Enabling a circular economy for chemicals in plastics

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Enabling a circular economy for plastics in Europe and beyond is an ambitious goal. To reach a fully closed loop, numerous challenges and knowledge gaps need to be overcome. This review provides a list of more than 6000 chemicals reported to be found in plastics and an overview of the challenges and gaps in assessing their impacts on the environment and human health along the life cycle of plastic products. We further identified 1518 plastic-related chemicals of concern, which should be prioritized for substitution by safer alternatives. At last, we propose five policy recommendations, including the need of a global and overarching regulatory framework for plastics and related chemicals, in support of a circular economy for plastics and of target 12.4 of the UN Sustainable Development Goals.

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Introduction
In 2015, the European Commission defined a Circular Economy Action Plan, in response to increasing environmental degradation and health impacts from inefficient use of resources and environmental emissions of greenhouse gases, air pollutants, and harmful chemicals [1]. This ambitious plan was adopted in 2020 as one of the main building blocks of the European Green Deal that aims to deliver ‘the first carbon-neutral continent’ by 2050 [2]. Europe’s Circular Economy Action Plan is well-aligned with the global Sustainable Development Goals (SDGs) and promotes initiatives along the entire life cycle of products. In priority, the Action Plan focuses on sectors that use the most resources and where the potential for improving circularity is high, such as the plastic sector where large challenges exist [2]. Indeed, with a rapid increase in global plastic production [3], humanity is facing a growing issue of related environmental pollution and human and ecological exposure (e.g. via plastic physical pollution, accumulation and degradation into microparticles) [4-7]. A particular dimension, often overshadowed by its numerous challenges and knowledge gaps, concerns the various chemical constituents present in plastics and their potential impacts on humans and ecosystems along plastic products’ life cycles [8,9].

Chemical compounds added during the manufacturing of plastics to fulfil specific functional requirements in the production process and/or in the final plastic material or consumer product are referred to as ‘additives’ [10,11]. Commonly applied additives include plasticizers, flame retardants, pigments, antioxidants, stabilizers, antistatic, and nucleating agents [12-14]. The concentration and type of chemicals present in plastics widely varies as function of product application and type of plastics [15]. In addition to additives, other chemicals might be present in plastics, such as solvents, unreacted monomers, starting substances or processing aids, as well as nonintentionally added substances (NIAS), such as impurities, reaction by-products, and breakdown products, which are usually present in low (residual) concentrations [13,15-18]. A comprehensive inventory of chemicals introduced during plastics manufacturing and present in different finished plastic materials is currently lacking. Such information is scattered across different sources focusing on specific materials or product applications (e.g. [19, 20]).

Except for few additives polymerized with the plastic chains, such as some organic flame retardants [11], chemicals present in plastics are usually not covalently bound to the polymer matrix [15]. Thus, they can leach from the plastic material by diffusion and partitioning along the material’s life cycle, exposing the surrounding environment and humans [8,13,15,20]. Exposure to leachable chemicals might pose not-negligible negative effects both on humans and ecosystems [22,23]. Examples of harmful chemicals in plastics include phthalate and chlorinated paraffin plasticizers, polybrominated diphenyl ether (PBDE) flame retardants, bisphenols (monomers in polycarbonate plastics), colorants and stabilizers containing metals, and biocides [9,24-27].

Numerous regulations are in force worldwide for limiting and controlling the application and content of harmful chemicals in new or recycled plastic-based
consumer products in particular in developed countries (e.g. POPs listed under the Basel and Stockholm Convention) [17, 28], but an overarching framework for managing chemicals in plastics along their life cycles is currently lacking. For example, in the EU chemicals management legislation, we observe a fragmented landscape composed by different legal frameworks [29,30]. A central piece is the European REACH Regulation (EC) 1907/2006, aiming at ensuring a high level of protection of human health and the environment. However, there are various additional directives and regulations in place, addressing substances in specific product applications, such as biocidal products (EU No 528/2012), food contact materials (EC No 1953/2004 and EU No 10/2011), toys (2009/48/EC), and electrical and electronic equipment (2002/95/EC), or targeting specific aspects around chemicals, for example, industrial emissions (2010/75/EU) and waste (2008/98/EC). With that, legal requirements across substances and product applications might differ based on the regulatory context, and a range of hazardous additives restricted in the EU are still allowed in developing countries. Under the Stockholm Convention, several listed POPs have still exempted uses as additives in plastic/polymers, such as SCCPs, decaBDE, and HBCD. For NIAS, the picture is even worse, because their risk needs to be assessed only if present in plastics intended for use as food contact material (EC No 282/2008), but not for other types of applications [9,13]. However, without regulating all harmful chemicals in plastic product applications, managing chemicals in plastics will remain challenging, and hamper European and global ambitions toward circularity.

To address this challenge, the present study aims at outlining the state-of-knowledge of chemicals in plastics, including (a) mapping their use, as well as the challenges and gaps in assessing their impacts on human and environmental health, (b) providing a first inventory of assessed and regulated chemicals in plastics and chemicals of concern, and (c) discussing ways forward for enabling a circular economy for plastics (Figure 1).

The three main blocks visualized in Figure 1 covering the status quo of chemicals in plastics, the challenges and gaps in assessing plastic-related chemicals’ impacts in a circularity context, and options and ways forward for enabling a circular economy for chemicals in plastics.

State of knowledge of chemicals in plastics

Overview of chemical additives

The production of chemicals used in plastics is continuously increasing in terms of both quantity and diversity, with several thousand chemicals used across many material applications. Estimating global additives production is not an easy task, because these data are usually not publicly available. However, with a global
plastic production of 368 Mt in 2019 [3], and assuming 1–10% additives mass fraction for nonfibre plastics, the total amount of additives used in 2019 might be around 20 (3.6–36.8) Mt. If plastic production follows current increasing trends, it is estimated that we will have produced 2000 Mt of additives by the end of 2050 [12]. Plasticizers are the most used additives and together with flame retardants cover almost 50% of globally applied additives [12]. Owing to their wide-ranging application and high-production volumes, these two types of additives have been receiving special attention (e.g. Commission Regulation (EU) 2018/2005).

Additives are applied during the production process at different concentrations based on the specific function that they need to fulfil. Table S1 provides an overview of functions, typical material application, chemical classes, and application ranges. For example, plasticizer application ranges vary across materials, and can reach up to 60–70% of the plastic mass in soft PVC products [11••, 31]. Other additives are usually applied at much lower concentrations, such as 0.7–25% for flame retardants or 0.05–5% for stabilizers and antioxidants [11••]. The concentration of unintentional residues is typically <1% [32]. Generally, it is accepted to consider as NIAS only compounds with a mass <1000 Da, assuming that substances with a higher molecular weight cannot be absorbed in the body (EU No 10/2011, although there might be some uptake in the gut [18,33]).

**Chemicals reported in plastics**

As of today, there is no publicly available database containing a complete and detailed list of chemicals used in the various plastic products, specifying typical function, plastic types, and mass fraction ranges. In an attempt to provide such an overview, we used the mapping of plastic additives conducted by the European Chemical Agency (ECHA) [14], and expanded it with data from 35 additional sources (Table S2). The considered sources include—among others—Annex I of Commission Regulation (EU) No 10/2011, also called the Union list, which is a positive list of monomers and additives authorized for use in plastic-based food contact materials, the work conducted by Groh et al. [13,19••], and the Chemicals and Product Categories database (CPCat; actor.epa.gov/epcat), which contains information across different categories and materials [34] (Table S2).

As a result, Table S3 provides a list of more than 6000 functional additives, pigments and other substances found (both currently and in the past) in plastics. For each substance, we provide CAS number, main chemical function, typical application range, and polymer type (when available). For building the data set, we checked and harmonized where needed the reported chemical names, CAS numbers, and functions. Chemicals were classified according to their specific function in plastic materials based on the information reported in the considered sources. Wherever such information was missing, we retrieved the function from other references (e.g. Ref. [35•]).

Table S3 aims at providing a comprehensive overview of chemicals found in plastics across different polymers and product applications. It contains various types of substances reported to be found in plastics; consequently, it is not limited to additives but also includes NIAS, solvents, unreacted monomers, starting substances, and processing aids.

**Challenges and gaps in assessing plastic-related chemicals’ impacts in a circularity context**

The goal of a circular economy is to move away from the current largely linear (take-make-waste) model, toward a 9-R modelb by minimizing the leakages of materials and chemicals along products’ life cycles into the environment as well as reducing and avoiding negative impacts on humans, ecosystems, and natural resources [36,37••]. Thus, the challenges and gaps in assessing chemical impacts are not related only to the disposal or recycling of plastic products, but include all life cycle stages [38].

**Single chemicals and chemical mixtures**

One of the major problems in assessing plastic additives is the poor characterization of many chemicals and the large data gaps regarding the chemical properties and (eco)toxicity information [39–41]. In addition, chemicals are generally assessed individually, but in practice, humans and ecosystems are exposed to hundreds of chemicals either individually or in combination from single or multiple sources [42,43]. Nevertheless, mainly due to the still ongoing discussion and linked research needs in this field, mixture risk assessment is lacking in current regulations, which might lead to a potential underestimation of chemical risks [44,45].

**Assessing exposure across population groups**

For workers, there is currently no approach for occupational exposure assessment to the chemical mixtures used in polymer production, and a lack of workplace/occupational exposure limits for a large share of additives used in plastics (e.g. Refs. [46–48]). For consumers, already obtaining reliable data on plausible ranges of chemicals content in products is difficult [13, 19••,20••]. In addition, exposure assessment methodologies to effectively assess and quantify chemical emissions and exposures are still lacking, especially due to the complexity of considering the thousands of

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b 9-R circularity concept of Refuse, Reuse, Reduce, Redesign, Repurpose, Remanufacter, Repair, Refurbish, Recycle.
chemicals involved in thousands of products used with different usage patterns [49–52].

Assessing environmental exposure
Reliable models for estimating not only the amounts of plastics leaking into different environments (aquatic, marine, and terrestrial) but also information on the fate of the chemicals present in these environments are mostly missing. For example, frameworks have been published for quantifying environmental losses of plastics across their value chains or specifically from landfills (e.g. Refs. [53,54]); however, the plastic-related chemicals’ dimension has not been included in such frameworks.

Aggregate and cumulative exposure assessment
Humans and ecological receptors are exposed to multiple chemicals via multiple pathways, as highlighted for instance for phthalates by numerous biomonitoring studies [55,56]. However, there is a lack of data on additives applications and quantities, across different products and sectors. Hence, both the different sources and quantities for a specific substance necessary for estimating aggregate (across sources per chemical) and cumulative (across chemicals) exposure are missing. Biomonitoring already helps to back-calculate such exposures for certain substances (e.g. Ref. [57]). However, conducting such toxicity assessments for thousands of different chemicals found in plastic products, including recyclates, is technically challenging and time-consuming.

Product design, raw materials, and manufacturing
The biggest gap in identifying safe, sustainable, and circular alternatives for substituting and phasing out harmful additives is an incomplete assessment of all relevant life cycle stages, impacts, and exposed receptors, leaving potential trade-offs unaddressed (e.g. various combinations of occupational, consumer, population and ecological exposures and hazards along plastic products’ life cycles) [58–61]. To understand, which aspects to focus on and where emissions and resources use reduction should be prioritized, targets are needed at the level of plastic materials and chemicals. Both are currently missing, leading to an ever-increasing diversity of marketed chemicals and materials. Current national and international regulatory frameworks are not yet able to promote the necessary innovation in material and product design, optimize for emission reduction in manufacturing processes, minimize plastic waste, and maximize the circularity of material flows.

In addition, in some specific applications (e.g. flame retardants in polymeric building materials), hazardous or otherwise problematic additives might fulfill essential functions and thus cannot be phased out easily in certain polymeric materials because of their role to reduce flammability. However, also for polymers in building insulation, alternatives are in fact available, such as inorganic insulation materials, which are not flammable but might be more costly. To some extent, also flame retardants can be avoided in insulation foams depending on the use of the foams and the building codes for covering polymers by, for example, gypsum boards. Scandinavian countries, for example, require such measures as they do not allow flame retardants in polymer insulation [62]. Clear definitions of essential functions and additive applications are required to evaluate these cases.

With respect to resources used for producing the chemical constituents of different plastic applications, around 99% of produced additives are still synthesized from fossil resources with biochemicals making the remaining 1% [63,64]. Both fossil resources and biofeedstocks come with their own challenges with respect to impacts on humans and ecosystems. For example, while being chemically similar in structure after synthesis, biochemical and fossil chemical supply chains differ widely as a function of feedstock (e.g. crude oil, corn) and related refinery processing. This implies that it is necessary to consider the entire supply chain to capture trade-offs across relevant impacts (e.g. climate change and ecotoxicity).

Waste management
The global trade in plastic waste has seen a movement of significant volumes from developed to developing countries, where environmentally unsound recycling and disposal practices are leading to exposures to toxic constituents [65–67]. Examples include landfill or dump site fires with associated releases of toxic plastic compounds [11–14, 68–71] as well as plastic additives released in leachates from landfills and detected in the surrounding areas [72,73]. While for few investigated plastic additives, releases from landfills and exposures are documented, such assessments are missing for the wider range of plastic-related substances. A few developing countries make progress in restricting certain plastic uses. In particular, Rwanda demonstrates that with bans, restrictions, and strict enforcements, a significant reduction of total plastic import can be achieved beyond the restriction of plastic bags [74]. This reduces at the same time also additives and littering and the lower volume of plastic waste generated can be better managed.

Recycling
When recycling polymeric materials, the chemicals they contain might be transferred to the newly manufactured products as contaminants (cross-contamination). Hence, humans and ecosystems may inadvertently be exposed to these substances through a number of recycled products and materials, as highlighted by different studies documenting the presence of harmful
organic chemicals, including brominated flame retardants, in children’s toys and food-contact articles due to bad recycling practices [74–77]. Such residual concentrations of, for example, flame retardants are usually substantially smaller compared to concentrations of many additives (see Table S1), but can nonetheless lead to non-negligible exposures and risks, depending on their hazard properties. In a circular economy context, the main challenge is hence to keep track of relevant chemical flows and to avoid the recycling of plastics containing hazardous substances. This currently fails due to information gaps on the chemical content of plastic waste and missing alternative end-of-life treatment processes. These are the main reasons for unintentional cross-contamination of recycled or upcycled materials with polychlorinated, brominated, and fluorinated plastic additives, which are persistent, mobile or bioaccumulative, and toxic to humans or the environment.

**Suggested chemicals of concerns in plastics**

From our data set of more than 6000 chemicals found in plastics (Table S3), we identified potential chemicals of concern, using as criteria existing regulatory and other substance prioritization lists, as well as human and environmental hazard classifications.

First, we matched the data set against existing (mostly regulatory) priority substances lists, which include—amongst others—the European Candidate List of substances of very high concern for authorisation (SVHC) [78], the CalSafer Candidate list [79], the California Proposition 65 list [80], and the German Federal Environment Agency’s PMT/vPvM substance list [81]. Figure 2 presents the resulting chemicals included in these prioritization lists, differentiated by chemical function. As the considered priority substances lists come from different countries, agencies, and

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**Figure 2**

Fraction of chemicals found in plastics that is included in regulatory or other ‘chemicals of concern’ prioritization lists. The x-axis represents the number of existing (mostly regulatory) priority substances lists in which each substance is listed. Chemicals are differentiated by function. The category ‘Residues’ includes all substances reported as NIAS, degradation or breakdown products. ‘Others’ covers both substances with other functions (e.g. adhesives), and all substances without an assigned chemical function. ‘Stabilizers’ include heat, light, and other stabilizers.
organizations, a substance might be listed in more than one list (see Table S3 for an overview of the considered priority substances lists and of the matching results). For around one-fourth of the substances \( (n = 1463) \), there is a match with at least one of the considered lists, confirming a high presence of chemicals of concern in plastics. Different trends are observed across chemical functions. For example, for flame retardants, stabilizers, catalysts, and antioxidants, around half of the substances found in plastics are covered by at least one prioritization list, while around one-third is covered for plasticizers, with specific, hazardous phthalate plasticizers listed in almost 20 different lists (e.g. DEHP, DBP, BBP). Other examples of chemicals covered by more than 5 prioritization lists include brominated flame retardants, colorants with metals, monomers with phenols, and biocides. The chemical function with the highest number of substances of reported concern \( (n = 71) \) is stabilizers.

In addition, we investigated potential environmental and human health hazards of the considered substances based on classifications aligned with the Globally Harmonized System for classification and labelling of chemicals, available in the CLP Regulation (EC 1272/2008). Annex VI. Figure 3 presents the chemicals found in plastics by functions that are associated with different CLP hazard classes. Note that a single substance might be assigned to more than one hazard class (e.g. carcinogenic and toxic to aquatic organisms). Among more than 6000 substances found in plastics, hazard information was available for \( n = 590 \), rendering around 10% of the considered substances as hazardous. The hazard classes with the highest number of substances are acute toxicity \( (n = 207) \), skin corrosion/irritation \( (n = 224) \), and chronic ecotoxicity to aquatic organisms \( (n = 185) \), highlighting the fact that substances present in plastics have potential hazard effects on both humans and ecosystems. Looking at specific chemical functions, pigments and colorants have the highest number of substances \( (n = 37) \) with at least one assigned hazard class, followed by stabilizers \( (n = 28) \). For pigments and colorants, we further observe a high number of substances \( (n = 29) \) with potential carcinogenic effects, mainly for colorants containing metals.

Figure 3

Number of chemicals found in plastics that is assigned to one or more hazard classes according to the Globally Harmonized System for classification and labelling of chemicals (GHS). Chemicals are differentiated by function. CLP classes: AT, acute toxicity; SC/I, skin corrosion/irritation; ED/I, serious eye damage/irritation; SRT/S, sensitization of the respiratory tract or the skin; GCM, germ cell mutagenicity; C, carcinogenicity; RT, reproductive toxicity; STOT, specific target organ toxicity; AsT, aspiration toxicity; AEaq, acute ecotoxicity to aquatic organisms; CEeq, chronic ecotoxicity to aquatic organisms.
### Table 1

Possible solutions and ways forward to overcome the identified challenges and gaps in assessing plastic-related chemicals’ impacts on human and environmental health, in support of enabling a circular economy for chemicals in plastics.

| Identified challenge                                                                 | Possible solutions and ways forward                                                                                                                                                                                                 |
|-------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| **Single chemicals and chemical mixtures:** Poor characterization of the chemicals and large data gaps regarding the chemical properties and toxicity information. | Starting from Table S3, build a global open-access database with full overview of chemicals in virgin and recycled plastics with quantified concentrations (including NIAS), then characterize potential toxicity of all plastic-related chemicals (e.g. by automatically curating and extrapolating data from sources such as REACH database or CompTox Chemicals Dashboard [82–84]) and stop and restrict toxic chemicals in plastics across all product application (phase out). For what concern mixtures, in cases where a relevant mixture can be tested as such, its potency can be characterized directly, and this is a useful approach to the testing of, for example, extracts from food contact materials. In parallel, the implementation of regulatory risk assessment schemes for mixtures is urgently needed. |
| **Assessing exposure across relevant human receptor groups:** Lack of methodologies to effectively assess, quantify, and reduce chemical emissions and exposures. | The key for an appropriate risk and hazard assessment is a detailed understanding of the exposure of workers in production and recycling, of consumers to the various plastic product applications, and finally of the general population and the environment via releases and emissions along the entire plastic products’ life cycles. Thus, it is fundamental to consider the wide range of plastic additives (e.g. stabilizers, antioxidants, plasticizers, see Table S1) as well as the present NIAS and their toxicity along the entire life cycles. For workers, key ways forward include the establishment of workplace exposure limits for all substances used and found in plastics and reduction of occupational exposure to hazardous chemicals in the production of plastics by Best Available Techniques (BAT) and Best Environmental Practices (BEP). While consumers can reduce their exposure to plastic additives and NIAS by reducing the overall use of plastic products in households and in particular by reducing plastic food packaging and avoiding microwaving and heating of food packed in plastic. In addition, producers need to share data on chemicals content in products to apply chemical risk screening approaches developed for alternatives assessment and chemical substitution as starting point to effectively assess, quantify, and regulate chemical emissions and exposures for the thousands of chemicals involved in thousands of products [50–52, 60]. |
| **Assessing environmental exposure:** Lack of information and methods on leaching of plastic additives in different environments. | More research and development of methods for assessing the implications of release of chemicals from plastics in different environments and for fully understand the magnitude of the issue. An ambitious proposal is the implementation of a global fully dedged efficient waste collection, management, recycling, and environmentally sound disposal systems that would guarantee an almost zero plastic release to the environment and practically solve the issue. However, this seems a financially challenging and long-term way forward [17+]. |
| **Aggregate and cumulative exposure assessment:** Humans and ecological receptors are exposed to multiple stressors via multiple pathways. | Producers need to share data on additives applications and quantities, across different products and sectors. In this way, both the different sources and quantities for a specific substance necessary for estimating an aggregate exposure would be available. In addition, as conducting biomonitoring studies for each different chemical–plastic material combination would be costly and time-consuming, reliable mathematical estimation methods might be applied instead, and thus urgently needed. |
| **Product design, raw materials, and manufacturing:** Lack of reduction targets with ever-increasing diversity of marketed chemicals and materials. | One bottleneck of reducing the use of hazardous substances globally is that additives are mainly listed and restricted after thorough risk assessments. For additives with POPs properties, the Stockholm Convention provides a mechanism for the global control and phase out (e.g. PBDEs, HBCD, PBB, see Table S1) with technical support for developing countries and options for exemption for time-limited, continued use. However, for the hundreds of other chemicals, which do not meet POPs criteria, such an international mechanism is missing. One option might be the inclusion of hazardous plastic additives as an issue of concern in the Strategic Approach to International Chemical Management (SAICM), where currently the intersessional process for SAICM beyond 2020 is ongoing, including a working group on issues of concern. Life cycle assessment tools can be applied at the level of entire products or product systems to optimize the use of chemicals across virgin and recycled materials in a circular economy. However, tools to assess life cycles at the level of individual chemicals are largely missing. To address this problem, we need to increase transparency in chemible starting point chains. A suitable starting point would be to understand the function that each chemical fulfills in a given material (e.g. cadmium compounds applied as heat stabilizers in PVC, see Table S1). Based on the chemical function, material, and product constituents can be identified |

(continued on next page)
Table 1 (continued)

| Identified challenge                                                                 | Possible solutions and ways forward                                                                                                                                                                                                 |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| **Product design, raw materials, and manufacturing: Risk of regrettable substitutions.** | To avoid regrettable substitution and manage the multitude of chemical additives in the different plastic applications following the principles of sustainable chemistry, a reliable assessment of the performances and impacts of these additives in their given applications is crucial considering all impacts along their life cycle to avoid unintended trade-offs [85]. A prerequisite to this process is a clear understanding of the interconnection between the life cycle of a given chemical additive and the life cycle of the related plastic product application. In addition, the complex mixtures of additives and NIAS require a robust toxicity assessment in the substitution process [86]. It is increasingly acknowledged that a traditional approach based on the identification/quantification of all substances in plastic together with their full toxicological characterization is not practical (highly resource-intensive) [87]. However, the toxicological effect of such complex mixtures needs to be considered and assessed to protect consumers and improve or substitute products. An option to assess and compare toxicity are bioassays and other screening technologies measuring relevant toxicological effects such as cytotoxicity, genotoxicity, or endocrine effects [87], these toxicity screening methodologies could be used in recycling of plastic for hazard control in a circular plastic economy. |
| **Product design, raw materials, and manufacturing: Indispensable additives**          | In case of hazardous or otherwise problematic additives, which cannot completely be phased out due to fulfilling essential functions without currently available options for substitution, we propose the application of an essential use approach as proposed for per- and polyfluoroalkyl substances (PFAS) [88••]. Similarly, for some hazardous chemicals in plastics, a complete restriction might not be feasible, such as for PAHs in rubber tires or NIAS, which are always present to some extent in plastic and can only be minimized to an acceptable level. For these chemicals, specific limits are needed for different uses. |
| **Waste management: Lack of knowledge on the fate of plastic additives during disposal.** | Minimizing the production of plastics and hazardous additives since the current waste management systems cannot cope with the high amounts of plastic waste. Even developed countries do not appropriately manage their huge and increasing amount of generated plastic waste and still export millions of tons of plastic each year to developing countries, which lack proper waste management and recycling technologies [85,89]. The use of plastics must be rethought where possible. Therefore, the highest priority of the waste hierarchy applies to the reduction of the use of plastic and in the reduction of hazardous plastic additives, which is an important bottleneck for improved recycling of plastic towards a more circular economy. For example, significant overall reduction of plastic use and consequent exposure to plastic additives has been documented for Rwanda with strict policy and regulation against GDP trend [7••]. At the global scale, a solution put forward in “Breaking the Plastic Wave” would reduce virgin plastic demand growth from 4% a year to under 1%, with a final peak in 2027 [90, 91••]. |
| **Recycling: Hazardous additives still found in current used products can lead to contamination of plastics in recycling.** | The implementation of recycling control mechanisms, such as the adopted amendments to Annexes II, VIII, and IX to the Basel Convention, is fundamental to control the transboundary movements of plastic waste and ensuring that waste and recycling are only traded with countries having the necessary infrastructure for an environmentally sound waste management. Yet, developing and emerging economies have little or no adequate destruction capacity and typically information on substances in waste is missing. Extending the producer responsibility to cover the entire life cycle is needed to overcome such barriers. By implementing a sustainable chemistry approach, the chemicals and manufacturing industry need to move toward a fully circular economy model, where production and consumption losses are reintegrated into the material or product life cycles. This, of course, requires that producers have the highest possible knowledge about the entire plastic supply chain, including information on the chemical composition of recycled materials that should be reintegrated into new products. |

By matching our data set of substances found in plastics with existing prioritization lists and hazard classifications, we identified \( n = 1518 \) chemicals of concern in plastics (Table S3). In support of enabling a circular economy for chemicals in plastics, these substances should be prioritized for substitution by safer alternatives, and receive special attention when recycling plastics, where these substances might accumulate as...

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**Table 1**

| Identified challenge                                                                 | Possible solutions and ways forward                                                                                                                                                                                                 |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| **Product design, raw materials, and manufacturing: Risk of regrettable substitutions.** | To avoid regrettable substitution and manage the multitude of chemical additives in the different plastic applications following the principles of sustainable chemistry, a reliable assessment of the performances and impacts of these additives in their given applications is crucial considering all impacts along their life cycle to avoid unintended trade-offs [85]. A prerequisite to this process is a clear understanding of the interconnection between the life cycle of a given chemical additive and the life cycle of the related plastic product application. In addition, the complex mixtures of additives and NIAS require a robust toxicity assessment in the substitution process [86]. It is increasingly acknowledged that a traditional approach based on the identification/quantification of all substances in plastic together with their full toxicological characterization is not practical (highly resource-intensive) [87]. However, the toxicological effect of such complex mixtures needs to be considered and assessed to protect consumers and improve or substitute products. An option to assess and compare toxicity are bioassays and other screening technologies measuring relevant toxicological effects such as cytotoxicity, genotoxicity, or endocrine effects [87], these toxicity screening methodologies could be used in recycling of plastic for hazard control in a circular plastic economy. |
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| **Waste management: Lack of knowledge on the fate of plastic additives during disposal.** | Minimizing the production of plastics and hazardous additives since the current waste management systems cannot cope with the high amounts of plastic waste. Even developed countries do not appropriately manage their huge and increasing amount of generated plastic waste and still export millions of tons of plastic each year to developing countries, which lack proper waste management and recycling technologies [85,89]. The use of plastics must be rethought where possible. Therefore, the highest priority of the waste hierarchy applies to the reduction of the use of plastic and in the reduction of hazardous plastic additives, which is an important bottleneck for improved recycling of plastic towards a more circular economy. For example, significant overall reduction of plastic use and consequent exposure to plastic additives has been documented for Rwanda with strict policy and regulation against GDP trend [7••]. At the global scale, a solution put forward in “Breaking the Plastic Wave” would reduce virgin plastic demand growth from 4% a year to under 1%, with a final peak in 2027 [90, 91••]. |
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residues in recyclates, potentially continuing to expose humans and ecosystems.

Beyond evaluating prioritization lists and hazard classification criteria, we also matched our substance data set against two recent scientific studies providing lists of chemicals of concern in two specific plastic applications, namely food contact materials and children’s toys [199,200]. These studies applied additional criteria to identify chemicals of concern (e.g. human exposure estimates for specific application contexts), which highlights the complexity of identifying chemicals of concern and the need for stricter and up-to-date regulations. Identified chemicals of concern in these two studies are generally in line with prioritization lists. However, they listed \( n = 50 \) substances found in plastics that are not included in any considered prioritization list nor labeled as hazardous substances under the CLP regulation. We have included and flagged these additional substances in our list of chemicals of concern in Table S3.

**Options for enabling a circular economy**

For each of the identified challenges and gaps in assessing impacts of chemicals in plastics in a circular economy context, we outline possible solutions and ways forward (Table 1). Achieving a closed loop and thus a fully circular economy for plastic materials across sectors is an ambitious yet necessary target. Owing to the complexity of the challenge, numerous steps are needed involving all relevant stakeholders at the global level. These steps range from maximizing the reduction of plastics and hazardous additives (Table S3) to implementing global recycling control mechanisms and an overarching regulatory framework for plastics and related chemicals.

Already in the 1980s, a set of 12 principles of green chemistry has been defined to move the chemicals industry to a more sustainable model [92], leading to cleaner products and processes over the past decades, and boosting sustainability for chemicals in industry and science. These principles range from less hazardous chemical synthesis to designing chemicals that are less persistent in the environment, clearly focusing on the direct sustainability assessment of chemical reactions. With that, the 12 principles of green chemistry are well-suited for the optimization of linear chemical production routes. However, to enable a transition to a true circular model for chemicals, these principles have been re-evaluated, accounting for the entire life cycles of chemicals and products in which they are used [379]. Some of these principles correspond more or less to principles already defined for green chemistry. Other principles, in contrast, go well beyond chemistry itself and consider a broader perspective to reach circularity. This includes, for example, to maximize atom circulation or to reject lock-in Ref. [93]. Only when these principles are rigorously applied, we will effectively pave the road toward an urgently needed circular economy model for chemicals in plastics.

**Conclusions and policy recommendations**

We have provided a comprehensive overview of chemicals found in plastics across different polymers and product applications, and discussed challenges and ways forward in assessing plastic-related chemicals’ impacts on humans and ecosystems in a circular economy context. Urgent global actions are needed for a successful implementation of Europe’s Circular Economy Action Plan and to reach Target 12.4 of the UN SDGs: “By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment”. In support of these ambitions, we propose five policy recommendations for enabling a circular economy for plastics including the role of plastic-related chemical substances (Text box 1).

All in all, our current society faces complex challenges around chemicals in a circular economy context. Among the main challenges are that current policy frameworks in Europe and elsewhere do not facilitate a circular and

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**Text box 1. Policy recommendations for enabling a circular economy for chemicals in plastics and supporting target 12.4 of the UN Sustainable Development Goals (SDGs).**

1. Facilitate collaboration and involvement of all relevant actors along entire chemicals and plastics life cycles with a transparent supply chain management toward a common vision based on the 12 principles of circular chemistry on country, continental, and global level.
2. Harmonize regulatory and legal frameworks, and enforce an overarching and global regulatory framework for plastics and related chemicals guided by systems thinking to connect the different actors of the plastics value chains. For example, needed reforms include an extended producer responsibility for plastic products (especially for the ones containing hazardous substances).
3. Implement funds to invest in mechanisms to strategically coordinate and support the transition of industries toward a circular economy in both upstream and downstream capacities and seeking synergies within the sound management of chemicals and waste SAICM beyond 2020 process.
4. Implement funds in research of new technologies in support of industries for efficient manufacturing of virgin and recycled plastics fit for a circular economy model.
5. Educate and support citizens, companies, and investors on the transition toward a circular economy for plastics and related chemical substances.
integrative perspective, the use of complex and difficult-to-decompose multichemical materials, such as plastics, and possible cross-contamination of recycled materials with harmful chemicals.

To address these challenges, we need to develop new technological capacity to separate contaminated polymers and destroy and recover these complex materials and waste, and at the same time develop frameworks for substituting harmful chemicals with safer, sustainable, and circular alternatives. This requires involving all relevant actors along entire chemical and product life cycles, along with a transparent supply chain management, capacitate policymakers, and improve the science–policy interface. A prevention and ‘Best Available Techniques and Practices’ approach, built on a holistic life cycle basis, could allow available resources and efforts to be focused on targeted measures to reduce the problem by directly attacking the source, similar to the way in which industrial toxic emissions were effectively curbed in some developed countries at the end of the last century, instead of relying on ‘end-of-pipe’ solutions [17].

With that, we will eventually be able to move toward a successful circular economy for chemicals in plastics in Europe and worldwide.

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

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Appendix A. Supplementary data
Supplementary data to this article can be found online at https://doi.org/10.1016/j.cogsc.2021.100513.

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