and ingestion by species of all trophic levels, including humans, connected with potential adverse effects on health¹³⁸ and the environment.¹³⁹ For instance, meta-analyses of the health effects of MNP consistently point towards adverse impacts on reproduction¹⁴⁰ and gut homeostasis^{141,142} as well as the induction of inflammatory and oxidative stress responses.^{143,144} What is more, the higher surface-to-volume-ratio of MNPs compared to larger plastics also promotes the leaching of plastic chemicals. Due to these health and environmental concerns, MNP release is, therefore, highly relevant for prioritizing polymers of concern.

Some polymers have a higher propensity to release MNPs, but a systematic assessment is lacking. Several scientific studies have investigated the MNP release from different polymer types during and after use. For instance, high-impact polystyrene (HIPS) and nylon shed most MNPs when comparing the abrasion rates of six plastics.¹⁴⁵ In terms of food packaging, an

analysis of 110 take-out food containers made of PP, PS, and laminated paper found higher average MNP concentrations released from PS into food, with individual PP-packaged foods still containing more MNPs.¹⁴⁶ A similar study compared the MNP release into water from LDPE, PP, PS, and PET food packaging and showed that PP and PET containers released more particles than the ones made of PS and LDPE.¹⁴⁷ This indicates that it might be the individual properties of a plastic product rather than the polymer types that drive MNP generation. Nonetheless, an identification of polymers that release particularly many MNPs will be feasible once more comprehensive research is performed that enables a comprehensive and systematic comparison of materials.

(Bio)degradability enhances the release of MNPs that compromise the safety of polymers.

While there is less research on biodegradable plastics, emerging scientific evidence shows that they often release larger quantities of MNPs compared to conventional plastics. Here, the case of oxo-degradable plastics (Box 5) shows that accelerated degradability is not necessarily a desirable property of plastics, as it causes the formation of more MNPs.¹⁴⁸ In addition, several studies compare the levels of MNP released from biodegradable and conventional plastics. While a systematic assessment is lacking, the evidence shows that materials based on PLA¹⁴⁹ and PBAT¹⁵⁰

shed more MNPs than non-degradable polymers.

The propensity of a polymer to release MNPs depends on its material properties and uses. A polymer's tendency for abrasion and degradation and its specific applications may either promote or reduce MNP release. For instance, amorphous polymers (e.g., PS, PVC) are more prone to degradation than crystalline ones (e.g., PE, PET). In addition, its production volume will determine the total quantity of MNP released when considering larger geographical scales. Hence, systematic analyses into the material properties and use scenarios that promote MNP shedding is required. For this to happen, comparative studies on virgin and processed plastic materials that cover the major polymer types are needed. Importantly, establishing relevant use and degradation conditions is an important prerequisite for such research.

Harmonized testing is required to prioritize polymers based on MNP generation. One proposed approach serving as an indicator of a polymer's propensity to generate MNPs are abrasion tests.¹⁴⁵ Nevertheless, testing is complex and challenging since the fragmentation pattern and the abundance of MNPs released depends not only on the polymer type but also on the environmental conditions and the use scenarios. As an example, polymers exposed

Box 5. The issues associated with oxo-degradable plastics.

Oxo-degradable plastics are designed to break down through oxidative processes initiated by light, heat, and oxygen, and have been promoted as a potential solution to plastic pollution. These plastics contain additives that accelerate polymer degradation, leading to smaller fragments that are more accessible for microbial degradation. However, the incomplete degradation and potential environmental impacts of oxo-degradable plastics are cause for concern.

Oxo-degradable plastics undergo a two-stage degradation process, starting with oxidation, followed by biodegradation. The oxidation phase, induced by pro-degradant catalysts and controlled by antioxidant additives, leads to a reduction in the polymer's molecular weight, making the material more susceptible to microbial consumption.¹⁵¹ However, this process can lead to the release of toxic chemicals and MNPs when these polymers are not degraded in closed systems. Additionally, there is uncertainty about the complete biodegradation of these materials and their long-term environmental impact.¹⁵² Oxo-degradable plastics also pose challenges in conventional recycling processes due to the presence of degradation accelerators that can affect other polymers. This complicates their end-of-life management and could potentially undermine recycling efforts.¹⁵³

In summary, while oxo-degradable plastics are intended to address the issue of plastic pollution, their environmental impacts, potential for complete biodegradation, and compatibility with recycling processes remain areas of concern. The degradation process, although accelerated by additives, leads to fragmentation, potentially exacerbating microplastics pollution. Based on these concerns, the European Union has banned oxo-degradable plastics.¹⁵⁴

to sunlight release more plastic particles due to photooxidation-induced fragmentation.¹⁵⁵ Furthermore, plastic chemicals can change the abrasion pattern, calling for testing at the product rather than the polymer level. This highlights the need to identify and agree on suitable testing conditions when aiming to prioritize polymers based on their potential to release MNPs.

Identifying polymers of concern based on circularity considerations

Impacts and circularity are usually assessed on a product rather than a polymer level.

Most life cycle assessments quantify the environmental impacts of plastic products in CO₂ equivalents to create specificity and account for the fact that the same polymer type is used in a multitude of applications, creating a variability of use and end-of-life scenarios. Criteria that render plastics (in)compatible with a circular economy have been proposed^{156–160} and can be adapted to identify polymers of concern, although this means that some specificity is lost. Indeed, higher-level insights can be gained from assessing the environmental impacts of polymers, such as comparing greenhouse gas emissions of different polymers across their life cycles on a global¹⁶¹ or national level.⁹ Taking such material perspective would facilitate the better integration of external cost created by making, using, and disposing of plastic polymers into policy decisions.

A consideration of alternatives should precede an assessment of the circularity of polymers.

Before deciding which polymers are most compatible with circularity, a holistic comparison with alternative services and materials should be considered. For many applications where plastic is used (e.g., tertiary packaging), other practices or services might deliver a similar benefit for society without requiring plastic or other materials.¹⁵⁶ If a material is required, alternative materials can be considered and used when a full life cycle consideration predicts lower environmental impacts. Importantly, such considerations need to include the chemical dimension discussed in this report. Here, substantial progress is required to integrate the hazards of plastic chemicals into life cycle assessment frameworks.

When plastics are the best option, life cycle impacts should be compared. At the highest level, comparing the environmental impacts in terms of greenhouse gas (GHG) emissions and

resource use (e.g., land, water) of polymers can serve as point of departure. Here, accounting for the full life cycle of a polymer is crucial. For instance, a recent analysis suggests that the GHG emissions of polyester, polyamide, and acrylic used for making plastic fibers as well as polyurethanes is substantially higher than of HDPE and LDPE.¹⁶¹ Importantly, other impact categories than global warming must also be considered, such as land and water use, eutrophication, acidification, and environmental harm from pesticides, especially when comparing petroleum- and bio-based polymers.

Polymers most compatible with circularity principles should be preferred. Additional criteria for plastic polymers' compatibility with circularity can be identified through the lens of life cycle stages (Table 11). Starting with the feedstock extraction, polymers that are most compatible with accepting alternative and secondary feedstocks (e.g., bio-based or recycled) could be preferred. In the manufacturing and processing phase, the criterion of material simplicity, meaning that a plastic has low chemical complexity, can be applied to avoid the spread of chemicals of concern and other compounds (e.g., NIAS) hindering circularity (see Box 6). In addition, polymers could be preferred that are compatible with circular design criteria, where products are designed for durability, reuse, and repair, facilitating multiple use cycles instead of a single use. One essential property here is the durability of a material extending its lifespan as well as its inertness, meaning that the release of chemicals and plastic particles is much reduced.¹⁴⁸ For the use phase, the same criteria would apply to promote reuse, repair, and repurposing of plastic polymers. However, at this stage, considering products rather than materials might be more suitable. At the end of life, polymers that generate minimal levels of waste via reuse, repair, recycling etc. would be preferred. As a second tier, the recycling rate, or a technical potential for recycling of a polymer could be assessed. For end-of-life situations in which a polymer is difficult to recover, its rapid degradability in natural environments is another consideration. Importantly, such a criterion should be expanded to the plastic chemicals present in degradable polymers. Finally, the propensity of a polymer to be emitted into nature can serve as criterion that is spanning the manufacturing, use, and end-of-life stage.

Table 11: Selected circularity criteria for plastic polymers. Note that this list is not exhaustive and should serve as a discussion starter.

Life cycle stage	Circularity criteria	Details
Feedstock extraction and production	Compatibility with alternative feedstocks	Refers to technical capacity to phase in bio-based or secondary feedstocks.
Manufacturing and processing	Simplicity of chemical and material composition	Refers to chemical simplicity to avoid spread of chemicals of concern and material simplicity to create clean circular material streams.
	Compatibility with circular design criteria	Refers to material properties that enable reuse, repair, repurposing etc., such as simplicity, durability, and inertness.
Use	Potential for reuse, repair, repurposing	Similar to above but rather on a product level.
	Extended life span	Requires polymers that are durable and inert.
End-of-life	Reduced waste generation	Result of the criteria above, high-level indicator that is easy to assess.
	Recycling rate	Empirical data can be gathered, but a polymer's capacity for being recycled in the future could also be used.
	Degradability	Degradability should only be considered beneficial for applications in which a polymer is difficult to retrieve from the environment.
	Tendency for leakage	Refers to contribution of a polymer to plastic pollution or it's propensity to be released into the environment, high-level indicator that is easy to assess.

Information on plastic flows through the economy can guide policy decisions

Material-flow analyses are essential for guiding policy decisions. By quantitatively determining the flow of plastic materials within a country's specific or the global economy, a material flow analysis can provide unique insight on the balance between production, demand, waste generation, waste management, and ultimately, emissions. Material flow analyses can thus aid the identification of measures across the value chain, to address challenges related to production, end-of-life fate, and emissions of plastic and plastic chemicals. However, there is a high variability

in the resolution of data reported for the global and regional material flow of plastics, as there are large variations in how data are reported and made accessible (see Annex A5).

Material-flow analyses allow identifying relevant sectors and polymer types. There are clear regional differences in the global plastic economy, which reflect sector-specific polymer demands (see Annex A5). China, as the world's largest producer of textiles, represent the region with the highest amount of PET (commonly known as polyester in textiles) placed on the market in 2020.¹⁷² To compare, the most abundant polymers put on the market in 2020 in Norway and Europe were LDPE, and PP, respectively,

Box 6. Chemicals of concern are a major obstacle for the circularity of plastics.

Plastic chemicals of concern are incompatible with a circular economy unless tightly managed. For instance, certain reuse or recycling approaches, such as mechanical recycling, can cause hazardous compounds to occur in recycled plastics. Sorting and recycling facilities can spread hazardous chemicals and microplastics generated from crushing, compacting, and grinding waste.¹⁶² Furthermore, hazardous chemicals are incompatible with a linear economy, too, as different end-of-life options, such as open and closed landfills, as well as mismanaged waste can be long-term sources of emissions of these compounds.¹⁶³ What is more, waste incineration creates additional hazardous chemicals (e.g., dioxins, PAHs).¹⁶⁴

Properly managing plastic chemicals of concern in recycled plastics is not straightforward, and chemicals of concern are an issue for all types of recycling (Table 12). One major concern is that recycling will contribute to a spread of hazardous chemicals that is difficult to control, especially in mechanical product-to-pellet recycling. Another issue is the creation of chemicals that can either damage recycling infrastructures or result in the creation of hazardous wastes, especially during chemical and solvent-based recycling. Importantly, the presence of chemicals of concern implies hazard, which means that the quality of products made with recycled plastics is inferior.

This emphasizes the need for thorough separation, clean waste streams, and minimal contamination that produces high-quality, secondary materials for plastic recycling. Best practice examples are available. For instance, colored EPS containing brominated flame retardants can be separated from white EPS that do not contain such chemicals.¹⁶⁵ The recycling of PET bottles is another case, where a managed waste stream enables recycling.⁹¹ A similar scheme has been proposed for HDPE packaging to maintain recycled materials of appropriate quality.¹⁶⁶ Additional details can be found in Annex A5.

Table 12: Brief overview of plastic recycling methods and considerations for chemicals of concern.

Recycling process	Chemicals of concern	Examples
Mechanical recycling – Product to Product A closed product-recycling chain where plastics are shredded, melted, pelletized, and remolded into a similar product (e.g., bottle to bottle)	Any chemical of concern in a product will be in the recycled product, additional compounds are potentially generated or added during recycling	During PET bottle recycling, concentrations of benzene, styrene, and bisphenol A increase with increasing recycling content ¹⁶⁷
Mechanical recycling – Product to Pellet Recycled plastics sorted by polymer type and shredded, pelletized and remolded to a different product	Chemicals of concern from diverse products will accumulate in pellets and, thus, in new products, along with additional compounds. NIAS levels and diversity increase with each recycling loop	A range of pesticides, biocides, and pharmaceuticals detected in recycled HDPE preproduction pellets from the Global South ^{168,169}
Chemical recycling Plastic is pyrolyzed or gasified, and turned into fuel and naphta, which may be distilled to make plastic monomers	Chemicals of concern are destroyed or transferred into byproduct fractions (e.g., air emissions or condensates), new hazardous chemicals may form	PVC, halogenated plastics, and plastics with high halogenated chemical content can release halogen radicals or acids that are extremely corrosive to recycling infrastructure ¹⁷⁰
Solvent-based recycling Plastic is dissolved in solvent, separated from additives, and re-pelletized and remolded	Chemicals of concern are mostly, but not completely, transferred to the solvents	Flame retardants are enriched in solvent extracts and represent a potential problem for safe disposal of the solvent concentrate ¹⁷¹

representing the market demand for the packaging sector).^{91,173}

About 70% of the plastic mass put on the market becomes waste in the same year.

Estimates for the amount of plastic waste relative to the amount of plastic mass placed on the plastic market vary widely. For instance, between 64–77% of plastic mass put on the market globally, in Europe, and in Norway between 2019 and 2020 were wasted within the same year.^{7,91,173} This trend is even more pronounced in China, where studies report that the plastic waste generated corresponded to 90% of the plastic mass placed on the market (see Annex A5).¹⁷²

High-resolution material flow analyses can provide the foundation enabling circularity.

Quantifiable material flow information can be analyzed to compare waste management practices between regions and thus quantify the environmental and societal impacts of end-of-life plastics (see Box 7). This type of information may also support innovation towards circularity. For instance, it may be possible to separate polymers based on density in specific sectors to enable closed loop recycling of plastic materials and products, such as in food packaging or electronics. Closed systems for the collection and management plastics containing hazardous chemicals are the most feasible way forward to ensure that chemicals of concern stay within the same industry or sector. In Norway, plastics from waste electrical and electronic equipment containing hazardous BFRs is managed and reported separately to prevent environmental emissions. Indirectly, this separate collection can also prevent BFR-containing plastics from being illegally recycled into food contact materials.

The flow of hazardous chemicals can be linked to flows of plastic and polymers.

Once the material flow of plastic polymers is established, modelling the flow of associated plastic chemicals becomes possible. Such substance flow analyses can be used to assess production and management scenarios and quantify environmental emissions and occupational exposures. Further, this information can then be used to restrict the recycling of polymers containing plastic chemicals of concern or landfilling plastics prone to emit MNPs. A study from the USA estimated that the plastic waste generated in 2018 contained 18 000 to 25 million tons of plastic chemicals, of which around 200 000 to 1 million tons were emitted

to the environment due to inefficient end-of-life management.¹⁷⁸ An assessment of different end-of-life management scenarios can identify opportunities to design a safer closed-loop recycling infrastructure which may handle plastic chemicals adequately and support the transformation of the USA' plastic economy from linear to circular.¹⁷⁸

Non-accessible and low-resolution information of plastic flows limits its application for decision-making.

The absence of accessible comprehensive data and non-extractable information within the plastic economy poses a significant challenge to the application of material flow analyses for informed decision-making. Incomplete datasets and inaccessible information hinder the accurate assessment of material pathways, impeding the ability to identify critical points for intervention and optimization within the system. As a result, the efficacy of strategic decision-making in enhancing sustainability and circularity within the plastic economy is compromised, highlighting the need for improved data accessibility and transparency.

Box 7. Case study on the waste management of commodity polymers in China, Europe, and Norway.

Recent studies from Norway and Europe report that most commodity polymers have been incinerated (51% in Norway, 42% in Europe), however in Europe, a significant proportion has also been landfilled (40%, Figure 28).⁹¹ In China, the end-of-life fate of commodity polymers is equally divided between landfilling (36%), incineration (34%) and recycling and reuse (30%).¹⁷² Interestingly, for all regions, PVC waste is primarily incinerated, despite toxic emissions of carbon monoxide, hydrogen chloride, and polycyclic aromatic hydrocarbons generated during incineration.¹⁷⁴ Further, a noticeable fraction of PVC waste is recycled, despite hazardous chemicals possibly comprising over 50% of the polymer by weight.¹⁷⁵

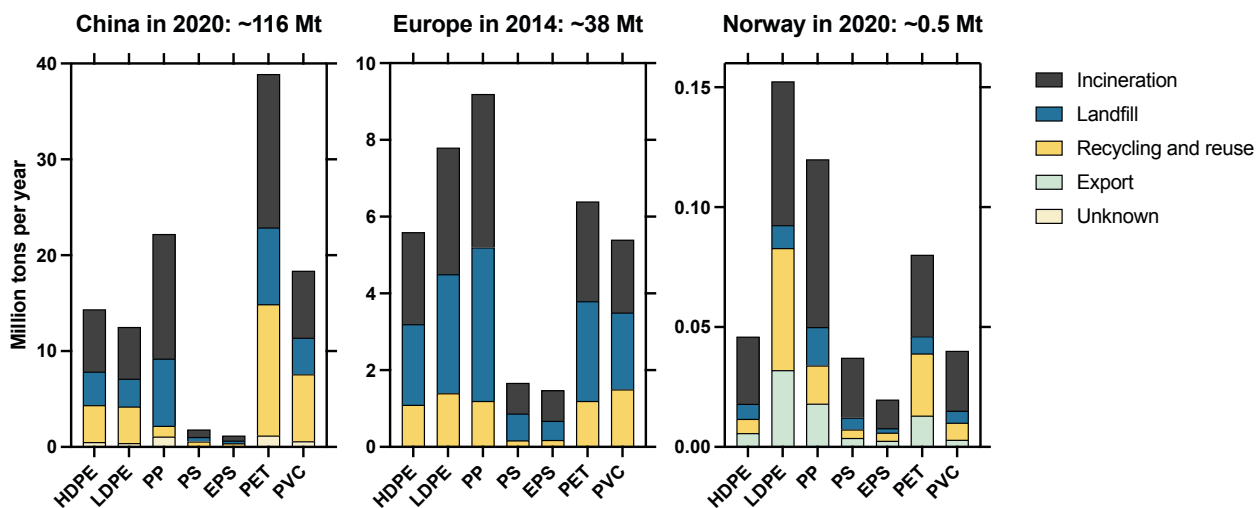


Figure 28: Polymer waste management options (million tons per year) in China, Europe, and Norway. The waste was either exported, incinerated, landfilled, recycled, and reused, or its fate is unknown. The uncertainties of the mass reported for each sector and region can be found in the original studies: China in 2020,¹⁷⁶ Europe in 2014,¹⁷⁷ and Norway in 2020.⁹¹

Identification of chemicals of concern

Processing of hazard data

To identify chemicals of concern, information gathered from authoritative regulatory and industry sources (Part II) was compiled and translated in a PlastChem Hazard Scoring system (Box 8, details in Annex A6). Four hazard criteria were used: Persistence, Bioaccumulation, Mobility and Toxicity, which each aggregate different hazard traits (Figure 29). Five hazard levels were established including hazardous chemicals, less hazardous chemicals, chemicals to watch, non-hazardous chemicals, and chemicals without hazard data (Table 13). Importantly, in the PlastChem database, chemicals evaluated and deemed non-hazardous are clearly differentiated from chemicals listed in the sources consulted but not evaluated. This highlights that a chemical lacking hazard data is not equivalent to a non-hazardous chemical. Therefore, such chemicals should not be deemed safe for use without further evaluation.

Hazard and Evidence Scoring System

The Hazard Scores assigned to each chemical, integrating the scores for the four hazard criteria (PBMT), permits identification of chemicals of concern in the PlastChem database and allows ranking them for further prioritization. The Hazard Score was used to identify chemicals of concern while the sum of Hazard Score per chemical aid to further prioritize chemicals of concern. The maximum possible sum of Hazard Score per chemical is 8, aggregating the maximum scores of each four hazard criteria. The minimum possible Hazard Score for a chemical to be considered hazardous is 1, and 0 was adopted when a chemical was classified as non-hazardous. In addition to the Hazard score, an Evidence Score was also assigned for each chemical with associated hazard information. This score informs about the number of consulted sources that indicated that the chemical is hazardous (details in Annex A6).

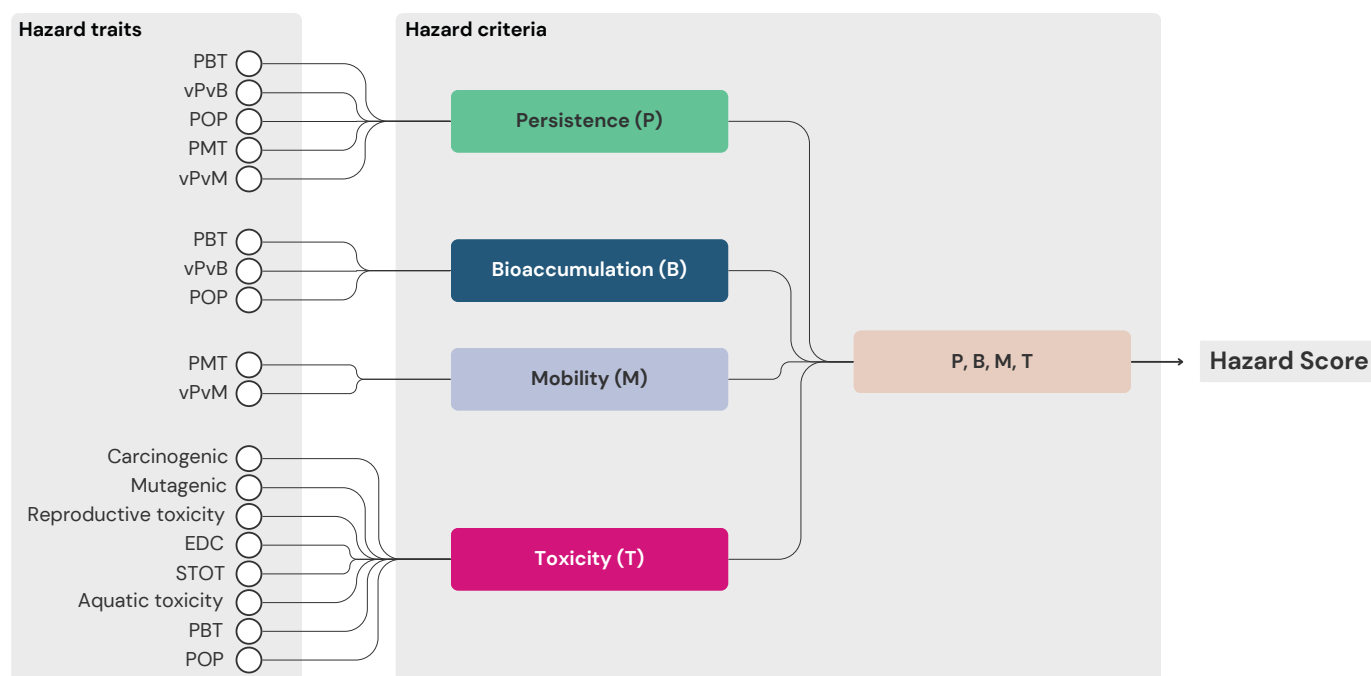


Figure 29: Approach to quantify the hazards of plastic chemicals.

Box 8. How is hazard information processed in the PlastChem database?

The PlastChem scoring system is based on the updated CLP regulation (EU) 2023/707 of 19 December 2022¹¹³ and, for aquatic toxicity, on the GHS Hazard Code according to REACH (ANNEX XIII).¹⁰⁷ The hazard information gathered from 15 sources was processed and translated into Hazard Scores in a three-step process:

First, a hazard score per chemical for each hazard trait was assigned by selecting the highest score among the consulted sources. Each hazard trait received then a hazard score ranging from 0 to 2, with 0 indicating that the chemical was recognized as non-hazardous for this particular trait, and 2 that the chemical was recognized as hazardous. In the cases where no information was available for the chemical in any of the consulted sources, the score was designated as blank. When the hazard evaluation of a chemical was under development, postponed, or pending, the score assigned in PlastChem was 0.25 and the chemical was classified as watch.

Second, the hazard scores per individual trait were then collated to a score per hazard criterion (PBMT) using the maximum value in case multiple traits per criterion had information. For example, a chemical classified as POP (score 2) and under assessment for PMT (score 0.25) received a score of 2 for Persistence, for Bioaccumulation and for Toxicity.

Finally, the maximum score per P, B, M, and T was then used to generate one Hazard Score per chemical that enabled creating lists of plastic chemicals of concern. Here, a maximum Hazard Score of 1 or 2 indicates that a chemical is classified hazardous for at least one hazard criterion. The sum of the Hazard Scores of P, B, M, and T was also used to provide more granularity in the scenarios for further filtering plastic chemicals of concern and ranged from 0 to 8.

Listing of plastic chemicals

Based on the Hazard Score, each plastic chemical was assigned to one of six lists. These lists classify chemicals based on whether they are already regulated globally, are of concern, are less hazardous, currently under assessment, non-hazardous, or data deficient.

1. **The MEA List** contains plastic chemicals identified in the PlastChem database that are regulated under existing MEAs. Since these chemicals are already regulated, no further prioritization was performed in the report. Nonetheless, the associated chemicals and their hazard information are included in the PlastChem database, for the sake of transparency.
2. **The Red List** contains plastic chemicals that have been classified as hazardous chemicals and are, therefore, chemicals of concern. These compounds are not regulated under existing MEAs.
3. **The Orange List** contains plastic chemicals that are less hazardous. These chemicals have been assessed and either are proposed to be included in regulatory lists or have been classified as less hazardous with hazard levels not included in the CLP regulations.

4. **The Watch List** contains plastic chemicals that have been evaluated for certain hazard traits and are classified as inconclusive or are currently under assessment with no clear classification. These chemicals are therefore placed on a watch list that requires monitoring.
5. **The White List** contains plastic chemicals that have been classified as non-hazardous for certain hazard traits, that is, there is no evidence of hazard based on the sources consulted.
6. **The Grey List** contains all the remaining chemicals for which no hazard data are available.

Prioritization of groups of plastic chemicals

Groups of plastic chemicals were prioritized based on how many chemicals of concern they contain. Starting with >100 groups of chemicals based on their structure, a stepwise approach was applied to narrow down the list of relevant groups (details in Annex A6). This involved excluding groups that were too large and unspecific (e.g., mixtures), that are regulated internationally, and groups with too few members. Importantly, groups for which less than 40%

Table 13: Overview of the hazard traits included in the PlastChem hazard scoring system and the different scores set for PlastChem.

Level	Hazard score	Persistence	Bioaccumulation ^a	Mobility ^a	Toxicity
Hazardous	2	vPvB, vPvM, POP	vPvB, POP	vPvM	Carcinogenic 1 A, B Mutagenic 1 A, B Reproduction 1 A, B Aquatic Toxicity 1 ^b Endocrine disruption (EDC) ^c , STOT RE 1, 2 POP
	1	PBT, PMT	PBT	PMT	Reproduction 2 Aquatic Toxicity 2 ^b PBT, PMT
Less hazardous	0.5	In proposed lists, PM	In proposed list	In proposed list, PM	Carcinogenic 2 Mutagenic 2 Aquatic toxicity 3, 4 ^b In proposed list
Watch	0.25	Under Development, Under Assessment, Inconclusive			
No evidence for hazard	0	The chemical does not fulfill the criteria to be considered hazardous			
No data	blank	There is no hazard information in any of the sources consulted			

Notes: ^a Bioaccumulation or mobility were considered in combination with persistence (vPvB, vPvM) and/or toxicity (PBT, PMT), ^b Aquatic Toxicity is not a CSS criterion but included following REACH (ANNEX XIII), ^c EDC is following EC 2023/707. Since this new EU regulation's entry into force is 2025, EDC levels were not differentiated.

of the chemicals were of concern were also excluded unless special considerations applied. The final selection of prioritized groups was ranked based on the proportion of chemicals of concern they contain, that is, chemicals of concern per group divided by total number of chemicals per same group. This follows the rationale that groups consisting of more hazardous chemicals have more evidence for being problematic. Priority was assigned to groups for which $\geq 40\%$ of the members are chemicals of concern or if additional scientific considerations pointed towards group-specific hazards.

unknown chemicals. To generate an overview of this emerging field of research, scientific studies of leachate toxicity were compiled and analyzed in an evidence map (details in the Annex A6).

Material Flow Information

Information published since 2018 on the material flow of plastic was reviewed, both globally and for selected regions, focusing on the material flow analyses and polymer types (details in Annex A6). Regions of interest selected for this report were China, Europe, and Norway. This information was used in [Part I](#) and [III](#).

Identification of polymers of concern

Toxicity of plastics leachates

The toxicity of plastic leachates from bioassay-based testing is an efficient approach to assess the combined toxicity of the chemicals leaching from plastic materials and products. Such leachate toxicity approaches integrate the adverse effects of the complex mixtures of all chemicals released from plastics, including



PART IV

How to translate evidence to policy?

Recommendations to address plastic
chemicals and polymers

KEY ASPECTS

1

Regulate plastic chemicals comprehensively and efficiently

- › Implement a **hazard- and group-based approach**
- › Set **criteria to identify** chemicals of concern
- › **Phase out** priority groups and Red List chemicals
- › Prioritize Orange and Grey List chemicals for **data collection and assessment**

16 000+

Chemicals known for use in plastics

4000+

Known to be hazardous

<6%

Subject to global regulation

2

Require transparency on plastic chemicals

- › Establish common **information requirements**
- › Establish a **common platform** for sharing information
- › Require **disclosure and clear labeling** of plastic chemicals of concern across value chains
- › Promote **disclosing information** on complex mixtures and non-intentionally added substances

66%

Of chemicals lack data for their assessment in the public domain

60%

Of plastic chemicals do not have information on their use or presence

Additional chemicals

Are assumed to be present in all plastics

3

Simplify plastics towards safety and sustainability

- › Develop stringent **safety and sustainability criteria** for plastic chemicals and materials
- › Develop clear **guidelines and goals** for achieving chemical simplicity in plastics
- › Promote **research and development** into simpler plastic materials

Chemical complexity

Prevents effective governance and transition to circularity

4

Build capacity to create safer and more sustainable plastics

- › Establish an open **knowledge-sharing** platform
- › Establish an open forum for **stakeholder dialogue**
- › Provide resources for **capacity building**
- › Leverage **international cooperation** to build relevant capacity

Lacking capacity

Prevents addressing plastic chemicals of concern and designing safe and sustainable plastics

1

POLICY PRINCIPLES

The principles of precaution, a full life cycle approach, and of independent evidence should guide the development of policies on plastic chemicals.

The sound management of plastics requires science-based policies to balance diverse societal needs. Given the complexity of these needs and the cross-cutting nature of chemicals and polymers in all policy processes related to the management of plastics, the principles of precaution, a full life cycle approach, and independent evidence, can guide policy making on plastic chemicals. Importantly, these principles will protect the human right for a clean, healthy, and sustainable environment for all humans.¹⁷⁹

Precautionary Principle

A “lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation,” according to the Rio Declaration agreed by all countries in 1992.¹⁸⁰ In other words, in the absence of conclusive evidence for policymaking, the Precautionary Principle can be invoked to avoid harm, when there is some scientifically based concern that detrimental effects could occur due to a novel technology or human-made materials.

The precautionary principle is compatible with evolving scientific evidence. In the European Union for instance, policies enacted based on the Precautionary Principle can *“be reviewed when more scientific information becomes available.”*¹⁸¹ Applying the principle in policymaking could be perceived as challenging, because it may be seen as hampering economic development. However, such considerations typically disregard the substantial external costs of pollution borne by society, such as the health costs of selected plastic chemicals which are estimated at 226–289 billion USD in 2018 in the USA alone.¹⁸²

Precaution implies an adaptive policy framework should account for evolving science. Policies should be designed to be agile and adaptive to account for advancements in the science on plastic chemicals and polymers. For instance, criteria for identifying plastic chemicals of concern may be updated when new scientific evidence becomes available for chemicals

currently lacking hazard data. Therefore, regulations would best ensure that any criteria and priority lists are regularly reviewed and updated, so they can be amended as required, along with emerging science.

The Precautionary Principle implies that plastic chemicals should be assessed based on their hazards. It would take many decades to gather robust scientific evidence on human and environmental exposures to >16 000 plastic chemicals. Hence, taking a hazard-based approach to identify plastic chemicals of concern is imperative to prevent decades of unnecessary human and ecosystem exposure to hazardous chemicals and avoid the associated societal costs. This is in line with available scientific evidence and numerous lessons learned from chemical management.¹⁸³

Full life-cycle approach

Addressing the full life cycle of plastics is essential to capture all plastic chemicals. Chemicals are intentionally added, non-intentionally present, and transformed at every step of the plastic life cycle, including feedstock extraction, manufacturing, use, and end of life. Chemicals sorbing to plastics throughout the life cycle, but especially during use or at the end of life, such as POPs, add to that challenge since they can contaminate recycled materials and cause unexpected exposure and effects.² Hence, the issue of chemicals of concern cuts across the full life cycle of plastics.

A full life cycle approach has been mandated by UNEA. The UNEA, in its resolution to end plastic pollution, decided that the global plastics treaty shall be *“based on a comprehensive approach that addresses the full life cycle of plastic”* and that the treaty shall address circular economy approaches.¹ This mandate requires consideration of all plastic chemicals. It should go beyond additives and include feedstocks, starting materials, processing aides, intermediates, and NIAS. Importantly, emphasis should be placed on the design stage of plastic materials and products, since this is the stage at which chemicals of concern can be avoided most effectively.¹⁰⁰

Independent evidence

The integrity of science is crucial for developing effective policies that protect human health and the environment. Special economic interests and agendas are sometimes disguised as scientific information.¹⁸⁴ Such manipulation not only obstructs evidence-based policymaking but also erodes public trust in scientific and political processes. This weakens democratic structures¹⁸⁶ and compromises human rights as the UN High Commissioner for Human Rights recently noted.¹⁸⁷

It is imperative to effectively manage conflicts of interest to safeguard evidence-based policymaking. A Conflict of Interest (Col) arises when financial or related benefits are to be gained by avoiding or delaying policy decisions, or by promoting a certain policy outcome.¹⁸⁴ Cols require adequate disclosure and management as demonstrated by successful examples of the WHO Framework Convention on Tobacco Control's prohibition of contributions by the tobacco industry^{188,189} and IARC's approach of not allowing experts with Col to partake in decision-making.¹⁹⁰ However, more awareness is yet needed to prevent actors with special interests from introducing policy-disrupting biases in the scientific evidence, and address intentional and disruptive biases in existing scientific evidence. Including the principle of independent evidence in the assessment of scientific evidence is, therefore, vital to counterbalance such biases and preserve evidence-based policymaking.

2

POLICY RECOMMENDATIONS

Four science-based policy recommendations to protect human health and the environment, and to ensure every human's right to a clean, healthy, and sustainable environment. Translating this report's scientific findings into concrete and actionable considerations for policymakers at a local, national, and international level, results in four recommendations, aiming to support informed policy making on plastic chemicals and polymers ([Table 14](#)).

Recommendation 1: Regulate plastic chemicals comprehensively and efficiently

Arguments: Why should this issue be addressed?

The large number of plastic chemicals, robust evidence on hazards, and the fragmented, narrow-scoped regulatory landscape are major challenges for protecting human and ecosystem health from hazardous plastic chemicals. These challenges can be best addressed by comprehensive national, regional, and international policies that regulate plastic chemicals of concern.

The plethora of plastic chemicals is a concern in and of itself. More than 16 000 chemicals are known for (potential) use or have been shown to be present in plastics based on an assessment of the state of the science. Many plastic chemicals are released from plastics and produced in substantial volumes, highlighting that many compounds have a high potential to contaminate human and natural environments.

Compelling evidence for the presence of chemicals of concern in plastics. One fourth is known to be hazardous, being persistent, bioaccumulative, mobile, and/or toxic to human health or the environment. Among them, despite limited scientific studies being available, the widespread use or presence of at least 1800 chemicals of concern in plastic materials and products on the global market has been clearly established.

Large global governance gap on plastic chemicals. Despite the presence of a vast array of chemicals of concern in plastics, less than 6% of these are subject to global regulation, pointing to a significant governance gap. The lack of specific regulatory mechanisms for plastic chemicals, combined with significant variations in

regulations across countries and regions, results in uneven and limited protection from hazardous plastic chemicals, not only in low- and middle- but also in high-income countries.

Advice: What can be done?

Adopting a hazard-based approach can address the shortcomings of traditional assessment strategies. As findings of the report show, new approaches are required to assess and regulate the multitude of plastic chemicals. Importantly, traditional risk assessments are time- and resource-intensive, often suffer from missing information and unduly complex processes, and are prone to create a false sense of safety. This makes such approaches ineffective for assessing and managing the broad range of plastic chemicals. A hazard-based approach overcomes these shortcomings and enables timely action on problematic chemicals. Thus, it mitigates continued exposure and associated external costs that would be caused by requiring additional evidence to perform a traditional risk assessment for each plastic chemical.

Adopting a group-based approach can streamline the assessment of plastic chemicals and prevent regrettable substitutions. It is reasonable to assume, based on scientific evidence, that chemically similar compounds generally share similar hazard properties. Grouping chemicals by their structures and prioritizing these groups for regulation is feasible, as demonstrated in this report. In addition, there is regulatory precedent for regulating groups of chemicals on a global level (e.g., PCBs, PCDD/Fs, and long-chain PFAS). By focusing on groups of chemicals with similar properties, policymakers can implement more effective and timely measures to tackle large numbers of hazardous chemicals, and at the same time, prevent plastic chemicals with similar problematic properties, so-called regrettable substitutions, from being placed on the market. This incentivizes innovative safe-by-design

Table 14: Overview of policy recommendations based on the state of the science.

Policy recommendations	Supporting evidence	Recommended approach	Specific measures
Recommendation 1 Regulate plastic chemicals comprehensively and efficiently	Plethora of plastic chemicals is a concern in and of itself. Compelling evidence for presence of chemicals of concern in plastics. Large global governance gap on plastic chemicals.	A hazard-based approach to address shortcomings of current assessment strategies. A group-based approach to streamline assessment and prevent regrettable substitutions. Adoption of established hazard criteria to identify plastic chemicals of concern. A comprehensive phase out of all chemicals of concern.	1-1. Implement a hazard- and group-based approach 1-2. Set criteria to identify chemicals of concern 1-3. Phase out priority groups and Red List chemicals 1-4. Prioritize Orange and Grey List chemicals for data collection and assessment
Recommendation 2 Require transparency on plastic chemicals	Many data gaps exist for plastic chemicals. Many unknown chemicals may be present in plastics. Essential information may exist but is unavailable to the public.	A unified approach for reporting information to create clarity for all actors. Considering chemical composition of plastics as Public Interest Information to create more transparency. A “no data, no market” approach to facilitate public disclosure of essential information across value chains. A strategic approach to close important data gaps.	2-1. Establish common information requirements 2-2. Establish a common platform for sharing information 2-3. Require disclosure and clear labelling of plastic chemicals of concern across value chains 2-4. Promote gathering and disclosing information on complex mixtures and non-intentionally added substances
Recommendation 3 Simplify plastics towards safety and sustainability	The complexity of plastic chemicals and materials prevents effective governance and impedes the transition to a circular economy.	Policies aimed at using fewer plastic chemicals to promote safety and sustainability. Essential-use and safe-by-design concepts to facilitate simplification of plastics. Improved waste management to eliminate chemicals of concern from the lifecycle of plastics. Support research and innovation aimed at developing simpler, safer, and more sustainable plastics.	3-1. Develop stringent safety and sustainability criteria for plastic chemicals and materials 3-2. Develop clear guidelines and goals for achieving chemical simplicity in plastics 3-3. Promote research and development into simpler plastic materials
Recommendation 4 Build capacity to create safer and more sustainable plastics	Lacking expertise and capacity prevents addressing chemicals of concern and designing safe and sustainable plastics.	Equal access to knowledge and capacities on plastics. Grow technical capacity and knowledge exchange to identify plastic chemicals and polymers of concern. Grow the regulatory capacity for assessing and managing plastic chemicals. Inspire trust and broad commitment towards positive change.	4-1. Establish an open platform for knowledge sharing 4-2. Establish an open forum for stakeholder dialogue 4-3. Provide resources for capacity building 4-4. Leverage international cooperation to build relevant capacity

practices, and creates a level playing field for businesses.

Established hazard criteria can be adopted to identify plastic chemicals of concern. The commonly used hazard criteria persistence, bioaccumulation, mobility, and toxicity (PBMT) offer a comprehensive framework for identifying chemicals of concern: Persistence reflects the longevity of plastic chemicals in the environment, bioaccumulation their build-up in living organisms, mobility their potential to move through the environment, and toxicity their adverse effects on human health and the environment. Importantly, the P, B, and T criteria are well-established across many national, regional, and international jurisdictions. The mobility criterion is so far only applied in the European Union but is considered for inclusion in the GHS. Incorporating these well-established hazard criteria into regulatory frameworks provides a solid foundation and avoids re-inventing the wheel.

A comprehensive approach would be required to regulate all chemicals of concern in plastics. Such an approach starts with rapid identification and management of known hazardous chemicals. This can include the 15 priority groups of chemicals and 3654 Red List chemicals of concern not yet regulated via existing MEAs. The approach also includes continuous monitoring of other plastic chemicals until sufficient evidence is generated to conclude they are not hazardous. Importantly, the lack of evidence demonstrating harm does not equal evidence of no harm. Given that two thirds of plastic chemicals are data-deficient, new policies should facilitate the continuous collection and assessment of missing hazard information. This would close the global governance gap on plastic chemicals.

A strategic approach would enable closing important data gaps. Recommendation 2 suggests making transparent basic information on all plastic chemicals, such as on their identity, chemical properties, production volumes, functions, and uses. However, given that more than 10 000 plastic chemicals also lack hazard information, a strategic approach is advisable to rank those for assessment. The reports suggest using public information for that purpose, such as production volumes or detection in plastics. While this can be a short-term solution, a prioritization framework built on additional information, such as the functionality of a plastic chemical and its proportion used in materials

and products, would allow for a more targeted identification of chemicals to be tested and assessed.

Approach: How can it be done?

Reflecting the findings and reasoning presented here, policymakers should consider taking the following steps:

1. Implement a hazard- and group-based approach

Policymakers may wish to adopt the hazard- and group-based approach outlined above to establish a comprehensive and cohesive regulatory framework that protects human health and the environment.

2. Set criteria to identify chemicals of concern

Policymakers may further wish to adopt criteria for identifying plastic chemicals of concern based on the hazard criteria suggested here. They may also consider expanding the criteria to include specific hazards not yet covered, especially those related to plastics used in or emitted to terrestrial ecosystems (i.e., terrestrial toxicity). Importantly, the criteria should be developed and regularly updated based on the latest science, following the principle of independent evidence.

3. Phase out priority groups and Red List chemicals

Policymakers may wish to take timely, comprehensive measures to not allow and to eliminate the 15 priority groups of plastic chemicals and the 3654 chemicals of concern on the Red List in the production of plastic polymers, materials, and products. While global action would be most effective national, or regional action may precede.

4. Prioritize Orange and Grey List chemicals for data collection and assessment

The Orange List chemicals and the more than 10 000 data-deficient plastic chemicals on the Grey List should be prioritized for data collection and hazard assessment. Here, a strategic approach is needed to identify the most relevant compounds. As for the Orange List chemicals, such a strategy could build on existing information, such as production and use volumes in plastics. Importantly, the financial burden associated with data generation, data collection, and hazard assessment should not be borne by the public.

Recommendation 2: Require transparency on plastic chemicals

Arguments: Why should this issue be addressed?

The lack of essential information on tens of thousands of plastic chemicals and the existence of many unknown compounds is compounded by the lack of transparency on the chemical composition of plastic materials and products. This underscores the need for a policy framework that mandates comprehensive disclosure of relevant information. Such a requirement is fundamental to ensure the safety of plastic chemicals.

Many data gaps exist for plastic chemicals.

The findings of this report show that most plastic chemicals lack essential information in the public domain to assess their safety: two thirds of chemicals do not have hazard information, 60% do not have information on their use or presence, half do not have information regarding their functions in plastics, and >1300 lack basic information on their structure and identifiers (e.g., poorly defined mixtures and polymers).¹⁹¹

Many unknown chemicals may be present in plastics. Based on current scientific evidence, it can be reasonably assumed that thousands of NIAS are present in all plastics because a multitude of reaction and degradation products will form when manufacturing, using, and recycling plastics. However, technical challenges in elucidating these NIAS result in their underrepresentation across information sources. Hence, only a few NIAS have been addressed in the regulation of plastic chemicals.

Essential information may exist but is unavailable to the public. While some of this information is unknown to all, other relevant information is known to some but not shared publicly. For instance, information on which chemicals are intentionally used in plastics is readily available in the value chain. However, it is typically not made publicly available under the claim of proprietary and confidential business information, or simply not reported as there is no regulatory mandate to do so.

Advice: What should be done?

Adopting a common approach for reporting information would create clarity for all actors. Setting clear norms on which type of information should be reported by actors across plastic

value chains is key to create the transparency required to address the more than 16 000 plastic chemicals. Importantly, such information requirements should be closely aligned with the goal to promote the safety and sustainability of plastics. For example, requiring the reporting of the identity, chemical properties, production volumes, functions, and uses of all plastic chemicals placed on the global market, as well as their hazard profiles, will facilitate phasing out chemicals of concern and adopting safe-by-design approaches. To enhance efficiency, it is sensible to require information that would serve multiple purposes (e.g., hazard assessments, life cycle analyses).

Considering the chemical composition of plastics as Public Interest Information can serve as point of departure towards more transparency. The right to information, as it is generally understood in a human rights context, primarily pertains to information held by the public sector. However, there is a growing recognition of the importance of access to certain information held by the private sector, especially when it involves issues of public interest. Indeed, plastic chemicals are closely tied to public interest, given their impacts on human health and the environment, as well as their link to consumer rights. Hence, addressing the lack of transparency and information on plastic chemicals, including the chemical composition of plastic material and products, through a lens of Public Interest Information can enable progress.

A “no data, no market” approach would facilitate public disclosure of essential information across value chains. Such an approach mandates the provision of sufficient information on a plastic chemical before it can be marketed or used in materials and products. It emphasizes the importance of mitigating chemical risks before they reach the market. The “no data, no market” approach is a cornerstone of the EU’s REACH regulation, where any chemical sold or used within its borders must be registered and assessed, and this information must be made publicly available.¹⁰⁷ Providing information on which chemicals are being used in plastics in a transparent way would not only allow for assessment, compliance, and enforcement, but also for independent review by civil society and scientists. A “no data, no market” approach would also enable material circularity, where transparency on chemical composition of materials in products throughout different life stages is imperative.¹⁹² Importantly, for a full-life

cycle approach and a safe circular economy, such information should be made available to other stakeholders in the entire value chain.

Approach: How can it be done?

Reflecting the findings and reasoning presented here, policymakers can consider the following:

1. Establish common information requirements

Such requirements should cover basic information on which chemicals are used in which materials and products, including their identity, properties, functions, and uses, to enable various types of assessments. A group of independent experts would be best equipped to suggest information requirements.

2. Establish a common platform for sharing information

All information essential to assess plastic chemicals should be made publicly available following the FAIR principles that stipulate information must be findable, accessible, interoperable, and reusable.¹⁹³ Establishing a common information sharing platform would facilitate the use of relevant knowledge by all stakeholders, especially those along plastic value chains. It would also solve the challenge of unharmonized information that is scattered across multiple sources. Such policy innovation is currently proposed in the EU which aims at creating a common data platform on chemicals.¹⁹⁴

3. Require disclosure and clear labelling of chemicals of concern across value chains

The actors introducing plastic chemicals, materials, and products to the market should be tasked with creating transparency. Besides a “no data, no market” approach, a clear disclosure and labelling of plastic chemicals, in particular those of concern, across value chains is essential. A transparent labelling of chemicals of concern on plastic materials and products would enable downstream users and waste managers to take informed decisions. Moreover, such transparency will also enable addressing certain claims, such as a product being “environmentally friendly” or “biodegradable,” by fact-checking for the presence of toxic or persistent chemicals. In this manner, transparency can increase the market value of safer and more sustainable plastics.

4. Promote gathering and disclosing information on complex and non-intentionally added substances

The presence of NIAS and UVCBs in all plastics is a major obstacle towards safer and more

sustainable materials. Yet, essential information on their identity, their structure, and hazards, are lacking. Here, a strategic, coordinated approach toward closing pertinent knowledge gaps related to complex mixtures and NIAS is necessary. Policies should allow for an accurate, publicly accessible overview of the chemical structure of mixtures, polymers, their impurities, and reaction and degradation products.^{191,195} For instance, expected NIAS and their hazards could be included in the data sheets of plastic chemicals and materials entering the global market. Such action would raise awareness for the issue of NIAS along value chains and promote innovation into plastic materials and products containing less hazardous chemicals and fewer NIAS.

Recommendation 3: Simplify plastics towards safety and sustainability

Arguments: Why should this issue be addressed?

The vast array of plastic chemicals poses substantial challenges for governance, regulation, and circular systems, which results in severe economic, environmental, and health risks. Consequently, decreasing the chemical complexity and simplifying the chemical composition of plastics can reduce the size of the problem and enable the transition towards a safe and sustainable plastic economy.^{90,192,196}

The chemical complexity of plastics prevents effective governance. The chemical complexity of plastics is immense, considering the more than 16 000 known plastic chemicals reported here as well as the many yet unidentified compounds and the multitude of plastic products on the market and in the environment. Accordingly, at “all stages of plastics’ lifetime [...] there is enormous chemodiversity.”¹⁹² Thus, the task of managing plastic chemicals through traditional avenues of risk governance seems insurmountable. This is supported by the findings in this report: Over 3600 chemicals of concern are not regulated on a global level, and more than 10 000 chemicals lack data for their assessment in the public domain. Thus, most plastic chemicals have escaped national, regional, or international governance.

The chemical complexity of plastics impedes the transition to a safe circular economy.

The vast number of plastic chemicals, including known and not yet identified chemicals of concern, poses a significant barrier to circularity, as it compromises safe reuse, repurposing, and recycling. Essentially, chemicals of concern can persist in and spread with reused plastic products and recycled plastic materials. The difficulties in removing such compounds during recycling complicates the creation of safe, high-quality secondary materials needed in a circular economy. This problem is compounded by the fact that circular systems will inevitably promote the spread of plastic chemicals with unknown hazards, essentially making adequate chemicals management very difficult. In addition, the chemical complexity reduces the compatibility of waste streams and may pose significant challenges in the technical infrastructure required for circularity.⁹⁰

Advice: What should be done?

Implementing policies aimed at using fewer plastic chemicals would promote safety and sustainability. To effectively simplify the chemical composition of plastics, policymakers should develop a strategic framework that reduces the number of plastic chemicals. One step towards achieving this is to phase out chemicals of concern in plastics (see recommendation 1). In addition, regulatory measures could be developed to better control the proliferation of new plastic chemicals that fulfill similar functions. For example, questions may be raised whether it is truly necessary to use more than 3600 colorants in plastics. Encouraging innovation towards materials that require fewer chemicals plays a crucial role. Such a streamlined approach would not only enhance environmental and public health protection but also support the viability and the broader goals of a safe circular economy.

The essential-use and safe-by-design concepts can facilitate the simplification of plastics.

The essential-use concept focuses on using chemicals (of concern) only when they are crucial for health, safety, or societal functioning and there are no safer alternatives (including non-chemical one) available yet.^{197,198} Drawing on successful precedents, such as the Montreal Protocol,¹⁹⁹ this approach would target the elimination or substitution of non-essential plastic chemicals. In this context, the essential-use approach can be applied for implementing control measures of chemicals of concern. While this tackles existing chemicals, the safe-and-sustainable-by-design concept may guide the innovation of new compounds and materials.²⁰⁰ It prioritizes safety and sustainability from the earliest design phases, ensuring that plastic chemicals and materials are inherently less hazardous and have a low environmental footprint. By mandating that plastic chemicals meet high standards for safety and sustainability before market introduction, policymakers can encourage innovation towards simpler materials that are compatible with a safe and circular economy.

Waste management should be improved to eliminate chemicals of concern from the lifecycle of plastics. Considering the Zero Waste hierarchy,²⁰¹ the goal of policy actions should be to minimize the generation of plastic waste. However, such transition also needs to consider minimizing chemicals of concern released from prevailing end-of-life treatments,

such as landfilling and incineration. This involves developing comprehensive management plans and regulations that support the use of non-toxic materials ([recommendation 1](#)) and enhance recycling processes that remove hazardous chemicals and do not produce hazardous waste. Adopting a “Toxic-Free Zero Waste Hierarchy” approach by fusing elements of the Zero Waste and the Toxic-Free Hierarchy,^{98,201} tailored to sector-specific needs, can guide this transition. Innovations in waste sector practices are also critical for achieving zero contamination and emissions in waste handling facilities.

Policymakers should actively support research and innovation aimed at developing simpler, safer, and more sustainable plastics. This involves providing funding, incentives, and a regulatory environment that encourages the redesign of existing plastic materials and the development of new materials and chemical processes. This could be achieved through funding for research into simpler materials. Additionally, incentivizing the private sector to develop and implement these materials can stimulate progress. Policymakers could also facilitate partnerships to design such materials by joining academia, industry, and government research to leverage the collective expertise. Implementing regulations that require transparency and set stringent safety and sustainability criteria can further drive the adoption of simpler plastics.

Approach: How can it be done?

Reflecting the findings and reasoning presented here, policymakers can consider the following:

1. Develop stringent safety and sustainability criteria for plastic chemicals and materials

Implementing policies that require plastic chemicals and materials to comply with stringent safety and sustainability criteria will set a regulatory environment towards simplification of plastics. Safety requirements could include the hazard criteria applied in this report as a baseline but could evolve to cover additional hazards (e.g., to terrestrial ecosystems). Sustainability criteria could be adopted from existing sustainable design frameworks as a baseline, such as material and energy efficiency, minimized emissions, and maximized potential for circularity.^{100,200} The criteria should be designed in an adaptive manner to align with scientific progress.

2. Develop clear guidelines and goals for achieving chemical simplicity in plastics

Much of the chemical complexity of plastics originates from placing on the market thousands of chemicals that fulfill a fairly small number of basic functions. As a result, there is much redundancy, where many plastic chemicals share the same basic function. To operationalize safety and sustainability criteria and the essential-use concept, practical guidelines can be developed to engage and support actors across plastic value chains in the pursuit to simplify the chemical composition of plastic materials and products. This could involve guidance towards the practical implementation of safety, sustainability, and essentiality aspects into the re-design of existing and the development of new materials. Additionally, setting clear goals and timelines for achieving chemical simplicity in plastics can help to monitor progress, adjust, and ensure effectiveness.

3. Promote research and development into simpler plastic materials

To develop a pathway towards simplification, research and innovation should focus on developing fully safe and sustainable materials, over the full life cycle. The processes for manufacturing and processing these materials should be designed in a way that minimizes the generation of NIAS. Alongside the need to redesign chemicals and materials, one area of research may be focused on how to develop and implement adequate testing approaches, such as leachate toxicity to ensure safety and compliance strategies regarding NIAS.¹²⁶ To implement this, coordination and support actions would be needed to leverage joint expertise in academia, the private and the public sector.

Recommendation 4: Build capacity to create safer and more sustainable plastics

Arguments: Why should this issue be addressed?

Missing institutional expertise and capacity to manage plastic chemicals and polymers, and to innovate towards better solutions are the major obstacles preventing transition towards a safe circular plastics economy. Accordingly, it is crucial to build regulatory and technical expertise and capacity across the private and public sectors and foster knowledge exchange between countries and stakeholders.

The lack of regulatory and technical capacity prevents addressing plastic chemicals of concern. As highlighted in this report, the number of plastic chemicals and polymers on the market outsizes the institutional capacity for testing, assessment, and management at an international, regional, and national level. This problem is exacerbated by lacking issue awareness and scientific expertise across the plastics value chain. In addition, the technical capacity to make a step change in terms of testing and assessing thousands of plastic chemicals, including NIAS, is limited. Jointly, all these challenges hamper informed decision-making towards phasing out chemicals of concern, illustrated by the fact that about half of the plastic chemicals known to be marketed for use have been classified as hazardous.

The lack of regulatory and technical capacity prevents designing safer and more sustainable plastics. Besides removing chemicals of concern from plastic materials and products, capacities are lagging for the re-design of existing plastics and the innovation into novel plastics that meet safety and sustainability goals ([recommendation 3](#)). This specifically refers to the lack of institutional capacities to bridge the divide between environmental, health, and material sciences that impede an implementation of safe-and-sustainable-by-design strategies for plastics at scale. This, in turn, is deepened by the absence of a regulatory environment that would provide economic and other incentives to implement such strategies. Indeed, overcoming the current gradient of knowledge and awareness is a prerequisite for future-proof policy development and the transition toward a safer and more sustainable plastics economy.

Advice: What should be done?

Equal access to knowledge and capacities on plastics should be ensured. Sharing knowledge and capacities relevant to plastic chemicals, materials, and products with all actors across the plastic value chain is critical, given the global scale of the plastics economy and the severity of plastic pollution. This includes, but is not limited to, bridging the geographic divide in terms of technical expertise, and integrating communities affected by plastics in an equitable way. Equal access to knowledge strongly relies on creating transparency ([recommendation 2](#)) and should involve all relevant actors, including the public and private sector as well as academia, civil society, and the public.

Grow technical capacity and knowledge exchange to identify plastic chemicals and polymers of concern. The striking knowledge gaps on plastic chemicals speak towards a lack of technical capacity to identify chemicals of concern in the scientific community but also in the private sector. Here, capacity building is needed for broader research and action to develop and validate new approaches for testing and assessing the vast number of chemicals and polymers on the market. This should be accompanied by a focused, strategic knowledge exchange within scientific disciplines, and involve the highly diverse private sector and academia as well as policymakers and regulators.

Grow the regulatory capacity for assessing and managing plastic chemicals. Mirroring the above, institutional capacities to manage plastic chemicals, materials, and products are lacking and are unevenly distributed on a global scale. Thus, capacity building in regulatory agencies is required to ensure a comprehensive assessment of plastic chemicals and polymers, monitoring progress towards safety and sustainability goals as well as a robust level of enforcement of relevant policies.

Inspire trust and broad commitment towards positive change. Building and sharing relevant scientific, technical, regulatory, and political capacities should be driven by a shared vision of a safer and more sustainable plastics economy. Political leadership is required to build trust amongst stakeholders and foster commitment to such a transformative vision, with resources allocated to developing and sharing the necessary skills, knowledge, and infrastructure. By fostering partnerships among government, industry, academia, and civil

society, policymakers can facilitate the sharing of best practices, innovations, and technologies that drive the transition to a safer and more sustainable plastics economy.

Approach: How can it be done?

1. Establish an open platform for knowledge sharing

Such a platform could host technical information, such as the PlastChem database, but also serve as a hub for global knowledge exchange with regards to technical and scientific resources. These should be accompanied by regular updates to ensure information is aligned with the state of the science and the principle of independent evidence. In addition, training activities, such as massive open online courses or dedicated scientific workshops, could be hosted by such a platform to facilitate capacity building globally.

2. Establish an open forum for stakeholder dialogue

The knowledge-sharing platform could be accompanied by an open forum for stakeholder dialogue. While being informed by independent science, such a forum could focus on the implementation of measures towards a safer and more sustainable plastics economy. It would serve as a collaborative platform bringing together policymakers, industry leaders, environmental organizations, researchers, and community representatives. This forum could operate through regular panels and workshops, collaborative projects on best practices and public engagement sessions.

3. Provide resources for capacity building

For managing plastics and plastic chemicals adequately, sufficient resources should be made available at local, national, and international level. Among others, adequate resources should be allocated to regulatory authorities and academic research institutions to support capacity building and training of future professionals. Policymakers may also choose to direct investment towards developing fully safe and sustainable novel materials and products. Recalling that the plastics economy and plastic pollution are global in scale, sufficient resources are required to make the relevant knowledge, technology, and infrastructures available in an open, fair, and equitable way that ensures the development of shared solutions.

4. Leverage international cooperation to build such capacity

The plastics treaty and other avenues of international cooperation are an important opportunity for building shared capacity and vision, and for providing scientifically robust, trustworthy information about plastics and plastic chemicals. Notably, the principle of independent evidence should also guide any steps pertaining to capacity building and raising awareness.

What are the positive impacts of addressing plastic chemicals?

Addressing plastic chemicals and polymers of concern comprehensively is expected to result in substantial benefits for the environment and human health, promote innovation into safer plastic chemicals, material, and products as well as support a transition to a non-toxic, circular economy. The proposed approaches to plastic chemicals and polymers are anticipated to reconcile the state of the science with policy and regulatory frameworks, thereby facilitating informed decision-making and responsible innovation across sectors.

Since no country has the capacity to address the transboundary issue of plastic chemicals and polymers individually, the state of the science implies that a collective global response is most appropriate to mitigate their environmental and health impacts. Adopting evidence-based policies that prioritize chemical safety and sustainability will provide a pathway towards a safe and sustainable future for plastics.

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Associated database

The state of the science report is accompanied by the PlastChem database which contains the information on the known plastic chemicals that was synthesized in this work. The database can be accessed under <http://dx.doi.org/10.5281/zenodo.10701706>.

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PART V

Annex

Glossary, methodology, detailed
findings

A1: Glossary	A3
A2: Abbreviations.....	A7
A3: Detailed findings from Part II	A11
Results of the expert consultations.....	A11
Expert feedback from the first round of consultations	A11
Expert feedback from the second round of consultations.....	A13
Overlap with previous databases of plastic chemicals	A16
Limitations of the PlastChem database.....	A18
Functions of plastic chemicals.....	A19
A4: Detailed methodology of Part II	A21
Expert consultations.....	A21
First round of consultations	A21
Second round of consultation	A22
Building the PlastChem database	A23
Backbone database	A23
Grouping of plastic chemicals.....	A26
Approach 1. Through keyword search	A26
Approach 2. Through match with existing lists of chemical groups	A27
Inclusion of hazard information.....	A30
Inclusion of additional information.....	A38
Information on regulatory status	A38

Information on the use, presence, and release of chemicals in plastic polymers	A42
A5: Detailed findings from Part III.....	A45
Hazard classification of plastic chemicals	A45
Presence of chemicals of concern in commodity and specialty plastics.....	A46
Leachate toxicity.....	A49
Status of global and regional plastic material flows.....	A51
Projected changes in material flow of plastic and plastic polymers, and respective environmental emissions	A55
Knowledge gaps in mass flow data	A58
End of life of plastics and circularity	A59
A6: Detailed methodology of Part III	A62
Identification of chemicals of concern.....	A62
Processing of hazard data	A62
Hazard and Evidence Scoring system.....	A63
Prioritization of groups of plastic chemicals	A66
Selection of relevant groups.....	A66
Prioritization of groups.....	A68
Inclusion of additional data.....	A69
Toxicity of plastic leachates	A69
Material flow analysis	A71
Annex references.....	A75

A1: Glossary

The glossary provides contextual information on terms used in the report and is not intended to imply any legal meaning or official definition.

Chemical or compound: Used synonymously in the report, also covers the more technical term substance.^a

Monomer: Individual chemical building block used to make polymers.

Polymer: A macromolecule that consists of repeating units of monomers, used in the report to either refer to plastic polymers or other polymers added to plastics.

Plastics: A *“material which contains as an essential ingredient a high molecular weight polymer and which, at some stage in its processing into finished products, can be shaped by flow.”*^b

Plastic polymer: A polymer used to make plastic materials and products, used in the report to refer to plastic materials or products that contain the polymer as essential ingredient (i.e., polymer backbone).

Intentionally added substances (IAS): These are chemicals deliberately incorporated into plastics to achieve certain characteristics or functionalities. The term does not include the polymer backbone.

Non-Intentionally Added Substances (NIAS): NIAS include impurities, degradation products, and compounds formed during the manufacturing, use, or end of life of

^a <https://echa.europa.eu/support/substance-identification/what-is-a-substance>

^b <https://www.iso.org/obp/ui/#iso:std:iso:472:ed-4:v1:en>, elastomers are considered plastics in the report

plastics that are not deliberately included in the material. Their identity is often complex and unknown.

Food contact materials (FCMs): Any material that is intended for use in the manufacture of an article intended for coming into contact with food. FCMs are typically in direct contact with food. Materials that are not in direct contact with the food but may be a source of chemicals migrating into food (e.g., printing inks) are also considered FCMs.

Plastics treaty: International legally binding instrument on ending plastic pollution based on a comprehensive approach that addresses the entire life cycle of plastics, from design to production and disposal. In March 2022, at the 5th session of the UN Environmental Assembly (UNEA) countries agreed to convene an Intergovernmental Negotiating Committee to develop the instrument, with the ambition of completing its work by the end of 2024.

Exposure potential: Chemicals that are likely to be taken up by organisms, refers to chemicals that have evidence for their use or presence in, or release from plastic products in the report. A high production volume can also serve as proxy for exposure potential.

Hazard: The potential of a chemical to cause harm to the environment, including living organisms.

Hazard criteria: This refers to the properties of a chemical that render it hazardous, including persistence, bioaccumulation, mobility, or toxicity.

Hazard traits: These are more detailed features of the individual hazard criteria. For instance, toxicity can be determined based on the carcinogenic properties of a chemicals but also based on its potential to adversely affect reproduction or aquatic wildlife.

Persistence: The ability of a chemical to remain in the environment without breaking down or degrading over a long period.

Bioaccumulation: The process by which a chemical gradually concentrate in organisms over time, reaching higher concentrations than in the surrounding environment.

Mobility: The capacity of a chemical to spread in the environment, often affecting its distribution within and across different compartments, such as soil, water, and air.

Toxicity: The degree to which a chemical can damage organisms.

Regulatory status: The official classification and restrictions imposed on the use, handling, or disposal of a chemical by governments or international regulatory bodies.

Use of a plastic chemical: This indicates that this chemical is marketed for its use in plastic materials or products.

Detection of a plastic chemical: Empirical evidence from scientific studies demonstrates that a plastic chemical using analytical chemistry.

Presence of a plastic chemical: Empirical evidence from scientific studies indicates that this chemical has been detected in plastic materials or products.

Release of a plastic chemical: Transfer of a chemical from a plastic material or product into aqueous or solid media via migration or into air via volatilization, in a more specific context this refers to empirical evidence from scientific studies indicating a release.

Plastic leachate: Mixture of chemicals released from individual plastic material or product via extraction or migration.

Micro- and nanoplastics (MNPs): Particles consisting of plastics which are smaller than 5 mm in their largest diameter.

High production volume chemicals: Chemicals that are produced in a volume of ≥ 1000 tons per year.

Endocrine Disrupting Chemicals (EDCs): According to the definition of the International Programme on Chemical Safety of the World Health Organization (WHO-IPCS), an endocrine disrupting chemical (EDCs) is an *“exogenous substance or mixture that alters function(s) of the endocrine system and consequently causes adverse health effects in an intact organism, or its progeny, or (sub)populations.”*¹

Per- and polyfluoroalkyl substances (PFAS): Fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), that is, with a few noted exceptions, any chemical with at least a perfluorinated methyl group ($-\text{CF}_3$) or a perfluorinated methylene group ($-\text{CF}_2-$).

Persistent organic pollutants (POPs): Chemicals that possess toxic properties, resist degradation, bioaccumulate and are transported, through air, water, and migratory species, across international boundaries and deposited far from their place of release, where they accumulate in terrestrial and aquatic ecosystems. They are listed under the Stockholm Convention.

A2: Abbreviations

Abbreviation	Meaning
ABS	Acrylonitrile butadiene styrene; refers to a plastic polymer
API	Application programming interface
B	Bioaccumulative or bioaccumulation; refers to a hazard criterion or chemicals that fulfil that criterion
BAU	Business as usual; refers to baseline scenarios representing the current situation
BFRs	Brominated flame retardants; refers to a group of chemicals
BRS	Basel, Rotterdam, Stockholm; refers to the respective multilateral environmental agreements on chemicals
CASRN	Chemical Abstracts Service Registry Number; refers to a chemical identifier
CDR	Chemical Data Reporting Program of the United States Environmental Protection Agency
CLP	Regulation on Classification, Labelling and Packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006; refers to a European Union regulation
CMR	Carcinogenic, mutagenic, and toxic for reproduction; refers to hazard criteria or chemicals that fulfil those criteria
Col	Conflicts of interest
CPPdb	Database of Chemicals associated with Plastic Packaging; refers to a list of plastic chemicals developed by Groh et al. in 2019 (DOI: 10.1016/j.scitotenv.2018.10.015)
CSS	Chemicals Strategy for Sustainability towards a toxic-free environment; refers to a European Union policy strategy
db	Database
decaBDE	Decabromodiphenyl ether; refers to a chemical used as brominated flame retardant
ECHA	European Chemicals Agency
EDCs	Endocrine disrupting chemicals; refers to a group of chemicals
EEA	European Environment Agency
EPS	Expanded polystyrene; refers to a plastic polymer, specific type of polystyrene
ES	Evidence score; refers to the score used to rank chemicals based on the available evidence
EU	European Union

Abbreviation	Meaning
FAIR	Findable, accessible, interoperable, and reusable; refers to a concept of open science and data
FCCdb	Database of intentionally added Food Contact Chemicals; refers to a list of plastic chemicals developed by Groh et al. in 2021 (DOI: 10.1016/j.envint.2020.106225)
FCCmigex	Database of migrating and extractable Food Contact Chemicals; refers to a list of plastic chemicals developed by Geueke et al. in 2023 (DOI: 10.1080/10408398.2022.2067828)
FCMs	Food contact materials; refers to all materials intended to be into contact with food, including production and processing
FPF	Food Packaging Forum Foundation
GHG	Greenhouse gases; refers to a group of chemicals
GHS	Globally Harmonized System of classification and labelling of chemicals; refers to an internationally agreed-upon standard managed by the United Nations
HBCDD	Hexabromocyclododecane, a brominated flame retardant (sometimes also abbreviated as HBCD)
HDPE	High-density polyethylene; refers to a specific plastic polymer
HIPS	High impact polystyrene; refers to a plastic polymer, specific type of polystyrene
HPV	High production volume; refers to a group of chemicals that is produced at a volume of ≥ 1000 tons per year
HS	Hazard score; refers to the score used to classify chemicals of concern
IARC	International Agency for Research on Cancer
IAS	Intentionally added substances; refers to a group of chemicals
INC	Intergovernmental Negotiation Committee; refers to the body negotiating the global plastics treaty
InChI	International Chemical Identifier; refers to a chemical identifier encoding a chemical's structure
LDPE	Low-density polyethylene; refers to a specific plastic polymer
LitChem	Database of plastic chemicals developed by Wiesinger et al. (in preparation)
M	Mobile or mobility; refers to a hazard criterion or chemicals that fulfil that criterion
MEAs	Multilateral environmental agreements
MNPs	Micro- and nanoplastics; refers to plastic particles < 5 mm in their largest diameter
NIAS	Non-intentionally substance(s); refers to a group of chemicals
NTNU	Norwegian University of Science and Technology
OECD	Organisation for Economic Co-operation and Development

Abbreviation	Meaning
P	Persistent or persistence; refers to a hazard criterion or chemicals that fulfil that criterion
PA	Polyamide, sometimes called nylon; refers to a specific plastic polymer
PAHs	polycyclic aromatic hydrocarbons; refers to a group of chemicals
PBAT	Polybutylene adipate terephthalate; refers to a plastic polymer
PBDEs	Polybrominated diphenyl ethers; refers to a group of chemicals used as flame retardants
PBMT	Persistence, bioaccumulation, mobility, toxicity; refers to hazard properties of chemicals
PBT	Persistent, bioaccumulative, and toxic; refers to hazard criteria or chemicals that fulfil those criteria
PC	Polycarbonate; refers to a plastic polymer
PCBs	polychlorinated biphenyls; refers to a group of chemicals
PCDD/Fs	Polychlorinated dioxins and furans; refers to a group of chemicals
PET	Polyethylene terephthalate; refers to a specific plastic polymer
PFAS	Per- and polyfluoroalkyl substances; refers to a group of chemicals that have multiple fluorine atoms attached to an alkyl chain
PFOA	Perfluorooctanoic acid; refers to a perfluorinated chemical
PLA	Polylactic acid; refers to a plastic polymer
PlasticMAP	Database of plastic chemicals developed by Wiesinger et al. in 2021 (DOI: 10.1021/acs.est.1c00976)
PM	Persistent and mobile; refers to hazard criteria or chemicals that fulfil those criteria
PMFCdb	Database of chemicals in plastic materials and articles intended to come into contact with food; refers to a list of plastic chemicals developed by the European Chemicals Agency according to the Union List of Authorized Substances: Annex I, Plastics Food Contact Regulation 10/2011/EU, as amended by Regulation (EU) 2023/1627, OJ L 201
PMT	Persistent, mobile, and toxic; refers to hazard criteria or chemicals that fulfil those criteria
POPs	Persistent organic pollutants; refers to a group of chemicals
PP	Polypropylene; refers to a specific plastic polymer
PS	Polystyrene; refers to a specific plastic polymer
PUR	Polyurethane, sometimes also PU; refers to a specific plastic polymer
PVC	Polyvinylchloride; refers to a specific plastic polymer
RCN	Research Council of Norway

Abbreviation	Meaning
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals; refers to a European Union regulation
SMILES	Simplified molecular-input line-entry system; refers to a chemical identifier encoding a chemical's structure
SPIN	Substances in Preparations in the Nordic countries; refers to a database containing the production volumes of chemicals
STOT	Specific target organ toxicity; refers to a hazard criterion or chemicals that fulfil that criterion
SVHC	Substance of very high concern; refers to a collection of hazard criteria or chemicals that fulfil those criteria
T	Toxic or toxicity; refers to a hazard criterion or chemicals that fulfil that criterion
TSCA	Toxic Substances Control Act; refers to a law of the United States of America
UBA	German Federal Environment Agency
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
USA	The United States of America
USD	United States dollars
UV	Ultraviolet; refers to a specific band of electromagnetic radiation
UV-328	2-(2H-benzotriazol-2-yl)-4,6-di-tert-pentylphenol; refers to a specific chemical
UVCBs	Substances of unknown or variable composition, complex reaction products or biological materials; refers to a group of chemicals
vPvB	Very persistent and very bioaccumulative; refers to hazard criteria or chemicals that fulfil those criteria
vPvM	Very persistent and very mobile; refers to hazard criteria or chemicals that fulfil those criteria
WHO	World Health Organization
XPS	Extruded polystyrene; refers to a plastic polymer, specific type of polystyrene

A3: Detailed findings from Part II

Results of the expert consultations

Expert feedback from the first round of consultations

General approach. All experts agreed that the overall approach of the project is clear, practicable, and logical. They also supported our idea of grouping the chemicals based on their structure. The majority suggested further grouping the chemicals by function and use as they acknowledged that grouping is not an easy task. Prioritizing chemicals or chemical groups based on their hazard was generally supported while the importance of considering exposure information in prioritization was rated differently. Some experts argued that exposure data are essential for regulation. Others shared our understanding that exposure data are limited and should be used supplementary as much as possible. One expert proposed using migration data as an indicator for exposure and others suggested including case-studies, that is, collecting information on exposure for one or two substances per group since this could be sufficient for regulating the whole group. In general, there was a consensus that P and M, as inherent chemical properties, are becoming more and more important in hazard classification and are especially important for global action (e.g., of interest for the Stockholm Convention).

Policy needs. Concerning policy needs, the experts agreed on using hazard classification to regulate chemicals although some also stressed the necessity of exposure (see above) and release information (e.g., to regulate plastic waste, recycling). Regarding hazards, many experts were in favor of only using hazards that are already established (e.g., CLP), ranking hazards (high, medium, low), and/or

having simple hazard scores. Many emphasized that it would be helpful if the project also provided substitutes for known chemicals of concern (by use) since alternatives would be needed when restricting chemicals. It was also mentioned to include a “positive list” of chemicals of no concern. One expert further pointed out the regulatory usefulness of having chemicals linked to human biomonitoring data and human disease.

Regarding the presentation of the project output, there was consensus that a comprehensive and searchable inventory of chemicals of concern would be most useful. To prove the credibility of the entries and allow the user to look up additional information, some experts recommended that references should be provided per chemical or chemical group. In the context of prioritizing groups based on their concern (e.g., to start phase-out), one expert suggested to differentiate between higher and lower scientific agreement in data presentation and another one to link chemicals with plastic types (e.g., to see which waste is hazardous).

Additional suggestions made by the experts. In addition to the questions asked, the experts made further suggestions summarized here:

- Select “marker chemicals” as representatives for each group which can be identified and monitored by the regulatory agencies as a measure to enforce regulation.
- Rank the hazard data based on the level of evidence as follows from high to low evidence: (1) harmonized classifications (e.g., ECHA SVHC list), (2) self-classification of the registrant, and (3) CLP notifiers. One expert mentioned that the criteria for prioritizing chemicals or for defining thresholds should be shared since it is helpful for other similar initiatives.

- Concerning exposure, one expert suggested starting by looking at typical concentrations of the chemicals in plastic (e.g., based on chemical safety reports under REACH, interviews with experts).
- Focus on the polymer instead of individual chemicals or create a link between a substance, a polymer, and a product. The latter would allow to identify and inform on potential substitutions.
- Waste was another topic frequently raised, especially by the experts from the Global South. Here, one expert explained that hazard is almost only assessed during use and regarding impacts on humans. On the contrary, evaluation of environmental hazards is mostly neglected even though these hazards are especially important when plastics become waste (after use). This would prevent regulations on plastic waste. To overcome this gap, it was mentioned that the project should also consider end-of-life of the product and the release of chemicals from waste.
- Finally, an expert pointed out the importance of cross-checking the project's findings with industry (e.g., via an agency) to see if the substances are still in use and are not legacy compounds.

Generally, the experts were aware of the comprehensiveness of PlastChem and suggested setting boundaries on what the project can provide and what it cannot. All agreed on a follow-up interview and expressed their interest in the outcome of the project.

Expert feedback from the second round of consultations

All experts agreed that the data compiled in the PlastChem project is very helpful and necessary for their work. They also highlighted specific aspects particularly useful for them, such as the MEA, red, and orange lists, the grouping of chemicals, and hazard assessment based on the groups, as well as the provided details on the

type and origin of the hazard information. The latter would help to assess the quality of the hazard data as well as to estimate the difficulty of regulating a certain chemical based on that hazard.

One expert further commented that our approach of prioritizing a chemical as hazardous based on one of the four criteria P, B, M, or T is “critical,” especially if persistence would be the only criterion. Instead, the expert recommended classifying a chemical as hazardous if considered harmful according to at least two out of the four criteria. Furthermore, it was recommended to clarify in the report that not every chemical on the list may currently be in use. A different topic that came up was the problem of data availability in the public domain. Here, one expert suggested mentioning that problem in our report supporting calls for more transparency.

Information we were unable to integrate into the project but of interest to the experts, included data on the tonnage of the chemicals (which was included after this feedback) and their presence in the environment and humans (exposure). Most often, experts mentioned the need for information on the chemicals’ function and use sector given the fact that chemicals are usually regulated by sector. Such data would further aid the evaluation of potential alternatives and their hazards. One expert clarified that hazard data can serve as a “trigger” but to regulate chemicals policymakers would need production volume, function, and exposure data. In addition, it was mentioned that a more comprehensive consideration of plastic waste would be of interest to the experts as well as a differentiation between functional additives and unintended substances. Although the experts made these suggestions, they agreed that the data compiled during the one-year project duration was already very comprehensive and that collecting additional data would require an extension or follow-up of the project.

Concerning the data presentation, the experts shared the opinion that one comprehensive (Excel) spreadsheet that can be filtered, used for own prioritization exercises, and which also includes references is highly relevant to their work. One expert suggested holding a webinar to explain how to use the database once published. In addition to this large dataset, one- or two-pagers with key messages and figures were considered useful. Also, when reaching out to the public, a more tailored communication strategy (e.g., an easy-to-understand and filterable dashboard) would be needed according to the feedback.

All experts expressed great interest in the report and emphasized that they would use the PlastChem database for their work.

Overlap with previous databases of plastic chemicals

The PlastChem database combines the previously scattered data on plastic chemicals in one comprehensive database. The chemicals and their associated information partly overlap between the sources. For instance, the PlasticMAP covers all chemicals listed by ECHA and the CPP databases, and the one by Aurisano et al. includes all the chemicals reported in the FCC database. However, almost 30% of the compounds in the PlastChem database are only mentioned in one of its sources. This shows the fragmented nature of the information on plastic chemicals. By combining and harmonizing seven databases, the PlastChem database becomes a comprehensive database providing one source that provides a comprehensive overview of all known plastic chemicals.

The PlastChem database provides comprehensive information on plastic chemicals by including their (a) identifiers, (b) hazards and associated level of evidence, (c) use and detection in plastics and polymer types, (d) inclusion in larger chemical groups, (e) regulatory status, (f) production volumes, (g) functionality and application sectors, and (h) information sources (Table A1).

Table A1. Type of information collated in the PlastChem database. Orange: original information from database was integrated and harmonized in the PlastChem database. Green: updated information was gathered from other sources (i.e., regulatory or industry sources) or newly created for PlastChem (i.e., grouping).

Type of information collected in the PlastChem database	CPPdb	FCCdb	FCCMigex	ECHA	PlasticMAP	LitChem	Aurisano et al.	PlastChem
(a) Chemical identifiers								
(b) Hazard information								
(b) Hazard scoring								
(c) Use in polymers								
(c) Detection in polymers								
(d) Grouping								
(e) Regulatory status								
(f) Production volume								
(g) Sectors								
(g) Functionality								
(h) Traceability to original source								

Limitations of the PlastChem database

The PlastChem database contains 17 932 entries in total, including 16 325 substances with CASRNs, that are or may potentially be used or present in plastic. This number is higher than previous studies^{2,3} and reports⁴ as PlastChem compiles previously fragmented information from seven databases and harmonizes the information to a unique and comprehensive database. However, the 16 325 chemicals with CASRNs can be an underestimate of the total number of plastic chemicals mainly due to a lack of transparency regarding the presence of plastic chemicals. In addition to this, some uncertainties may remain in the PlastChem database despite several measures for quality assurance and quality control (QA/QC). First, 400 duplicates were identified and are presented as an additional file of the PlastChem database. These duplicates arise from both the wide use of different names for the same chemical substance or the lack of unique identifiers as some CASRNs directed to different substances. Out of these 400 duplicates, 188 chemicals were manually selected by expert judgement for inclusion in the main PlastChem database as most probable chemicals associated to specific CASRNs. While we curated and validated the CASRNs in the PlastChem database to minimize duplication, additional duplicates may be present in the database that would require extensive manual curation (see method section below). Second, the grouping of substances based on chemical structure was conducted manually through eyeballing and this may result in some inconsistencies. Finally, some manual curation of some entries was necessary which could also result in a few inconsistencies.

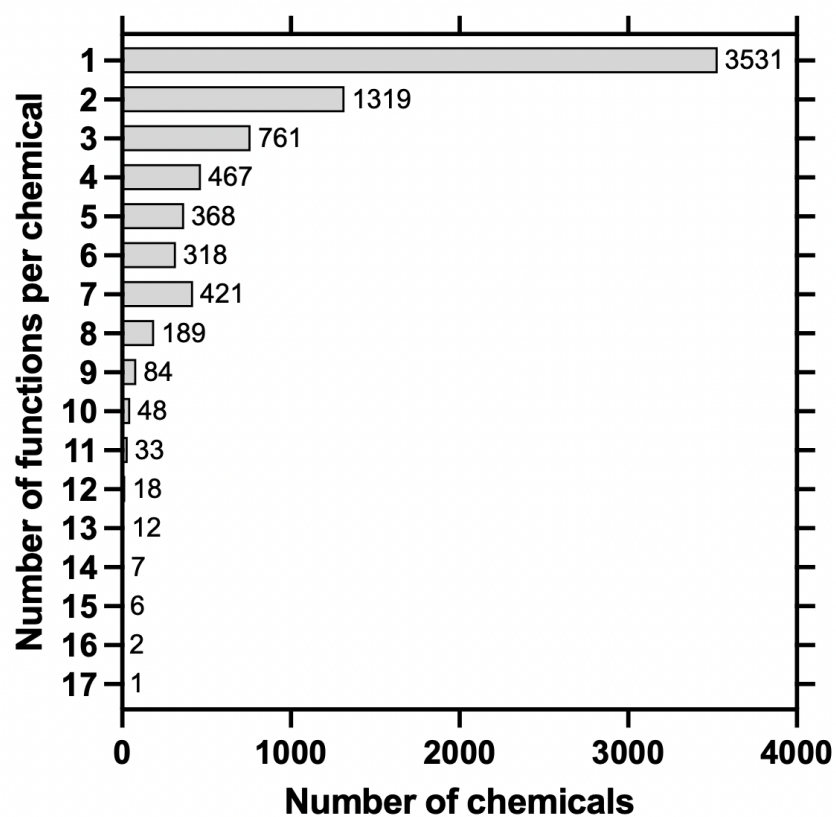
Functions of plastic chemicals

Table A2. Overview of functional classes assigned to plastic chemicals. This information is based on LitChem, CPPdb, and Aurisano et al. (2021).

Known function in plastic ^a	Larger category ^b	Number of chemicals
Adhesive	Additive	6
Anti-fog_additive	Additive	3
Antioxidant	Additive	595
Antistatic_agent	Additive	205
Biocide	Additive	1252
Blowing_agent	Processing aid	103
Catalyst	Processing aid	723
Colorant	Additive	3674
Crosslinking_agent	Processing aid	897
Degradation_product	NIAS	30
Emulsifier	Processing aid	12
Filler	Additive	1836
Flame_retardant	Additive	389
Heat_stabilizer	Additive	215
Impact_Modifier	Additive	31
Impurity	NIAS	5
Initiator	Starting substance, Processing aid	478
Intermediate	Processing aid, NIAS	1741
Light_stabilizer	Additive	764
Lubricant	Processing aid	1687
Monomer	Starting substance	959
NIAS	NIAS	47
Odor_Agent	Additive	843
Other_Processing_Aids	Processing aid	3028
Pigment	Additive	2
Plasticizer	Additive	883
Polymerization_aid	Processing aid	3
Solvent	Processing aid	83
Stabilizer	Additive	862
Surfactant	Processing aid	7
Ultraviolet-absorbing_agent	Additive	2
Unspecified_additive	Additive	74
Unspecified_raw_material	Starting substance	15
Viscosity_Modifier	Processing aid	128

Note: ^a also includes NIAS, which do not have a function, ^b categories might overlap

Figure A1. Number of known functions per plastic chemical.



A4: Detailed methodology of Part II

Expert consultations

Throughout the project, we conducted two rounds of expert consultations to align the project with the policy needs, receive feedback on our approach in general and the prioritization chemicals of concern specifically, as well as input on the reporting of our results.

Experts interviewed. We aimed for diversity of expertise in our interview by also assuring gender balance and global representation. Hence, seven experts from academia, national regulatory agencies, and international bodies were interviewed in six consultations (Table A3). Four were women and three men, four were from the Global North and two from the Global South. Two project members were present in each 30–45-minute interviews to briefly present the project, ask questions, and take notes which were elaborated with the meetings' recordings.

First round of consultations

The first round of interviews was performed in March and April 2023 with the aim to align and tailor the PlastChem project with the policy needs and to ensure its relevance for policymaking.

Questions asked. After briefly introducing the PlastChem project, we asked for feedback on the general approach of the project, specifically on the grouping of chemicals based on the chemical structure, the prioritization of chemicals based on hazard, the importance of including exposure information, and transboundary transport related to persistence (P) and mobility (M). Next, we requested insights

into the policy needs concerning the evidence needed to regulate plastic chemicals and the most useful way to present our project results.

Table A3. Experts consulted in the PlastChem project.

Expert	Institution	Region
Kei Ohno Woodall	BRS secretariat	Global
(prefers not to say)	Regulatory agency	Europe
Frauke Averbeck	Federal Institute for Occupational Safety and Health, Germany	Europe
Irina Talamoni	Ministry of Environment and Sustainable Development, Argentina	South America
Thabile Ndlove	University of Eswatini, Secretary General at the Eswatini National Commission for UNESCO	Africa
Tobias Wächter	Federal Institute for Occupational Safety and Health, Germany	Europe
Tobias Dan Nielsen	European Environment Agency	Europe

Second round of consultation

The second round of interviews was performed in November 2023 to get feedback on the approach, preliminary results, potential weak points as well as on the reporting, and to further align the report with policy needs.

Questions asked. After briefly presenting the preliminary findings of the PlastChem project, we asked the experts for any general feedback, as well as if the data generated during the project is useful for them and what is of particular importance. We further requested their opinion on whether we were missing any important aspect and how we could cover their policy needs. Moreover, we wanted to know if they would use the compiled data and which format would be most useful.

Building the PlastChem database

Backbone database

To assemble the PlastChem database, seven relevant sources were used (Table A4). For each source, the original identifier was kept for traceability (except for LitChem, as it was under development when integrated in the PlastChem database) and a binary mapping score is provided for each chemical to provide an easy and quick overview of the data sources.

Table A4. Overview of the sources used to assemble the PlastChem database.

Data source	Release information	File access	Number of entries
Aurisano <i>et al.</i> , 2021	https://doi.org/10.1016/j.cogsc.2021.100513	https://ars.els-cdn.com/content/image/1-s2.0-S2452223621000699-mmc2.xlsx	5983
CPPdb	https://zenodo.org/record/1287773	https://zenodo.org/record/1287773/files/CPPdb_ListA_ListB_181009_ZenodoV1.xlsx?download=1	4227
ECHA PMFC	https://echa.europa.eu/plastic-material-food-contact	Download of Excel file	1046
FCCdb	https://zenodo.org/record/4296944	https://zenodo.org/record/4296944/files/FCCdb_201130_v5_Zenodo.xlsx?download=1	3543 (Lists S07–S15) ^a
FCCmigex	https://www.foodpackagingforum.org/fccmigex	Provided by the authors	4257 ^a
PlasticMAP	https://pubs.acs.org/doi/full/10.1021/acs.est.1c00976	https://pubs.acs.org/doi/suppl/10.1021/acs.est.1c00976/suppl_file/es1c00976_si_001.zip	10 547 (List S8)
LitChem	Draft version (June 24)	Provided by the authors	3467

Note: ^a only the subset of plastic chemicals was used

To identify chemical structures in the data sources, CASRNs or substances names (when CASRNs were invalid or missing, see below) were used with the automatic API services of PubChem.^c Other identifiers were dismissed as only CAS Registry Numbers and substance names were available across all data sources. Information retrieved from the PubChem API services included the PubChem CID, molecular formula, molecular weight, canonical SMILES, isomeric SMILES, InChI, InChIKey, IUPAC name, XLogP, exact mass, monoisotopic mass, TPDS, complexity, and charge.

CASRNs were validated as described in the documentation of CAS.^d Invalid CASRNs were tried to be repaired in a three-step approach: 1) removing leading or trailing characters, such as spaces and apostrophes. Both are common to prevent Microsoft Excel from automatically transforming CASRNs to dates. 2) Converting dates to CASRNs assuming either DD-MM-YYYY or MM-DD-YYYY date formats, and each result was checked for validity again. If the procedure resulted in a valid CAS Registry Number, available substance names were used to verify the correct CASRN via the CAS Common Chemistry platform.^e In cases where CASRN and substance name did not match, the CASRN was discarded. 3) Manual checking of the remaining invalid CASRNs for solvable faults, such as accidental doubling of digits. This was again done using the substance names as reference, and discarding the CASRN if the information did not match.

The PlastChem database was assembled using unique CASRNs, substance names, and inventory IDs as basic information. An overview of the assembly workflow is shown in Figure A2. Because of the nature of the data at hand, we cannot guarantee the presented database does not contain de facto duplicates. However, extensive

^c <https://pubchem.ncbi.nlm.nih.gov/docs/pug-rest>

^d <https://www.cas.org/support/documentation/chemical-substances/checkdig>

^e <https://commonchemistry.cas.org>

QA/QC procedures have been applied, together with manual curation to ensure the highest degree of quality possible for the database.

All data engineering work for PlastChem was done using the R programming language (R Consortium, 2023). All code necessary to assemble the PlastChemDB (except for the confidential parts) is publicly available on the GitHub repository and the Zenodo community.^f

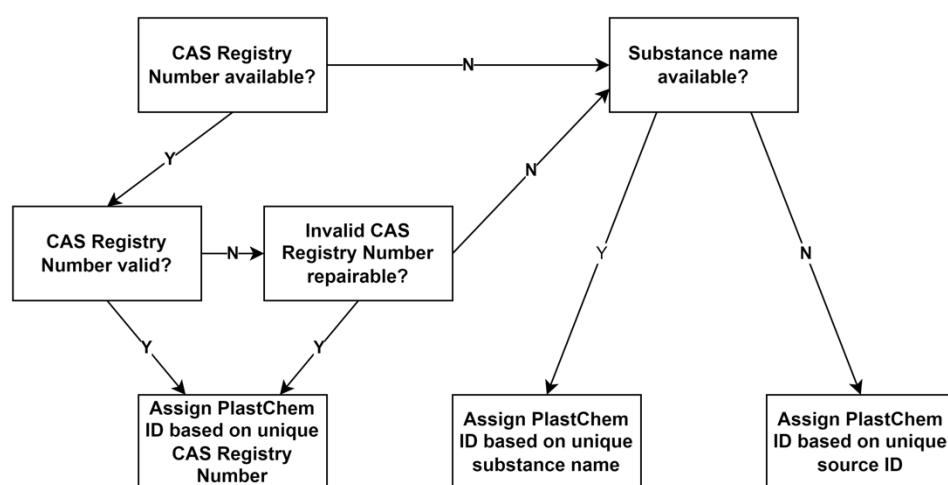


Figure A2. Principal workflow to assign PlastChem IDs based on CAS Registry Number, substance name, or source IDs.

^f <https://github.com/PlastChem>, <https://zenodo.org/communities/plastchem>

Grouping of plastic chemicals

To group the chemicals, we followed two approaches, first, through keyword search and second, through match with existing lists of chemical groups.

Approach 1. Through keyword search

A pre-defined set of keywords were used to identify the following groups of chemicals by searching the keywords in the chemical names. The pre-defined set of keywords can be found in Wang et al. (2020)⁵ and include: inorganic compounds, organometallics and metalorganics, substances of unknown or variable composition, complex reaction products, or biological materials (UVCBs), polymers, and mixtures.

The name and chemical symbol of respective elements were used as keywords to identify the following groups of chemicals by searching the keywords in the chemical names and SMILES.

The groups included were: (1) organofluorine chemicals, (2) organochlorine chemicals, organobromine chemicals, (3) organoiodine chemicals, (4) organophosphate chemicals, (5) organosilicon chemicals, (6) chemicals containing antimony, (7) chemicals containing arsenic, (8) chemicals containing barium, (9) chemicals containing beryllium, (10) chemicals containing cadmium, (11) chemicals containing chromium, (12) chemicals containing lead, (13) chemicals containing magnesium, (14) chemicals containing manganese, (15) chemicals containing mercury, (16) chemicals containing nickel, (17) chemicals containing selenium, (18) chemicals containing tellurium, (19) chemicals containing thallium, (20) chemicals containing tin, (21) chemicals containing vanadium, (22) chlorinated and brominated furans and dioxins, (23) DDT, DDE and DDD, and (24) benzothiazoles. A manual inspection was performed after all the keyword searches to correct wrong assignments and add missed chemicals.

Approach 2. Through match with existing lists of chemical groups

The following existing lists were used to identify the corresponding groups of chemicals by matching CASRNs and SMILES (wherever applicable). Some of the lists created were used for tagging chemicals under regulation.

List 1. US EPA CompTox Chemicals Dashboard.^g This list includes:

- ALLSURFACTANTS – last updated in 2020 – A set of surfactants made from the assembly of multiple surfactants lists contained within the dashboard.
- AROMATICAMINES – last updated in 2020 – Substances Restricted Under REACH as represented by Annex XVII to REACH includes all the restrictions adopted in the framework of REACH and the previous legislation, Directive 76/769/EEC. Appendix 8 lists aromatic amines associated with azocolourants.
- AZODYES – last updated in 2021 – List of Azo Dyes assembled from public sources including Wikipedia.
- BISPHENOLS – last updated in 2018 – This list represents a collection of bisphenols available at NILU (Pawel Rostkowski) and from Table 3 of report 5/17 by KEMI (Swedish Chemicals Agency, in Swedish with English summary), hosted on the NORMAN Suspect List Exchange.^h
- CIDYES – last updated in 2021 – a list of dyes associated with the Color Index list and associated identifiers.
- C10CHLOROPARAFF – last updated in 2019 – List of chemical substances classed as "chloroparaffins". Includes short chain (C10–C13), medium chain (C14–C17) and long-chain chloroparaffins (>C17).

^g <https://comptox.epa.gov/dashboard/chemical-lists>

^h <https://www.norman-network.com/nds/SLE>, DOI: 10.5281/zenodo.3779854

- DIOXINS – last updated in 2020 – Dioxins and dioxin-like compounds (DLCs) are those for which toxic equivalency factors (TEFs) were reported in the WHO report.
- EPAPCS – last updated in 2017 – The entries in this list have been classified in the U.S. as pesticidal “active ingredients” (conventional, antimicrobial, or biopesticidal agents), and were sourced from the Pesticide Chemical Search database created by US EPA’s Office of Pesticide Programs.ⁱ
- EUBIOCIDES – last updated in 2018 – This is a list of compounds currently used in the EU as biocides (and partly also as plant protection products or industrial chemicals under the respective EU regulations) or compounds recently banned in the EU as biocides from the 2015 NORMAN priority list, which have been prioritized and assessed for exposure by NORMAN using data from ECHA and other sources.
- FLAMERETARD – last updated in 2019 – List of Flame Retardants including all polybrominated diphenyl ethers (PBDEs). Sources include the Wikipedia Flame Retardants list and a text-mining exercise using MeSH identifiers.
- NONYLPHENOLS – last updated in 2022 – list of all possible nonylphenol isomers.
- PAHLIST – last updated in 2018 – list of polycyclic aromatic hydrocarbons (PAHs).
- PBDES – last updated in 2018 – A list of all 209 polybrominated diphenyl ethers, many of which, in mixture form, are flame retardants.
- PCBCHEMICALS – last updated in 2018 – a list of all 209 polychlorinated biphenyl chemicals with associated CASRNs.

ⁱ <https://iaspub.epa.gov/apex/pesticides/f?p=chemicalsearch:1>

- PHENANTIOX – last updated in 2019 – A list of possible phenolic antioxidants with exposure scores compiled by Stellan Fischer (KEMI) and Pawel Rostkowski (NILU). Mapped to CompTox information using CASRNs.
- REFRIGERANTS – last updated in 2019 – a list of refrigerants.
- TBUTYLPHENOLS – last updated in 2020 – A list of tert-butyl phenols from KEMI (Swedish Chemicals Agency), hosted on the NORMAN Suspect List Exchange.^j
- WIKIANTIOXIDANTS – last updated in 2020 – a list of antioxidants extracted from the Wikipedia Category page:
<https://en.wikipedia.org/wiki/Category:Antioxidants>.

List 2. European Chemicals Agency. This list includes: Assessment of regulatory needs list^k with the group name of (1) aliphatic ketones, (2) aliphatic primary amides, (3) alkyl nitrates, (4) aromatic ethers, (5) cyclic acetals, (6) cyclic ethers, (7) dialiphatic ethers excluding unsaturated, (8) diazo amino hydroxyl naphthalenedisulfonic acid dyes, (9) dibenzoyl peroxide derivatives, (10) dihydropurinediones, (11) ethanediols, (12) isophthalates, terephthalates and trimellitates, (13) paraben acids, salts and esters, (14) pyrazoles, (15) salicyclic acids, and (16) salicylate esters.

List 3. Australia Industrial Chemicals Introduction Scheme. This list includes nonylphenol and octylphenol ethoxylates and related compounds: human health tier II assessment.^l

Other lists included:

- Wikipedia page on polychlorinated naphthalenes^m

^j <https://doi.org/10.5281/zenodo.3779849>

^k <https://echa.europa.eu/assessment-regulatory-needs>

^l https://www.industrialchemicals.gov.au/sites/default/files/Nonylphenol%20and%20octylphenol%20ethoxylates%20and%20related%20compounds_Human%20health%20tier%20II%20assessment.pdf

^m https://en.wikipedia.org/wiki/Polychlorinated_naphthalene

- Ortho-phthalatesⁿ
- Acetophenones and benzophenones^o
- Benzotriazoles and benzothiazoles group^p

Expert judgement. In addition to the previous approaches, expert judgements were made to identify PFAS from all the organofluorine chemicals, as well as those PFAS and short-chain chlorinated paraffins that are regulated under the Stockholm Convention. Expert judgements were also made to merge the overlapping listed from the previous two steps.

Inclusion of hazard information

Hazard information was compiled following the EU Chemicals Strategy for Sustainability (CSS, EC 2020) and the updated version of the Regulation on Classification, Labelling and Packaging of chemicals (CLP)^q by the Commission Delegated Regulation (EU) 2023/707 of 19 December 2022 (amending Regulation EC No 1272/2008). The hazard traits included in the PlastChem database are carcinogens, mutagens and reproductive toxicants (CMR), endocrine disrupting chemicals (EDC), specific target organ toxicity (STOT), as well as hazards related to persistence–bioaccumulation (i.e., persistent, bioaccumulative and toxic – PBT substances, very persistent and very bioaccumulative – vPvB substances) and related to persistence–mobility (i.e., persistent, mobile and toxic – PMT substances, very persistent and very mobile – vPvM substances). In addition, aquatic toxicity

ⁿ <https://www.plasticisers.org/plasticiser/ortho-phthalates>

^o <https://www.biosynth.com/category/acetophenones-and-benzophenones?viewtype=2>

^p <https://www.canada.ca/en/health-canada/services/chemical-substances/chemicals-management-plan-3-substances/benzotriazoles-benzothiazoles-group>; <http://111.89.200.130/en/details/products04>

^q The CLP governs the EU implementation of the Global Harmonized System of Classification and Labelling of chemicals (GHS).

was included as a criterion for environmental toxicity following Groh et al. (2021) and Aurisano et al. (2021).^{3,6}

To retrieve information on the hazard traits of the chemicals in the PlastChem database, 15 publicly available databases were used, combining, and updating the strategies from Wiesinger et al. (2021)², Zimmermann et al. (2022)⁷, and Aurisano et al. (2021)³ (Table A5). At the first level, information was gathered from recognized hazard lists, that is, 14 lists of harmonized hazard information from regulatory agencies and harmonized lists of Classification and Labeling of chemicals (C&L), containing substances for which a set of classification and labeling data has been agreed at an authoritative level. At the second level, identified hazard information was gathered from C&L industry reported dossiers, containing chemicals for which classification and labelling data have been submitted to ECHA for registration under REACH or notified by manufacturers or importers under CLP, as well as hazard information self-classified under REACH. Both types of information were integrated together as a unique hazard information per chemical. In all cases, the information used first was from the Harmonized C&L lists, REACH information was used as second option, and finally C&L industry information was used if it was the only type of information available. This procedure was adopted since ECHA maintains the C&L notifications or registrations dossiers but does not review or verify the accuracy of the information.^r

^r <https://echa.europa.eu/regulations/clp/cl-inventory>

Table A5. Overview of hazards traits included in PlastChem, the sources consulted, the tracking system used, and the comparison with the lists used in previous works.

Hazard class	Lists consulted	List number in PlastChem	Comparison to previous work		
			[1]	[2]	[3]
CMR	International Agency for Research on Cancer (IARC)	List 1	X		
Carcinogenic, Mutagenic, or Toxic to Reproduction	Classified Agents List				
	European Chemical Agency's Classification and Labelling (C&L) inventory – Harmonized C&L aligned with Globally Harmonized System (GHS)	List 2.1	X	X	X
	ECHA REACH CLP/C&L registration dossiers	List 2.2	X		
	ECHA REACH authorization list	List 3	X		
	Australian Hazardous Chemicals Information System (HCIS) aligned with GHS and Australian Workplace Exposure Standard	List 4	X		
	Japanese GHS classification by the National Institute of Technology and Evaluation (NITE)	List 5	X	X	
	European Union Registration, Evaluation, Authorization and Restriction of Chemicals candidate list of substances of very high concern (SVHCs)	List 6		X	
	California Office of Environmental Health Hazard Assessment (OEHHA) Proposition 65 list	List 7		X	X
EDC	ECHA REACH authorization list	List 3	X		
	EU REACH SVHCs list	List 6	X	X	X
	ECHA Endocrine Disruptor assessment list	List 8	X		
STOT	ECHA C&L Inventory – Harmonized C&L GHS	List 2.1	X	X	X
Specific Target Organ Toxicity	HCIS – GHS Australia	List 4	X		
	Japanese GHS Classification NITE	List 5	X	X	
	EU REACH SVHCs list	List 6		X	

Aquatic toxicity	European Chemical Agency's (ECHA) Classification and Labelling (C&L) inventory – Harmonized C&L aligned with Globally Harmonized System (GHS)	List 2.1	X	
	ECHA REACH CLP/C&L registration dossiers	List 2.2	X	
	HCIS – GHS Australia	List 4	X	
	Japanese GHS Classification NITE	List 5	X	
PBT, vPvB	EU REACH SVCH list	List 6		X
Persistence-	ECHA PBT assessment list	List 9	X	X
Bioaccumulation	ECHA PBT/vPvB assessment list	List 10		X
related hazards	ECHA REACH authorization list	List 3	X	
	United States (US) Environmental Protection Agency (EPA) Toxics Release Inventory (TRI) list	List 11		X
POPs	ECHA list – inclusion in POPs Regulation	List 12		X
	ECHA list – subject to POPs Regulation	List 13		X
PMT, vPvM	German Environment Agency (UBA) report	List 14		X X
SVCHs	ECHA SVCH proposal list	List 15		

Note: [1] Wiesinger et al., 2021; [2] Zimmermann et al., 2022; [3] Aurisano et al., 2021

Detailed information on the hazard traits gathered from each list and the harmonization of the hazard scoring is showed in Table A6. Additionally, further information on the meaning of the hazard levels based on the CLP regulation is provided in Table A7.

Table A6. Overview of the hazards information included in the PlastChem database.

Lists included in PlastChem	Year	Source	Hazard traits included											Harmonization of hazard scoring (original scoring = PlastChem scoring)
			Number of chemicals	Chemicals with CASRN	Included in PlastChem	CMR	EDC	PBT	PMT	STOT	Aq. Tox.			
1. IARC List	2022	IARC	1040	899	449	X								1=1, 2AB = 2, 3 = 0
2.1. Harmonized C&L Inventory	2023	ECHA	902	902	864	X						X	X	1 or 1AB = 1, 2 = 2, 3 = 3, 4 = 4, blank = blank
2.2. C&L and REACH Inventory	2023	ECHA	10 035	10 035	9874	X						X	X	1 or 1AB = 1 2 = 2, 3 = 3, 4 = 4, blank = blank
3. Authorisation List	2023	ECHA	140	117	76	X	X	X						X = 1; blanks = blanks
4. HCIS List	2016	HCIS	6827	6232	2048	X						X	X	1 or 1AB = 1, 2 = 2, 3 = 3, 4 = 4, blank = blank
5. NITE List Japanese	2022	NITE	4934	4918	1871	X						X	X	Hazard = 1, 2, 3, 4; not = 0; blank = blank
6. Candidate List of SCVHs for Authorization	2023	ECHA	475	426	261	X	X	X				X		X = 1, blanks = blanks
7. Proposition 65 List	2023	OEHHA	973	857	337	X								X = 1
8. ECHA EDC	2023	ECHA	154	145	88		X							EDC = 1, not = 0, under evaluation = 0.5, inconclusive = 0.25 (aggregating EDC environment and EDC human health)

9. PBT	2023	ECHA PBT	307	264	167					X		PBT/vPvB = 1, not = 0, under development = 0.25
10. PBT/ vPvB assessment list	2007	ECHA PBT/vPvB	128	127	95					X		PBT/vPvB = 1, not = 0, under evaluation = 0.25
11.PBT	2022	EPA	676	676	453					X		X = 1
12.POPs	2023	ECHA POPs	223	216	125							X = 0.5 (in proposal lists)
13.POPs	2023	ECHA POPs	309	292	179							X = 1
14. EC proposition PMT/vPvM	2022	UBA	342	333	187					X		PMT/vPvM/PM = 1, not = 0, potential = 0.5
15. Proposals to identify SVHCs previous consultations	2022	ECHA SVHCs	231	247	216	X	X	X			X	X = 1, blanks = blanks

Table A7. Overview of the hazard traits included in PlastChem, their hazard code, meaning, CLP criteria as well as the Hazard Score provided in PlastChem.

Hazard criteria	Abbreviation	Code	Meaning	CLP criteria ^a	Hazard Score
Environment					
Hazardous to the aquatic environment – Chronic exposure	Aq. Toxicity 1	H410	Very toxic to aquatic life with long lasting effects	-	2
	Aq. Toxicity 2	H411	Toxic to aquatic life with long lasting effects	-	1
	Aq. Toxicity 3	H412	Harmful to aquatic life with long lasting effects	-	0.5
	Aq. Toxicity 4	H413	May cause long lasting harmful effects to aquatic life	-	0.5
Human Health					
Specific target organ toxicity – repeated exposure	STOT RE 1	H372	Cause damage to organs	hazard	2
	STOT RE 2	H373	Cause damage to organs	hazard	2
Reproductive toxicity	Repr. 1A	H360	May damage fertility or the unborn child.	hazard	2
	Repr. 1B	H360	May damage fertility or the unborn child.	hazard	2
	Repr. 2	H361	Suspected of damaging fertility or the unborn child.	hazard	1
Carcinogenicity	Carc. 1A	H350	May cause cancer.	hazard	2
	Carc. 1B	H350	May cause cancer.	hazard	2
	Carc. 2	H351	Suspected of causing cancer.	-	0.5
Germ cell mutagenicity	Muta. 1A	H340	May cause genetic defects.	hazard	2
	Muta. 1B	H340	May cause genetic defects.	hazard	2
	Muta. 2	H341	Suspected of causing genetic effects.	-	0.5
Environment and human health					

Endocrine disruption	EDC category 1	EUH380 EUH430	Known or presumed endocrine disruptor for human or environmental health.	hazard	2
	EDC category 2	EUH381 EUH431	Suspected endocrine disruptor for human or environmental health.	hazard	Not applied ^b
	PBT	EUH440	Persistence, Bioaccumulative, Toxicity – Accumulates in the environment and living organisms including in humans	hazard	1
Persistent, bioaccumulative, toxic	vPvB	EUH441	Very Persistence, very bioaccumulative – Strongly accumulates in the environment and living organisms including in humans	hazard	2
	PMT	EUH450	Can cause long-lasting and diffuse contamination of water resources	hazard	1
Mobility	PM	-	Not defined	-	0.5
	vPvM	EUH451	Can cause very long-lasting and diffuse contamination of water resources	hazard	2

Notes: ^a CLP criteria based on EU 2023/707 amending Regulation (EC) No 1272/2008 as regards hazard classes and criteria for the classification, labelling, and packaging, of substances and mixtures. A “-” means that this hazard is not considered in CLP criteria. ^b Since the new regulation is not required to be applied until 2025, there is no differentiation of EDC levels (1, 2) in PlastChem.

Inclusion of additional information

Information on regulatory status

Two lists were created to integrate the regulatory status of the plastic chemicals in the PlastChem database.

1. The MEA List

The MEA list includes information from four global regulatory instruments, the Stockholm Convention, the Montreal Protocol, the Minamata Protocol, and the Basel Convention. Specifically, of the Stockholm convention we included all chemicals listed in Annex A (elimination), Annex B (restriction) and Annex C (unintentional production) (Stockholm Convention, 2023), as well as those included recently in the eleventh meeting held from 1.–12.03.2023 (i.e., Methoxychlor, Dechlorane Plus, UV-328). We further included PAHs as they are considered Persistent Organic Pollutants (POPs) under the UNECE Convention on Long-Range Transboundary Air Pollution,^s as well as PBDD and PBDF. From Montreal, all chemicals listed in Annexes A, B, C and E, as well as for the phasing-down of production and consumption of hydrofluorocarbons (HFCs) listed in Annex F were included. Opposed to previous studies/reports^{2,4} which did not include the Basel convention as MEA, we integrated it in the MEA list because it provides appropriate regulatory measures to eliminate import and export of the chemicals listed in Annex A of the Convention. In addition, the chemicals listed in Annex A or B can only be imported for purposes permitted for that Party under Annex A or B. Export is only allowed to a Party that is permitted to use that chemical under Annex A or B, or under specific conditions. Finally, the Minamata Convention was integrated.

^s <https://unece.org/environment-policy/air/protocol-persistent-organic-pollutants-pops>

2. The Precedent List

The Precedent List was built by aggregating updated information from regional and national regulations (date of revision August 2023) and includes the chemicals regulated in the EU (lists: REACH restriction, REACH authorization, REACH SVHCs, EU toy restriction and EU toy allergenic fragrances, and ROHS Directive), Japan (lists: ISHA and CSCL), Republic of Korea (lists: Accidents, CMR, Hazardous chemicals and Intensive Control), and the US (list: California P65). The Rotterdam Convention and the prior informed consent (PIC) procedure (both lists from version 2020) was also included in this list as it informs importing countries about the hazards associated with chemicals listed in Annex III and, therefore, enables informed decisions about their import. Many more regional and national legislations exist but could not be included due to lack of access. The authors acknowledge that by including them, the Precedent List may further increase in number and be more inclusive and globally representative.

The specific sources for the different lists are provided below:

From the European Chemicals Agency (ECHA, EU)

- Substances restricted under REACH^t
- List of substances subject to POPs Regulation^s
- Candidate list of substances of very high concern for authorization^u
- Assessment of regulatory needs list^v with the group name of
 - Aliphatic ketones
 - Aliphatic primary amides
 - Alkyl nitrates
 - Aromatic ethers

^t <https://echa.europa.eu/substances-restricted-under-reach>

^u <https://echa.europa.eu/candidate-list-table>

^v <https://echa.europa.eu/assessment-regulatory-needs>

- Cyclic acetals
- Cyclic ethers
- Dialiphatic ethers excluding unsaturated
- Diazo amino hydroxyl naphthalenedisulfonic acid dyes
- Dibenzoyl peroxide derivatives
- Dihydropurinediones
- Ethanediols
- Isophthalates, terephthalates and trimellitates
- Paraben acid, salts and esters
- Pyrazoles
- Salicyclic acids
- Salicylate esters
- Annex II, Sec III – allergenic fragrances banned/restricted in toys^w
- Toy safety directive – substances restricted in toys^x

From the Environmental Protection Agency (EPA, US)

- The Proposition 65 List from California Office of Environment Health Hazard Assessment^y

From the National Institute of Technology and Evaluation (NITE, Japan)

- Chemical Substances Control Law (CSCL) – Class I and Class II Specified Chemical Substances, and Industrial Safety and Health Act – Chemical substances prohibited to manufacturing, etc. And requiring permission for manufacture^z

From the Korea Testing and Research Institute (KREACH, South Korea)

^w <https://echa.europa.eu/assessment-regulatory-needs>

^x <https://echa.europa.eu/substances-restricted-toys>

^y <https://oehha.ca.gov/proposition-65/proposition-65-list>

^z https://www.nite.go.jp/en/chem/chrip/chrip_search/sltLst

- Korean Lists of toxic substances, substances requiring preparation for accidents, restricted/prohibited/permitted substances, and substances subject to intensive control^{aa}

From the Australia Industrial Chemicals Introduction Scheme

- Nonylphenol and octylphenol ethoxylates and related compounds: human health tier II assessment^{bb}

In addition to the previous two approaches, expert judgements were made to identify PFAS from all the organofluorine chemicals, as well as those PFAS and short-chain chlorinated paraffins that are regulated under the Stockholm Convention.

^{aa} <https://kreach.me.go.kr/repwrt/mttr/en/mttrList.do>

^{bb} https://www.industrialchemicals.gov.au/sites/default/files/Nonylphenol%20and%20octylphenol%20ethoxylates%20and%20related%20compounds_Human%20health%20tier%20II%20assessment.pdf

Information on the use, presence, and release of chemicals in plastic polymers

PlastChem includes information on the potential use, presence, and release of chemicals from plastic. Data were collected from three databases. First, FCCMigex and LitChem were used to compile information on the presence and release of chemicals from plastic. The data in both databases originates from exhaustive reviews of the scientific literature that analyzed chemicals in plastics, mostly from extraction and migration studies. This empirical information was considered as high level of evidence in PlastChem (Figure A3). Second, PlasticMAP was used to compile information on the potential use of chemicals in plastic. The information used in PlasticMAP originates from industry repositories and therefore there is no empirical evidence on the presence of those chemicals in the plastic. PlastChem considered this information as medium-level evidence.

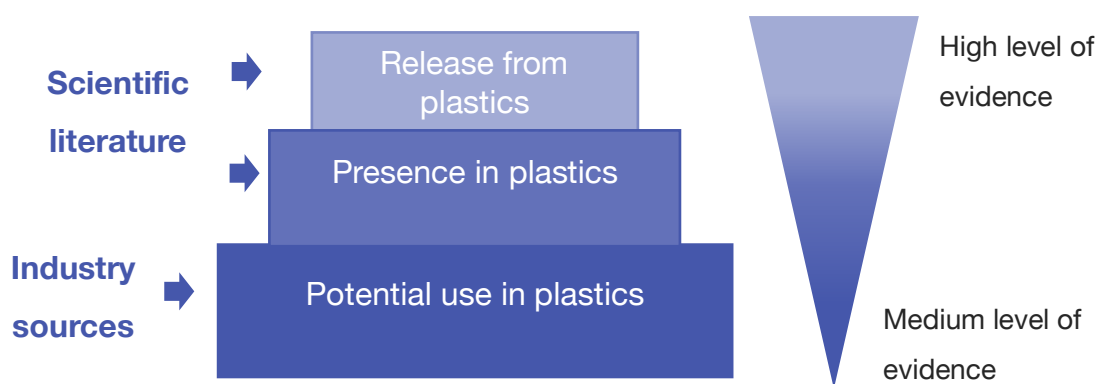


Figure A3. Level of evidence that a chemical is used, present or released. The evidence is considered highest when scientific study demonstrated release from plastics, followed by the detection in plastics, and lower when a chemical is marketed for use in plastics.

We followed a stepwise procedure to compile and harmonized the information and assemble the PlastChem database:

1. Compilation and harmonization of information from FCCmigex and LitChem.
 - a. Distribution of the data in two columns for detection and release per each type of plastic polymer, being detection when the chemical has been detected in extraction experiments and release when the chemical has been detected in migration experiments. A binary index was created for each column, with 1 when detected in extract or migrate and 0 when no detected. Blanks were used when no data was available.
 - b. Homogenization of the terms accordingly to PlastChem database. In the case of FCCmigex, Migration_food and Migration_into_food were both considered as migration.
 - c. Creation of new columns per polymer with one unique score as described as follows:
 - A score of 2 was assigned to the chemicals with evidence for release, 1 for detection. In cases multiple data was available, the data retrieved from the different databases were merged for leachates and extracts (FCCmigex and LitChem) retaining the information with the highest level of evidence. A worst-case scenario was selected in case of conflicting information.
 - When there was no information provided for the substance in any of all the sources consulted, the score provided was blank.
 - When the evaluation was inconclusive, the substance was classified as 0.25.
 - When the substance was experimentally evaluated and not detected as in either extraction or migration experiments, the substance was classified as 0.

- d. Checking of CAS inconsistencies and correction if necessary.
2. Compilation and harmonization of the information from PlasticMAP.
 - a. Creation of new columns for each polymer type with the following scoring:
 - A score of 0.5 was assigned to the chemicals that have been identified in PlasticMAP as potentially used in plastic. If the same chemical had also information from LitChem or FCCMigex for release/extraction, they were scored as 2 or 1 respectively as the level of evidence was considered higher for those sources.
 - b. Similar to LitChem and FCCmigex, when there was no information provided for a substance in any of all the sources consulted, the score provided was blank.
 - c. Checking of CAS inconsistencies and correction if necessary.
3. Merging of the three databases and scoring each polymer type in three levels of evidence. The final score per chemical was the following: 2 (release) > 1 (presence) > 0.5 (use) > 0.25 (inconclusive) > 0 (not detected in empirical studies) > blank (no data available).

In all cases, validation and cross-checking of the databases created was conducted by two team members independently. All data engineering work for potential use, presence and release data compilation and harmonization was done using the R programming language. All code necessary to assemble this part of the database (except for the confidential parts) is publicly available on the GitHub repository and the Zenodo community mentioned above.

A5: Detailed findings from Part III

Hazard classification of plastic chemicals

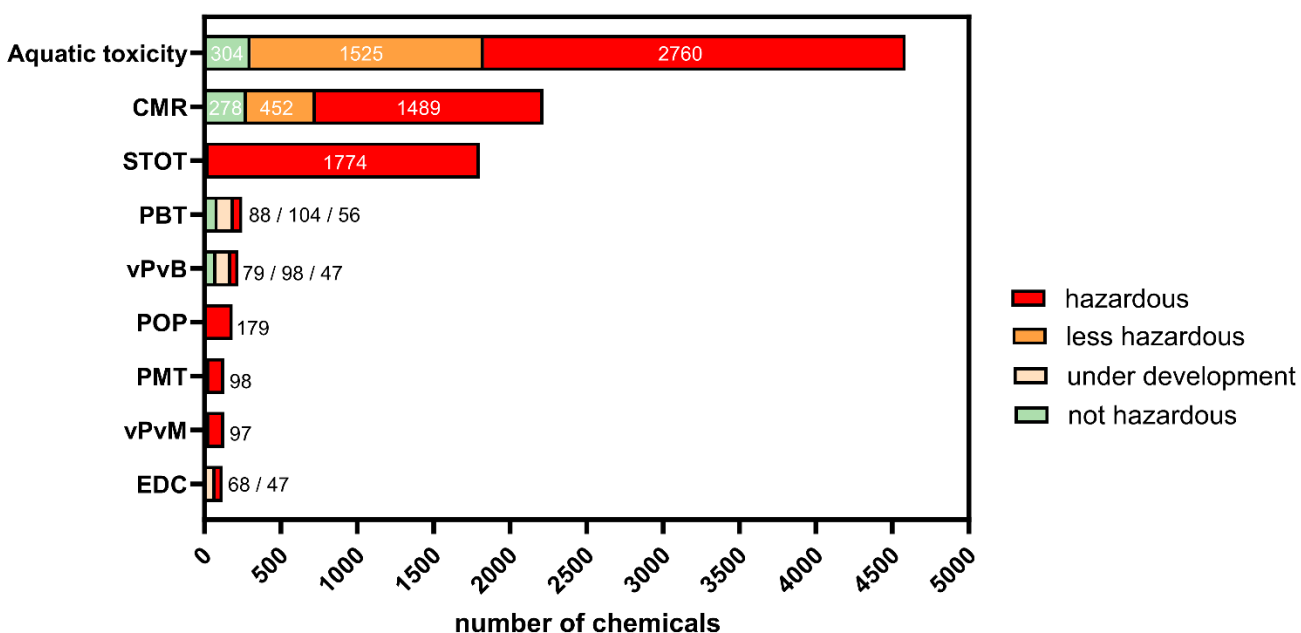


Figure A4. Number of plastic chemicals with hazard information, including their hazard classification for each trait.

Presence of chemicals of concern in commodity and specialty plastics

More than 1400 chemicals of concern are used or detected in commodity plastics. Commodity plastics, that is, those polymer types with the highest market shares, have most information regarding which chemicals are used or have been detected in them. Based on this, 1483 chemicals of concern, or 29% of all compounds with information, can be present in these plastic materials or products (Figure A5). This represents almost 80% of all chemicals of concern used or detected in plastics, highlighting that information availability is skewed towards plastics that are most widely produced and used.

Material flow information further informs about quantity and fate of chemicals of concern. Commodity plastics may contain a smaller proportion of chemicals of concern compared to other polymer types. While this may seem to imply a lower exposure probability from these materials, these are produced and used in much larger quantities. Hence, the chance of exposure to chemicals of concern is probably much larger than for other materials. Considering that commodity plastics, especially PE, PP, and PET, most likely to be landfilled or recycling, key exposure pathways at the end of life for these polymers would be emissions related to landfilling and via in recycled products.

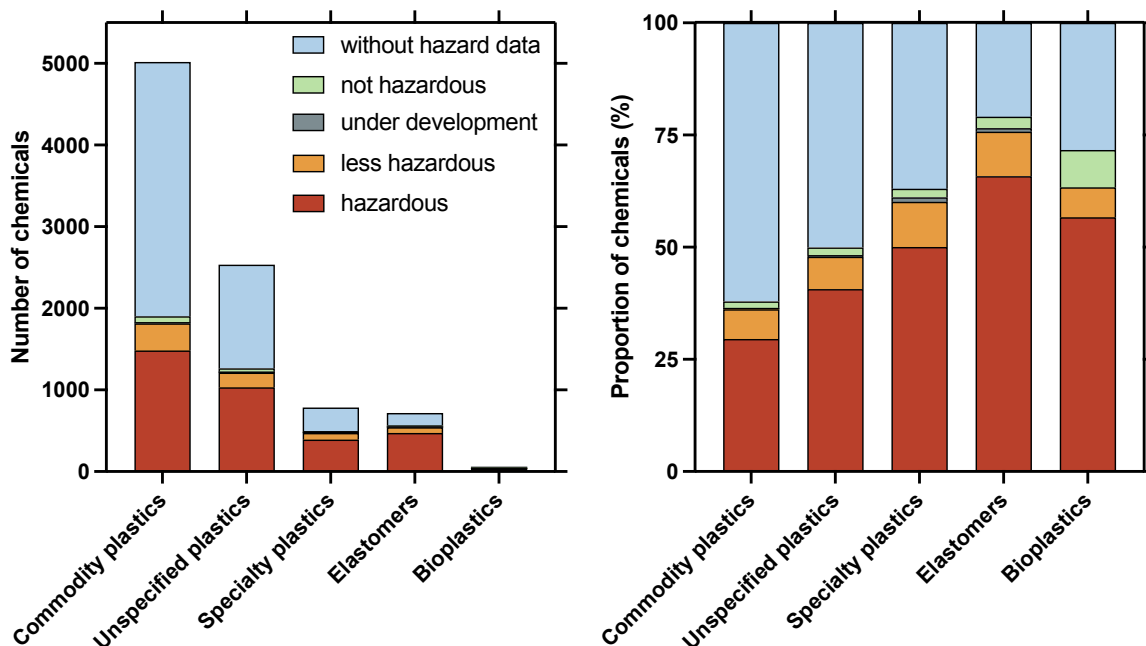


Figure A5. Hazard information for chemicals used or detected in plastics according to major polymer classes. The left graph presents the number of chemicals, the right graph the proportion of chemicals normalized to the number of chemicals used or detected in each group. Unspecified plastics include multilayer materials and plastic materials for which the polymer type was not reported.

Many chemicals of concern cannot be linked to specific polymers. 981 chemicals of concern have evidence for their use or detection in plastics but that information lacks granularity. For instance, market data indicates that a certain compound is marketed as additive but does not specify the polymer type it is used in. The same is true for a large share of scientific studies that report the presence or release of a chemicals from plastics but do not report the polymer type. Another case is multilayer materials usually used in food packaging, such as bricks used for milk or juices. These materials consist of multiple polymer types and other materials (e.g.,

cardboard, aluminum). The evidence shows that multilayer materials contain 257 chemicals of concern, representing 55% of all chemicals used or detected in this type of plastic. The usefulness of such evidence is limited because attribution of which specific polymer type contained the chemicals of concern is impossible. Nonetheless, it again highlights that many chemicals of concern being used or detected in plastics in general.

More than half of the chemicals in specialty plastics, elastomers, and bioplastics are of concern. While much less information is available for these groups of polymers, >300 chemicals of concern have evidence for their use in specialty plastics and elastomers, each. Out of the 60 chemicals used or detected in biobased and bio-degradable plastics, 34 are of concern. This demonstrates two things: Firstly, the data availability for these groups of polymers is very limited compared to commodity plastics. This is particularly problematic for bioplastics due to their increasing use. Secondly, these groups of polymers contain a high proportion of chemicals of concern and, thus, deserve the same regulatory scrutiny as commodity plastics.

Leachate toxicity

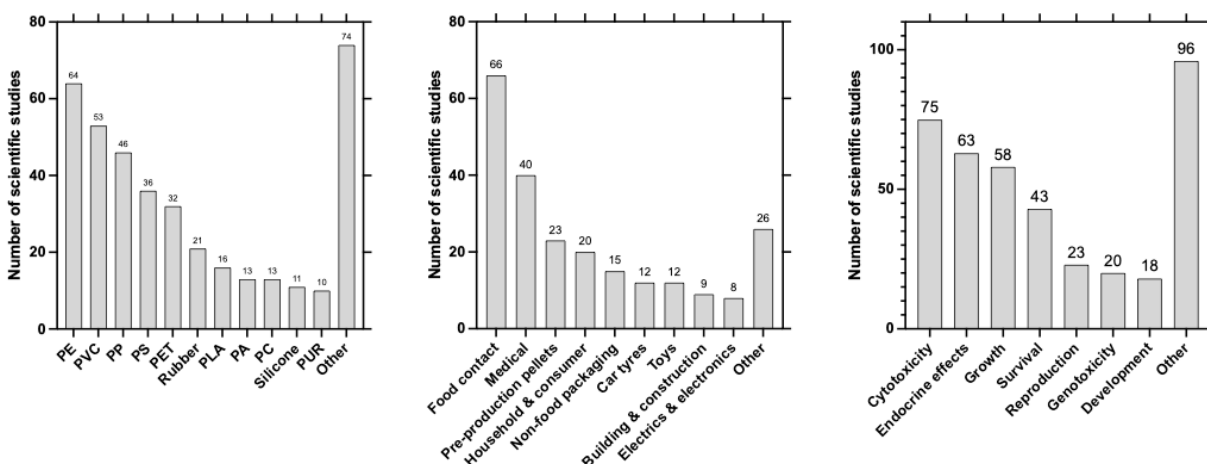


Figure A6. Overview of the content of the evidence map of plastic leachate toxicity studies. Each figure represents the number of leachate toxicity studies stratifies according to polymer type (left), product type (middle), and investigated toxicological endpoints (right). Note that analyze multiple polymer types, products, and endpoints are counted multiple times.

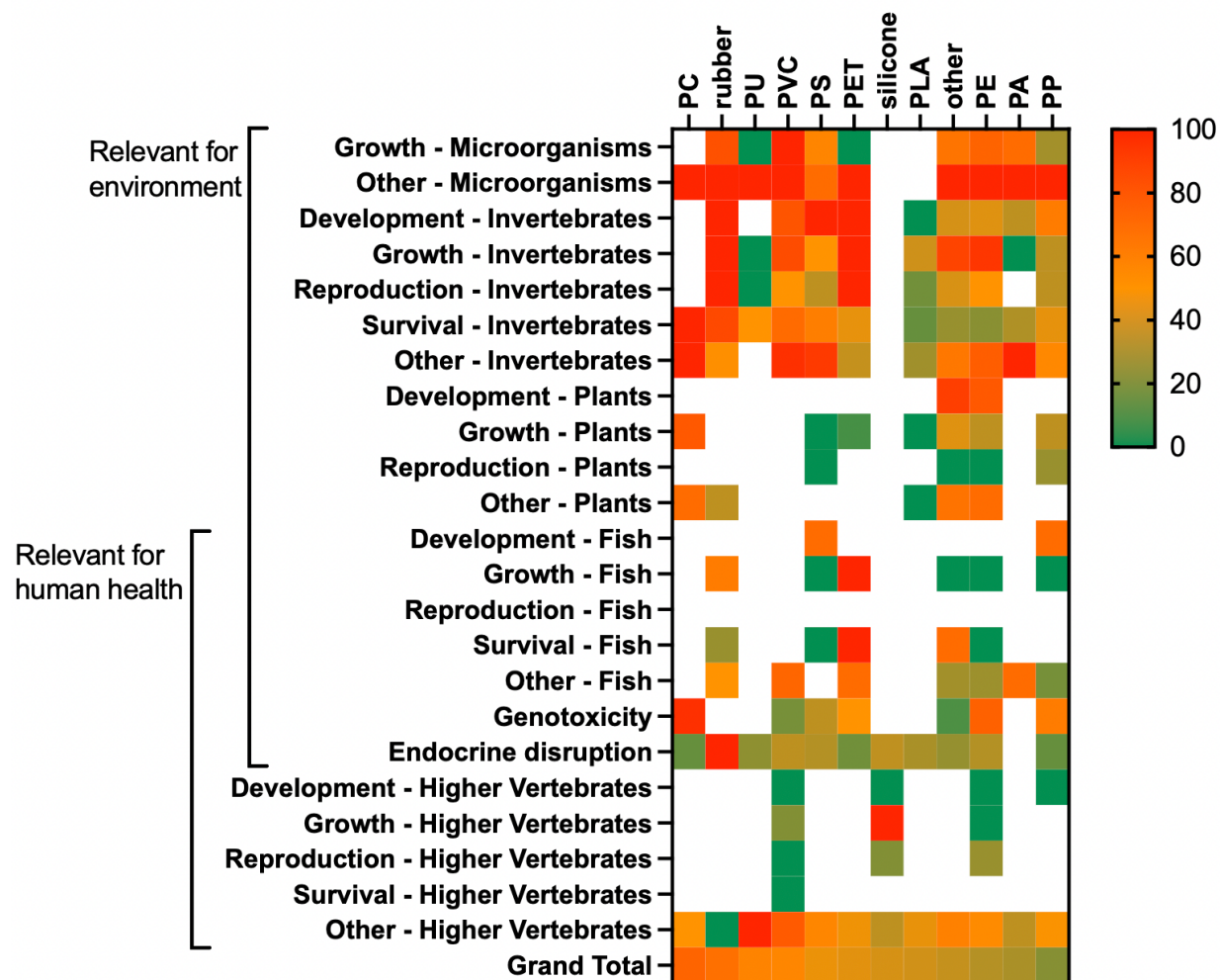


Figure A7. Heatmap of leachate toxicity across polymer types as well as affected taxa and toxicological endpoints. The color of the heatmap represents the proportion of datapoints that indicate an adverse effect. White squares refer to a lack of data. The category "other" aggregates data for other than the shown polymer types. The numbers next to the heatmap refer to the number of datapoints per category.

Status of global and regional plastic material flows

Global plastic market and consumption. There is a high variability in the resolution of data reported for global and regional material flow of plastics, as there are large variations in how data on the life cycle of plastics and polymers are reported and made accessible globally. Figure A8 presents regional differences in the global plastic markets and consumption per sector from the most recent published material flows of plastic globally,⁸ in Europe,⁹ in China,¹⁰ and in Norway.¹¹ The different sectors represented are “Packaging”, “Construction”, “Agriculture”, “Transportation”, “Electronics”, “Other plastics” which include, for instance, personal care and cosmetic products, household plastics as well as “Textiles” which includes technical textile, household textile and garments. Most of the plastics produced ultimately end up as waste, however the lifetime of the products is highly variable, spanning from a few days or months for packaging materials to decades for certain construction materials.¹²

Polymer production is driven by sector demands. The seven commodity polymers are used in all sectors. HDPE (67%), LDPE (43%), PET (43%) and PP (42%) are mainly used in packaging materials, and EPS (70%) and PVC (58%) are primarily utilized for construction materials.^{9,11,13,14} In Norway, LDPE alone constituted ~40% of put-on-the-market (POM) plastics in the packaging sector.¹¹

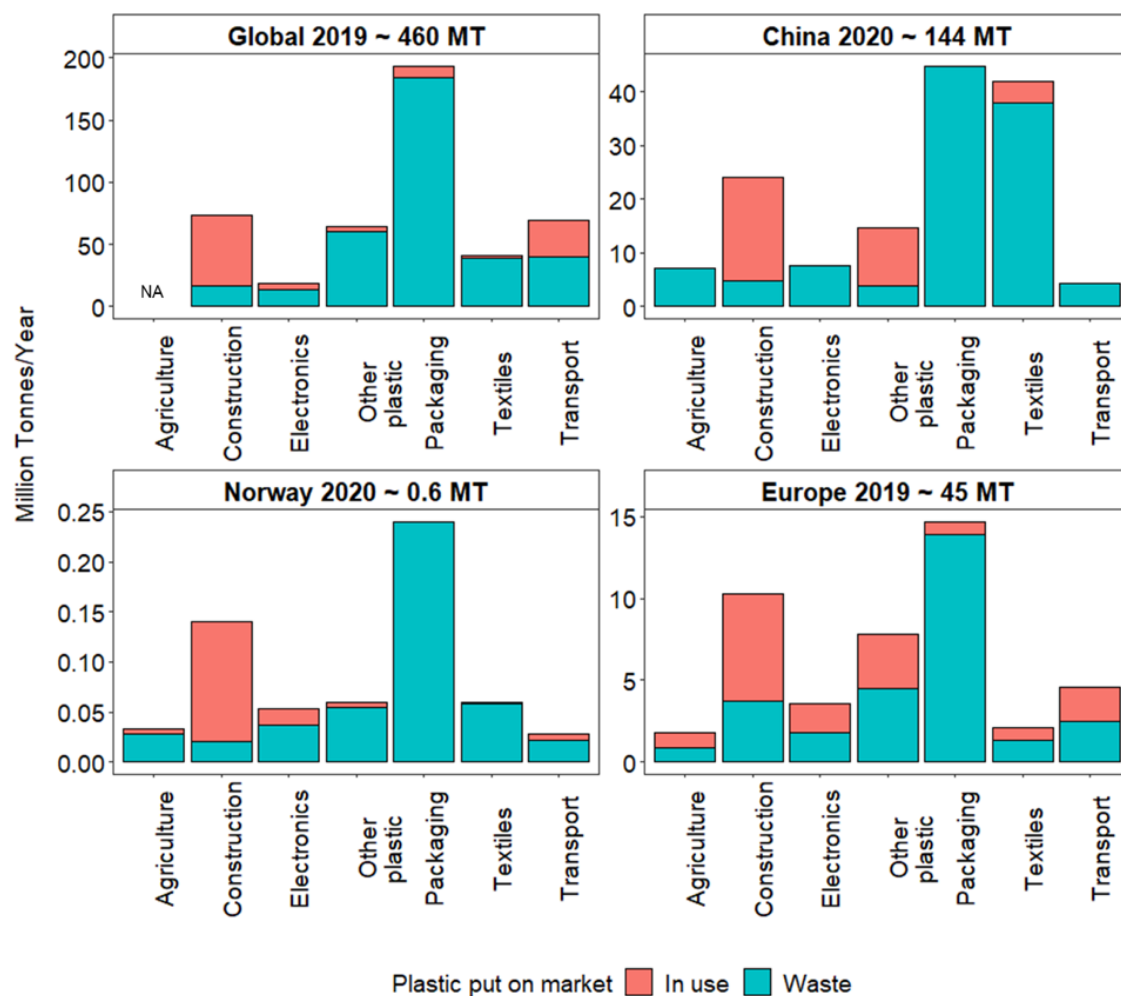


Figure A8. Mass of plastic put on market per year in different sectors on a global level, in China, Europe, and Norway. The red and blue categories represent how much of the annual plastic material is retained in the market (red, in use) and how becomes waste (blue). The uncertainties of the mass reported for each sector and region can be found in the original studies: China in 2020,¹⁰ Europe in 2019,⁹ Global level in 2019,⁸ and Norway in 2020.¹¹

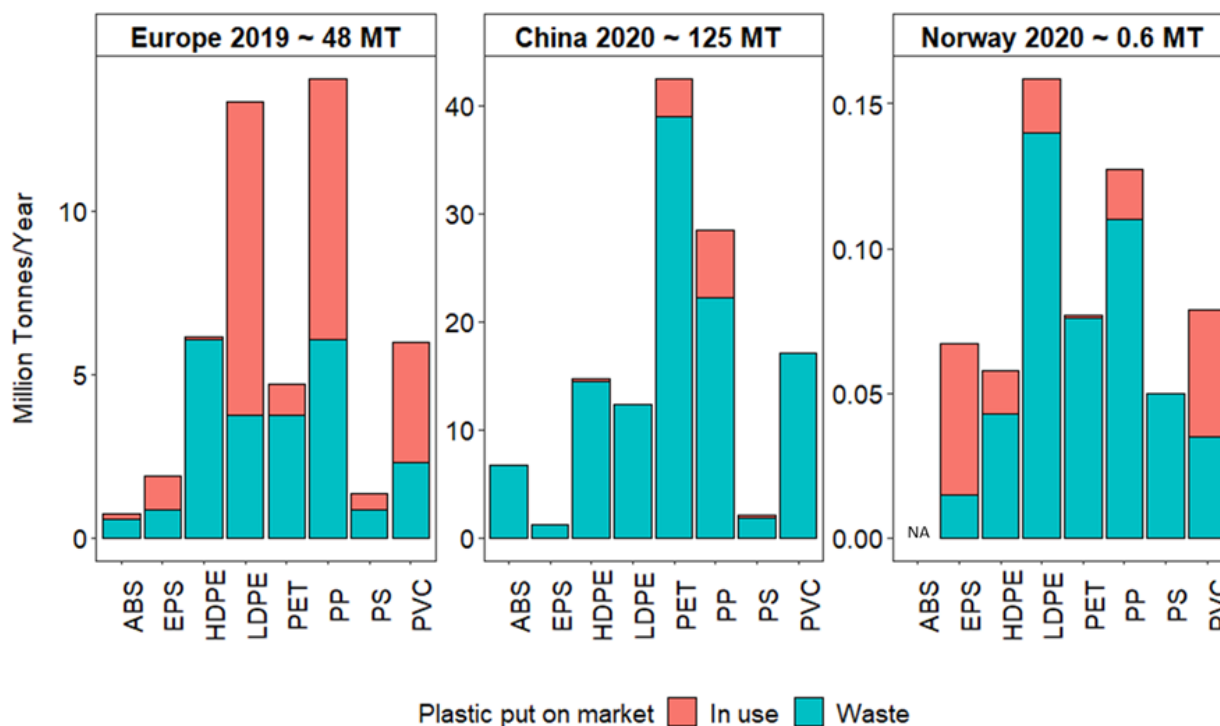


Figure A9. Mass of polymer types put on market per year in different sectors in Europe, China, and Norway. The red and blue categories represent how much of the annual plastic material is retained in the market (red, in use) and how becomes waste (blue). The uncertainties of the mass reported for each sector and region can be found in the original studies: China in 2020,¹⁰ Europe in 2019,⁹ Global level in 2019,⁸ and Norway in 2020.¹¹

There are large regional differences in market demand for polymers, reflecting regional industry demands. China, as the world's largest producer of textiles, represents the region with the highest amount of PET (i.e. polyester) that is put on the market (Figure A9, 81%).¹⁰ For Norway and Europe, LDPE, and PP, respectively, were the most abundant polymers put on the market in 2020, representing the market demand for example the packaging sector.^{9,11}

Global and regional differences in waste management of plastics. There are large variations in global and regional waste management of plastics (Figure A10). On a global level, most plastics are landfilled, despite being the least preferred end-of-life management in a circular economy. Regions such as China, Europe, and Norway are mainly incinerating the plastic waste, and increasingly recycled or reused. Though, the global and European recycling rates for plastics are very low, about 9% and 25%, respectively, which is much lower than recycling rates for glass (Europe ~75 %),^{cc} paper (Europe ~70%)^{dd} and aluminum (Europe ~70%).¹⁵ A substantial amount of the global plastic waste is also mismanaged or has an unknown end-of-life fate (22%)⁸ which may contribute, together with landfilling and littering of plastic, to environmental emissions of plastics as macro- or microplastics. In 2016, Borelle et al. (2020) estimates that between 19 and 23 million tons, or 11%, of the globally generated plastic waste, entered aquatic ecosystems.¹⁶ This corresponds to OECD (2022) global estimates of 22 million tons of plastics leaking into the environment each year, with macroplastics accounting for 88% and manufactured microplastics for 12%.⁸

^{cc} <https://www.statista.com/statistics/1258851/glass-recycling-rate-in-europe/> (Accessed 2023-12-13)

^{dd} <https://www.paperforrecycling.eu/download/1462/?tmstv=1703077262> (Accessed: 2023-12-06)

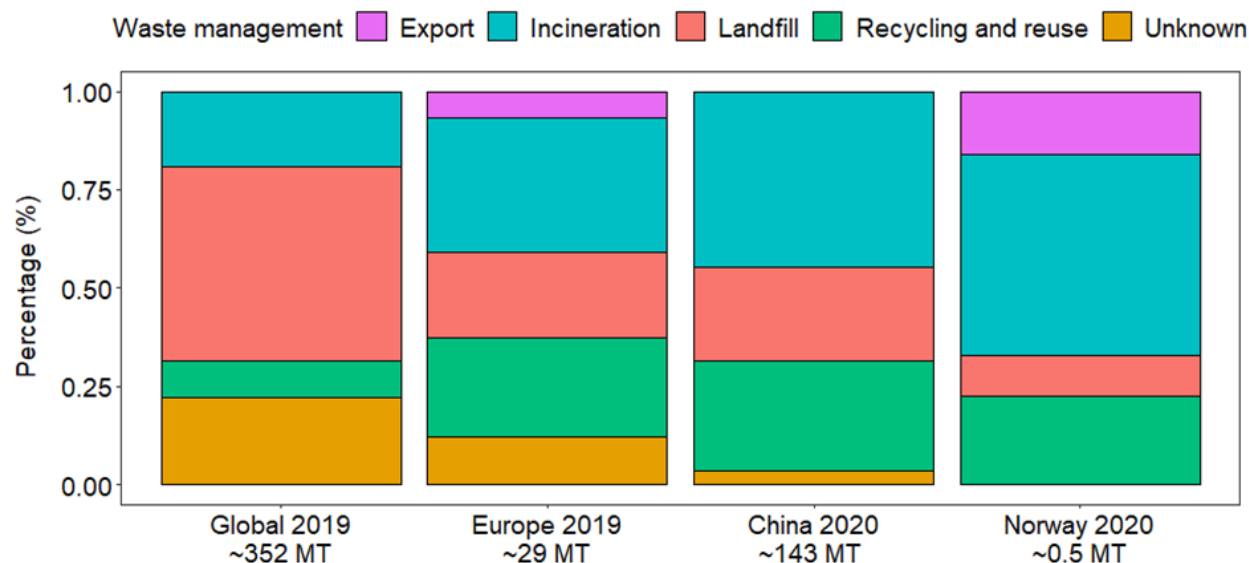


Figure A10. Comparison of waste management strategies globally, in Europe, China, and Norway. The uncertainties of the mass reported for each sector and region can be found in the original studies: China in 2020,¹⁰ Europe in 2019,⁹ Global level in 2019,⁸ and Norway in 2020.¹¹

Projected changes in material flow of plastic and plastic polymers, and respective environmental emissions

If the current plastic production and consumption is maintained in the future, referred to as the business-as-usual (BAU) scenario, it is indicated that the global production of plastics would continue to expand from 460 to 1230 million tons by 2060,⁸ implying a growth rate since the 2019 estimate of 2.5% per year, though some estimates are up to 4.6% a year since 2012 (Plastics Europe, 2020). In total tons produced, this would imply that circa 8 billion or giga tons (Gt) of plastic have been produced by 2023 and by 2060 there will be 40 billion tons produced. Of the 8 billion tons by 2023, 6 billion tons and their associated chemicals are somewhere

on the planet, either in use (~30%), in landfills or sorted for waste management (~60%) or a pollution the oceans, waterways and terrestrial environments (~10%).¹⁷ In Norway, it is predicted a 65% increase in plastics put on market from 2020, reaching 1 million tons in 2050.¹¹

Towards 2060, plastics use is projected to increase for all sectors, however packaging, transport (vehicles) and electrical and electronic sectors are projected to increase the most due to economic development, increasing digitalization and electrification.^{8,11} As such, a substantial fraction of this is the single-use and short-lived plastic, which is currently 35–40 % of the global plastic production and growing increasing, despite regional phase outs of some single-use plastics (Charles et al., 2021).^{ee} Furthermore, plastic waste is projected to almost triple, rising from 353 million tons in 2019 to 1014 million tons in 2060, of which packaging materials will drive this increase, as well as construction, especially from regions with emerging economies.^{8,11}

As plastic use is projected to increase for all sectors, the production and use of all polymers is also projected to increase, as inputs for the different applications also increase. Since the same polymers can be used in different ways in various applications, and some polymers represent a wide range of different plastics that are grouped in one category because they share certain characteristic, the links between polymers and applications within the sectors are quite complex. Eriksen et al., (2020) have estimated a 400% increase in consumption of PET, PE, and PP in Europe over 50 years from 2016, even when including collection and recycling rates of 42%.¹⁸ The most pronounced growth in Europe for these three polymers is predicted within the automotive, fiber (textile) and packaging sector. On a global scale, the same polymers are projected to more than double by 2060.⁸ The

^{ee} <https://cdn.minderoo.org/content/uploads/2021/05/27094234/20211105-Plastic-Waste-Makers-Index.pdf>

projected increases expected for PVC, mostly used in construction, and for fibers used for textiles, such as PET or polyamide (PA), are almost three times the current production. The use of polymers to produce vehicles, and especially PP, is also projected to increase substantially.⁸ Production and use of alternative – and bio-based materials and recycled polymers (secondary plastics) are also predicted to increase towards 2060 as measures to reduce plastic pollution.^{8,19}

Under the BAU scenario, established models predict plastic emissions, to steadily increase, reaching 53–90 million tons per year by 2030¹⁶ or 34–55 million tons by 2040¹⁹ to aquatic environments, which ultimately may accumulate to 5 billion tons of micro- and microplastics found in aquatic and terrestrial environments by 2050.²⁰ Mismanaged waste is of course contributing to these emissions; however, it is projected that the share of unknown or mismanaged waste will grow more slowly than other end-of-life fates, decreasing from 22% in 2019 to 15% in 2060. This is due to the predicted outcome of economic growth, with emerging countries investing in improved waste collection and waste management facilities. However, under the BAU scenario, it is still predicted that landfilling will be the main waste management strategy on a global scale (50%), followed by incineration (18%) and recycling (17%) in 2060.⁸

On the path to circularity and sustainability, simply increasing collection and dispose rates of plastic and/or implementing more state-of-the-art end-of-life technology to increase recycling rates is not sufficient to reducing emissions and the global footprint of plastics.^{16,18,19} A more systemic approach is proposed, which also considers changes in the production of plastics, as well as reduced consumption and increased collection and recycling of plastics – a system-change-scenario (SCS).^{18,19} Under SCS, a substantial reduction in mismanaged and disposed waste can be achieved through reducing the virgin plastic demand or increasing the

proportion of plastics substituted by alternative materials and plastics recycled. Both Borelle et al. (2020) and Lau et al. (2020) predicts that under a SCS, the future rates of aquatic plastic pollution could remain at current ~20 million tons/year also in 2030–2040, despite increasing production volumes.^{16,19}

Knowledge gaps in mass flow data

Whilst reviewing the available literature on global and regional material flows of plastic, only a few studies were detected reporting high-resolution and extractable data on polymers and plastic chemicals within regions and sectors. This was confirmed by King and Locock (2022) who made an extensive review of plastics focused on circular economy covering the last 21 years and 391 articles.²¹ Most of the articles appeared to address plastics in a more general nature, not specifying polymer types (52%) or plastic use per sector or category (70%). This can limit the findability of this information and the translation of research into practical, implementable solutions and frameworks towards circularity. This was especially apparent for this report, as few MFA studies were reporting extractable data on specific polymers from production to management end-of-life. King and Locock (2022) discovered a focus in the literature on system-based approaches and recycling interventions, which constituted 53% of all articles examined.²¹ In contrast, early-stage interventions involving production and use appear as relative gaps, collectively making up only 17% of the articles examined. There is a lack of research that comprehensively describes a circular economy for plastics that includes all parts of the supply chain. Further, we see a lack of information on which chemicals are currently integrated in plastic applications for the different sectors, as well as substance flow analyses with extractable data representing concentrations or content ranges of plastic chemicals or chemical groups.

End of life of plastics and circularity

For mechanical processes, where plastics are remolded into either the same product or into pellets and different products, material containing hazardous chemicals would have to be sorted out as an initial step to ensure a safe recycling. In principle, sorting out such materials may be possible for specific plastic waste streams (product to product). Examples include EPS that are colored if they contain hazardous chemicals (e.g., brominated flame retardants) and are white if not, for recycling into new EPS packaging,²² or recycling a product like a plastic bottle back into a plastic bottle, such as PET bottles in Norway where 92% of bottles are sent for recycling and this covers up 75% of the PET demand for packaging.¹¹ Abbasi et al. (2023) suggests introduction of a similar return scheme for rigid HDPE packaging, such as shampoo bottles, to secure high quality secondary materials and circular economy of HDPE.¹¹ Another consideration is that some of the chemicals in the plastic may not be considered hazardous but could lower the quality of the recycled product. A high-quality secondary material can only be achieved with a high degree of separation and a low degree of impurities and/or cross-contamination among various polymer types.¹¹

Chemical recycling is a technology that has been implemented in several pilot facilities, but there is yet to be a commercially viable operation.^{ff} In a nutshell, the process involves pyrolyzing plastic waste (heating in the absence of oxygen), which breaks many of the chemical bonds to produce naphtha along with chars, volatile chemicals, fly ash, and condensates. The naphtha is similar to naphtha from the petroleum industry and can be further cracked to make chemicals, such as plastic monomers. However, several logistical concerns are preventing chemical recycling

^{ff} <https://cen.acs.org/environment/recycling/Plastic-problem-chemical-recycling-solution/97/i39>

from being a solution, particularly that a high degree of sorting is needed to ensure a consistent naphtha is being produced and that no materials or chemicals are introduced that can gum-up or corrode the pyrolysis unit. For example, PVC can release chlorine radicals that can corrode much machinery. Based on extensive experience with pilot projects, it appears that chemical pyrolysis units at extremely large scales would be needed for this technology to take off, requiring extensive shipments to single facilities, but this has yet to be achieved.^{gg} A key logistic hurdle is the amount of plastic waste that would have to be continuously shipped to facilities to keep them running. Further, there are unique waste management considerations with chemical recycling, such as the formation of mixed condensates, chars and ashes that may not be suitable for recycling but hazardous waste.^{hh}

Solvent based recycling currently is also being developed as an alternative technology that can potentially separate additives, including hazardous chemicals, from polymer matrices via use of solvents.²³ Some polymer types are much easier to recycle by this method than others, for instance PS can be recycled by use of solvents at room temperature, whereby the impurities and additives (e.g., brominated flame retardants) are separated. This can be contrasted to polymers like PP which require high-temperature solvent extraction. As with all plastic recycling technologies, this method will work best if plastics are well sorted into pure polymer types and contain known additives. The unique challenges with this recycling technology are to safely use the large quantities of solvents that would be

^{gg} <https://www.acs.org/pressroom/presspacs/2022/acs-presspac-october-12-2022/controversial-approach-aims-to-expand-plastics-recycling.html>

^{hh} https://static1.squarespace.com/static/5eda91260bbb7e7a4bf528d8/t/655791f76ad9bb07d10e1290/1700237880522/10-30-23_Chemical-Recycling-Report_web.pdf

needed at scale, and further, to manage the hazardous chemicals that would be extracted, as these extracts would need to be managed as hazardous waste.

Sorting based on polymer and chemical content is the only way to ensure compatibility of plastics with circularity. In some cases, this can be done manually by consumers, such as with labelled bottled containers, or white EPS packaging being disposed of in designated containers, provided there is adequate local infrastructure. Within specific sectors, such as food packaging or waste from electrical and electronic equipment, it may be possible to separate polymers based on their density, but this is rather crude when it comes to control of chemical composition. Otherwise, state-of-the-art end-of-life technology for polymer sorting and reprocessing technologies would be needed, such as hyperspectral or near-infrared sorting, to recover black plastics effectively, or enable synthetic fiber-to-fiber recycling.¹⁸ However, in the short term such expensive sorting technologies would only exist in certain regions and would increase the costs of recycled plastic. Closed systems of collection and recycling of plastic from sectors known to contain concentrations of hazardous chemicals, such as plastic from e-waste, construction, or automotives, are the most feasible way forward to ensure that polymers with chemicals of concern stay within the same industry or sector in a closed loop.

Without such tight controls, recycling will never be an effective management strategy, for plastics. The most efficient recycling will involve a product-to-product recycling, where the chemical composition is tightly managed.

A6: Detailed methodology of Part III

Identification of chemicals of concern

Processing of hazard data

To identify chemicals of concern, information gathered from authoritative, regulatory and industry sources was compiled and processed in a PlastChem Hazard Scoring system, based on the updated regulations CLP (EU) 2023/707 of 19 December 2022²⁴ and for aquatic toxicity, on the GHS Hazard Code according to REACH (ANNEX XIII).²⁵ Refer to Table A7 for an overview of the hazard traits included in PlastChem, their hazard code, meaning, CLP criteria as well as the hazard score provided in PlastChem.

The different hazard traits were aggregated into four hazard criteria: Persistency, Bioaccumulation, Mobility and Toxicity. The hazard traits aggregated in each criterion were: PBT, vPvB, PMT and vPvM, for Persistency, PBT and vPvB for Bioaccumulation, PMT and vPvM for Mobility, and CMR, EDC, STOT and aquatic toxicity for Toxicity. Bioaccumulation and Mobility were always considered in combination with Persistency (for example vPvB or vPvM) and/or toxicity (PBT, PMT). The final score provided for each hazard criteria was assigned by selecting the highest score among the individual sources consulted. Each hazard trait received a score ranging from 0 to 2 (see Table A7), with 0 indicating that the chemical was recognized as not hazardous and 2 that the chemical was recognized as highly hazardous. In the cases where no information was available for the substance in any of the consulted sources, the score was designated as NA, signifying unknown. When the evaluation was categorized under development, postponed, or pending, the score assigned in

PlastChem was 0.25 and classified as watch. Lastly, when conclusive evidence demonstrated that the adverse effects were not relevant to human health or the environment, the substance was scored as 0 and considered non-hazardous. Therefore, five different levels of hazardousness were identified, from higher to lower levels: hazard chemicals, less hazard chemicals, watch chemicals, non-hazard chemicals, and chemicals without associated hazard data or unknowns.

Hazard and Evidence Scoring system

To create a unique Hazard Score for each chemical, the maximum scores calculated for Persistency (P), Bioaccumulation (B), Mobility (M) and Toxicity (T) were summed up. Thus, the maximum possible Hazard Score was 8 when a chemical is classified as hazard (2) for all four criteria. The minimum Hazard Score is 0 when a chemical is considered non-hazardous, and blank when there is no hazard information available. A minimum of 1 for one hazard criterion was established for considering a chemical as hazardous.

The Evidence Score was calculated by summing up the number of sources per hazard trait that provided information that the chemical is considered hazardous (score as 1 or 2) and range from 1 to 25 (Table A8). An example of the PBMT scoring system is presented in Table A9 for the most hazardous substance identified in the PlastChem database.

Table A8. Overview of the number of sources consulted per each hazard trait and the maximum score possible Evidence Score.

	Number of sources consulted		Maximum Evidence Score
	Harmonized	Industry	
Carcinogenicity	8	1	9
Mutagenicity	6	1	7
Reproductive toxicity	7	1	8
Endocrine disruption (EDC)	4	0	4
Specific organ toxicity (STOT)	5	1	6
Aquatic toxicity	3	1	4
PBT, vPvB	6	0	6
PMT, vPvM, PM	1	0	1
POP	3	0	3
Sum			48

Table A9. Example of the PlastChem scoring system using the highest scoring chemical in PlastChem (melamine, CAS 108-78-1). The scores column showed how we produced the P, B, M, T scores, the Hazard Score (HS) and the Evidence Score (ES).

Criterion	Persistence (P)					Scores
Traits	PBT	vPvB	PMT	vPvM		
Sources	0/6	0/5	1/1	1/1		ES P: 2
Score	0.25	0.25	1	2		HS P: 2
Criterion	Bioaccumulation (B)					
Traits	PBT	vPvB				
Sources	0/6	0/5				ES B: 0
Score	0.25	0.25				HS B: 0.25
Criterion	Mobility (M)					
Traits	PMT	vPvM				
Sources	1/1	1/1				ES M: 2
Score	1	2				HS M: 2
Criterion	Toxicity (T)					
Traits	CMR	EDC	STOT	Aq. Tox	T (PBT/PMT) ^a	
Sources	3/9	0/4	1/5	1/4	1/7	ES T: 6
Score	1	0.25	2	1	1	HS T: 2
						Final ES: 6
						Final HS: 6.25

Notes: ^a In the case of T (PBT/PMT), the maximum was considered for PBT or PMT as they include T in their classification. ES: The final ES per each chemical the number of sources that classify this chemical as hazardous, i.e., scoring of 1 or 2. In the case of PMT, when a hazard trait serves multiple criteria, the source is only counted once for the final ES.

Prioritization of groups of plastic chemicals

Selection of relevant groups

We followed a stepwise procedure to select relevant chemicals groups based on the specificity of the groups, data availability, and expert judgement:

1. *Remove* groups that are “too broad” based on how they are defined (e.g., fluoro and bromochemicals, ketones, salts because they have an alkaline metal):

chloro, inorganic_compounds, alkenes, fluoro, bromo, epa_Cldyes, alkanes, magnesium, barium, iodo, ketones_simple, alkynes, alkane_ethers, aliphatic_primary_amides, aliphatic_ketones, homo_CCO, aldehydes_simple

2. *Remove* complex groups for **highlighting data gaps** because of their complexity and unclear composition (e.g., polymers, mixtures, UVCBs). Note these polymers and mixtures are the largest groups. The following groups were selected to highlight data gaps but not selected for prioritization:

polymers, mixtures, UVCB_process, UVCB_bioorigin

3. *Remove* groups that are somewhat broad and overlap with other groups: phenolic antioxidants are mostly bisphenols and this is anyway a blending of structure and property, organophosphates (organoP) are a group but should be separated into more specific groups, such as halogenated organoP.

4. *Remove* MEA groups for highlighting **known problematic substance groups** as a precedent for our approach.

POPs, PCBs, PBDD_PBDF_PCDD_PCDF, epa_PAHs, mercury, epa_dioxins, epa_PBDEs, DDT_DDE_DDD, Polychlorinated_naphthalenes

5. Remove the remaining smallest groups with ≤ 6 chemicals:

diazo_amino_hydroxyl_naphthalenedisulfonic_acid_dyes,
dibenzoyl_peroxide_derivatives, cyclic_acetals, homo_CF2, thallium,
dialiphatic_ethers_excluding_unsaturated, salicyclic_acid, Beryllium, alkyl_nitrates,
dihydropurinediones, pyrazoles

6. Remove groups in which <50% of members are hazardous, except if special considerations applied:

silanes_siloxanes_silicones, carboxylic_acids_salts, arsenic, manganese,
isophthalates_terephthalates_trimellitates, selenium, ethanediols, cyclic_ethers

7. Identify relevant subgroups for aggregation in the group organometallics:

tin, chromium, cadmium, lead, nickel, antimony

8. Final selection based on the process above:

Groups	Sum HS	Relative HS	Number of chemicals...			
			hazardous	without data	sum	per cent hazardous
aromatic_amines	52.5	2.39	22	0	22	100.00
aralkylaldehydes	12.5	1.79	7	0	8	87.50
aromatic_ethers	12	1.71	7	0	10	70.00
salicylate_esters	15	1.88	8	1	11	72.72
alkylphenols	101.5	2.03	50	11	66	75.75
epa_bisphenols	39.5	1.98	20	11	34	58.82
orthophthalates	57.75	1.75	33	23	62	53.22
benzotriazoles	45	3.46	13	13	30	43.33
organometallics	305.25	1.90	161	173	373	43.16
parabens	7.5	1.88	4	5	10	40.00
benzothiazole	25.5	2.13	12	13	25	48.00

9. Addition of groups based on special considerations as described in the report.

Groups	Sum HS	Relative HS	Number of chemicals...			
			hazardous	without data	sum	per cent hazardous
epa_azodyes	81	2.31	35	27	89	39.33
Acetophenones_ benzophenones	43	2.05	21	28	54	38.88
chlorinated_paraffins	10.5	2.63	3	5	9	30.00
PFAS	219.8	2.37	76	186	274	27.73

Prioritization of groups

All groups selected above were considered a priority given that they at least 40% of their members are hazardous or if special considerations applied. The resulting list of priority groups of plastic chemicals was further ranked based on the proportion of chemicals of concern compared to the total number of group members in the PlastChem database.

Inclusion of additional data

Toxicity of plastic leachates

Data compilation for the PlastChem toxicity evidence map was carried out using a semi-systematic procedure that ensured transparent recording of the outcomes of literature searches, study screening and selection, and data extraction, curation and analysis. To manage the study team, handle the literature sources, and record the screening and selection outcomes, the online tool CADIMA was used.²⁶ A custom-built SciExtract tool was used to facilitate data extraction.²⁷

Pilot literature searches were carried out in March 2023 and the final literature search was performed on April 5, 2023, using PubMed, Scopus, and Web of Science, and the following search strings:

PubMed: ("leach*" [All Fields] OR "migrat*" [All Fields] OR "extract*" [All Fields]) AND ("toxic*" [All Fields] OR "vitro*" [All Fields] OR "vivo*" [All Fields] OR "assay*" [All Fields] OR "bioassay*" [All Fields]) AND ("plastic*" [All Fields] NOT "plasticity" [All Fields]) NOT "surgery" [All Fields])

Scopus: (TITLE-ABS-KEY (*leach** OR *migrat** OR *extract**) AND TITLE-ABS-KEY (*toxic** OR *vitro* OR *vivo* OR *assay** OR *bioassay**) AND TITLE-ABS-KEY (*plastic** AND NOT *plasticity* AND NOT *surgery*)) AND (LIMIT-TO (DOCTYPE , "ar"))

Web of Science (core collection): (leach* OR migrat* OR extract*) (toxic* OR vitro OR vivo OR assay* OR bioassay*) plastic* NOT plasticity NOT surgery

Scopus and Web of Science entries were filtered for the document type "article". After removal of duplicates and of sources that lacked primary data, such as reviews, conference abstracts or editorial material, 5854 sources remained in the

resulting dataset. Literature screening was carried out according to a protocol published in Zenodo repository on April 23, 2023.ⁱⁱ This protocol lays out the main question, general considerations and inclusion/exclusion criteria applied at the study screening and selection stage.

Specifically, the PlastChem toxicity evidence map addresses the following main question: “Which types of toxicities or bioactivities have been measured for chemical mixtures released from which plastic polymers, materials or products, and mixtures from which plastic polymers or products were found to exhibit which types of toxicities/bioactivities?” For study selection, three criteria were used. First, The Population (P) criterion, considering plastic materials or products, including pre-production pellets as well as virgin, recycled and compounded materials. Second, the Intervention/Exposure (I/E) criterion, considering release of chemical mixtures from plastic materials or products in any type of medium, that is, leachates, including migrates, extracts etc. of chemicals in aqueous, solid, or gaseous media. Finally, the Outcome (O) criterion, considering toxicity or bioactivity testing of chemical mixtures released by plastic materials or products in any type of bioassay, regardless of the results obtained in that bioassay. Note that the study selection criteria did not include the Comparison (C) criterion, because this would have led to exclusion of many relevant studies where only one polymer or product type was tested. In the subsequent analysis, the testing outcomes for different plastic polymers, materials and products were compared.

Based on these three criteria, 5566 sources were excluded after the title/abstract screening stage, and further 88 after the full-text evaluation stage. In addition, 87 more studies were excluded because full text could not be found, or accessed, or assessed, or because they were previously undetected duplicates. The remaining

ⁱⁱ <https://zenodo.org/records/8136442>

201 studies were used for data extraction based on the predefined parameters set up in the dedicated data extraction project within the SciExtract tool. The types of data to be extracted were organized around the three criteria described above, specifically (i) Population – type of polymers and products, where details on the polymer type, product type, number of samples in that category, country of origin or sampling, and polymer treatment were recorded; (ii) Exposure/Intervention – Leaching conditions, where details on the leaching setup, leaching medium, leaching temperature, leaching duration and sample treatment were recorded; and (iii) Outcome – Bioassay, where details on the assay name, species name, organism type, bioassay type, organismal endpoint, cellular/molecular endpoint, detection of effect, number of detects and number of non-detects were recorded.

At the conclusion of data extraction, 2045 record lines were generated in total, forming the preliminary PlastChem toxicity database. This preliminary database was then subjected to clean up and quality checks, which included the harmonization and/or correction of terms used to describe leaching solutions, assay names and assay endpoints, as well as verification of the matching between the recorded number of test samples corresponded to the sum of the numbers recorded for respective detects and non-detects. Other mistakes noticed during this process were also corrected and some lines were deleted or inserted new where necessary to accommodate the correct records. The final PlastChem toxicity database generated as described above contains 2161 lines extracted from 201 studies).

Material flow analysis

Studies published after 2014 reporting material flow analyses of plastic and polymer types were collected through a search on Google Scholar using key words such as “mass flow or MFA plastic”, “mass flow MFA plastic polymer”, “material flow plastic polymer”, “plastic circular economy MFA”, in combination with “Europe”, “Norway”,

“China” or “global”. After snowballing and reverse snowballing of papers, a set of relevant research articles and reports were selected for the review of material flow analyses of plastic (Table A10).

The sectors considered for graphical representation were “packaging”, “construction”, “agriculture”, “transportation”, “electronics”, “other plastics” which includes personal care and cosmetic products, household plastic, and “textiles” which includes technical textile, household textile and garments. OECD (2022) has reported material flow of plastic within sectors of higher resolution than most other studies.⁸ To make mass data for polymers and plastics more comparable with other studies, data from OECD (2022) reported sectors clothing and other textiles were combined to “textiles”, tires and vehicles were combined to “transportation” and packaging and consumer products were combined to “packaging”. Similarly, data from the European Joint Research Centre (2022) from the sectors healthcare, fishing and other were combined to “other plastics”.⁹

Table A10. Overview of studies and reports where material flow of plastic has been reported (since 2014) or projected (until 2060) for China, Europe, Norway, and globally.

Country/ Region	Year	Polymers considered	Data per sector	Data on waste management	Reference
China	2017, 2020	LDPE, HDPE, PP, PS, EPS, PVC, PET, ABS	Yes	Yes	Chen et al., 2023
China	1950-2050	PE, PP, PS, PVC, ABS, PET, others	Yes, but no extractable data	Yes	Luan et al., 2021
Europe	1950-2016	LDPE, HDPE, PP, PS, EPS, PVC, PET	Yes	Yes	Kawecki et al., 2021
Europe (EU28) and Switzerland	2014	LDPE, HDPE, PP, PS, EPS, PVC, PET	Yes	Yes	Kawecki et al. 2018
Europe	2016-2056	PE, PP, PET	Yes, but no extractable data	Yes	Eriksen et al., 2020
Europe (EU28)	2016	LDPE, HDPE, PP, PS, EPS, PVC, PET, others - but no extractable data	Yes, but no extractable data	Yes, but not by polymer type	Hsu et al., 2021
Europe (EU28)	2018	PUR, ABS, PA, PC and PMMA	Yes	Yes	Liu & Nowack 2022
Europe (EU27)	2019	LDPE, HDPE, PP, PS, EPS, PVC, PET, ABS, PUR, PC, PA, PMMA, others	Yes	Yes, but not by polymer type	JRC 2022
Norway	2020	LDPE, HDPE, PP, PS, EPS, PVC, PET	Yes	Yes	Abbasi et al., 2023
Denmark	2017	No	No	Yes, but not by polymer type	Vingwe et al. 2020
US	2018	LDPE, HDPE, PP, PS, PVC, PET, PLA, other	No	Yes	Chea et al., 2023
Global	1950-2060	No	Yes	Yes, but not by polymer type	Landrigan et al, 2023
Global	2016-2040	No	No	Yes, but not by polymer type	Lau et al., 2020
Global	2016-2040	No	Yes	Yes, but not by polymer type	Pew & Systemiq, 2020
Global	2019-2060	LDPE, HDPE, PP, PS, EPS, PVC, PET, PUR, SA, other	Yes	Yes, but not by polymer type	OECD, 2022

For those sectors or polymers where the amount of waste managed each year was reported higher than the amount of material put on the market within the same sector or polymer the same year, the whole column was labelled as waste. In Luan et al. (2021), the waste generated per sector was not clearly reported with numbers for all selected sectors, so the amount of waste generated for sectors “Transport”, “Electronics” and “Other plastic” are estimates extracted visually from Figure A8 (panel China) as 4% or 4.7 million tons, 12% or 15.6 million tons, and 3% or 3.9 million tons, respectively.

The categories considered for graphical representation of waste management in the present report are “incineration”, “landfill”, “recycling and reuse”, “export” and “unknown”. “Unknown” refers to the plastics whose waste disposal compartments were not recorded in the statistics or waste that is mismanaged such as littering.

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