Plastics recycling and hazardous substances – Risk Cycle 2026

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Preliminary remark:

This paper is a translation and update of the authors' contribution to the Innsbruck Waste and Resources Day 2026 – Material Flows in the Cycle – Challenges & Opportunities – Quotas & Pollutants, on February 4, 2026 [1].

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Structure

1. Introduction

Material recycling of plastics involves processes and concepts in which the polymer molecule of end-of-life plastics, i.e., waste products, remains largely intact. In addition to the classic mechanical processes, in which plasticization takes place again after collection and sorting, there are processes that dissolve the polymer molecule and then precipitate it again (solvolysis), which are on the borderline with chemical recycling[1]. Chemical recycling – which is not discussed further in this paper – breaks down the polymer molecule to varying degrees and then rebuild polymers or other materials from the resulting fragments.

For material-based plastic recycling, the qualities achieved by the recycled materials and their potential applications are relevant. The quality of the recycled materials and their (possible) areas of application are interrelated. The authors make a broad distinction between upcycling, recycling, and downcycling.

- **Upcycling** is achieved when the recycled materials are of such high quality that they can be processed into a product of higher value than the original products.
- **Recycling** refers to cases in which a recycled material of the same substance replaces a new material (hereinafter referred to as "virgin plastics") of the same quality. Therefore, these recycled materials must be of approximately the same quality as virgin plastics.
- In **downcycling**, the quality of the recycled materials only allows the plastic to be used purely as a material in products with lower requirements in terms of purity and quality of the material and/or performance of the product. These are usually products that are used outdoors and could also be made of concrete, asphalt, wood, or iron.

The quality of recyclates for material recycling is defined by the purity of the input at the filling opening of the extruder. The renewed plasticization results in intermediate products that are traded (e.g., granulates) or processed directly (possibly in mixture with virgin plastics and recycling additives) into end products. Purity refers primarily to the respective polymer molecule, but also to the additives and other impurities contained in the input. A level of purity that allows upcycling of the recyclate is difficult to achieve. For level-equivalent recycling, it is necessary that the starting material for the recyclate is a polymer fraction as homogeneous as possible (> 95%, preferably > 99%), which – as a rule – cannot be achieved with today's sorting processes.

Only separate collection of used products can roughly deliver this quality, as the example of single-use PET beverage bottles shows. This also fulfills a second prerequisite for recycling: the additives in the recycled materials are similar or identical to those in virgin PET.

Recycling is particularly possible for raw materials from the pre-consumer sector. For example, cutting scraps and similar waste from the manufacture of plastic products are very homogeneous and similar in terms of additives. These types of waste can be recycled at the same level.

The quality of today's sorted fractions from post-consumer packaging in Germany or Austria regularly does not allow for recycling, but only downcycling. The quality of the sorted fractions ranges from 80 to 85% for the respective polymer, sometimes even lower. Several fires in various sorting plants – caused primarily by the uncontrolled return of devices with lithium

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[1] We classify solvolysis as a chemical process because the plastic undergoes significant changes as a result of the process and also because, from the perspective of the "risk cycle" issue, solvolysis can differ significantly from material recycling.

batteries and loose rechargeable batteries [2] – have reduced plant capacities in Germany, forcing the remaining plants to operate at high throughputs, which in turn further deteriorates quality.

Added to this are difficulties resulting from packaging design that cannot be solved by today's sorting and recycling techniques. One example of these difficulties is yogurt cups: these are increasingly being wrapped in a (wet-strength) paper sleeve. This saves plastic – the polystyrene content is reduced by about 20%, but about three times as much cardboard is needed to replace the polystyrene saved [3] – and consumers are led to believe that this is environmentally friendly packaging. However, the opposite is true: the (composite) cup can no longer be sorted as polystyrene in sorting plants. Either it is added to the film fraction via wind sifters (because it is so light) and contaminates it, or it ends up in the liquid carton/cardboard fraction and contaminates that. As a result, many sorting plants are increasing the screen sizes of their inlet screen drums in order to sort out these materials at the same time – primarily as sorting residues for thermal recycling.

Another example is multilayer films. This type of packaging is on the rise because it ensures high quality food presentation in supermarkets, for example, and has become indispensable in this sector. Around one third of packaging consists of multi-layer films. This development is a minor disaster for material recycling because there is no recycling solution for these films. Even downcycling reaches its limits here. The multi-layer structure can also be found in another type of packaging. There are multi-layer plastic bottles, one of which has a thin glass layer, or – for fruit juices that are sensitive to oxidation – with a middle layer of polyamide (PA) or ethylene vinyl alcohol copolymer (EVOH).

A third example is black plastics, which is widely used in both households and industry. This plastic cannot be identified by polymer type using the techniques commonly working in sorting facilities today – NIR light (near-infrared) –, because it absorbs the light and leaves nothing to be detected.

Downcycling is worse for the environment than high-quality recycling (e.g., in terms of direct greenhouse gas emissions [4]). When mixed waste plastics are mechanically recycled without first being sorted by polymer type, the material quality decreases significantly in the first cycle. Further material recycling is then usually no longer possible, and the material must be sent for energy recovery (waste-to-energy). The decline in quality is also reflected in the price: in downcycling, the recyclates replace, for example, concrete, which costs the equivalent of approximately 7–8 cents/kg[2] on the market (e.g. [5]), or low-quality wood with a price (e.g. [6]) of the equivalent of approximately 20–40 cents/kg[3]. In high-quality recycling, on the other hand, virgin plastics are replaced at a significantly higher price.

The quality of the recycled material is sometimes so poor that even the low prices for the respective recycled materials, e.g., from post-consumer waste [7], can no longer be realized on the market. In many cases, additional payments are even made; the recycled material manufacturer pays the product manufacturer a defined price to "store" its material in a product (up to €300/Mg). This practice is not uncommon in Germany.

The chemical industry in Germany is in a difficult position because its fossil fuel-based business model is no longer profitable. Therefore, phasing out petroleum and natural gas would be a

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[2] Concrete: Ø density 2.4 Mg/m^3; ex-works price: €160–200/m^3 (e.g., Holcim, see above) corresponds to €0.07–0.08/kg

[3] Wood: Ø density 0.5 Mg/m^3; price: €192 (US-$224)/$m^3$ (e.g. Finanzennet) corresponds to €0.38/kg

way out. This would require a transition to other carbon sources, also in order to achieve greater resilience. And for climate protection reasons, this transition would be necessary in any case (defossilization). The carbon that is currently being downcycled **does not contribute** to the defossilization of the chemical industry; in fact, it is a waste of carbon.

2. The fine art of developing plastics

2.1. Preliminary remark

Until a few years ago, the addition of additives to plastics was not a major issue in waste management or recycling [8,9,10]. However, the topic had been of central importance to experts in the plastics industry since the early 1950s. At that time, it became clear that polymers cannot be processed into products without additives. This realization celebrates its 75th anniversary in September this year [11]. Today, it is not only the sheer volume of plastics that poses a problem for people and the environment, but also their heterogeneity and the additives they contain [12,13,14,15,16].

2.2. Developments in polymers

Much has also changed in the field of polymers in recent decades. In practice, plastics made from a single polymer has decreased. Instead, combinations are increasingly being used. These combinations include mixtures (known as blends) as well as copolymers and cross-links. One example that illustrates the chemical complexity of the real world of plastics is MBS, a popular copolymer that is "transplanted" into PVC, polycarbonates, or polycarbonate /polybutylene terephthalate mixtures for stabilization purposes. MBS itself is not a single substance, but rather a mixture of **m**ethyl methacrylate, **b**utadiene rubber, and **s**tyrene.

2.3. Developments in additives

There is a whole arsenal of chemical compounds that have been and continue to be used in plastics for a wide variety of purposes. Their proportion in plastic products is generally in the percentage range, but can also be well above 10% by weight. For example, antioxidants account for 0.5–3% of the weight of products made from PE, PS, and ABS. Light/UV stabilizers in products made from PE, PP, and PVC range from 0.1–10% by weight. Flame retardants can account for 2–28% by weight, while PVC products can consist of up to 70% by weight of plasticizers [17].

At this point, it is important to understand the diversity of additives from the perspective of plastics development. Plastics are primarily formulated resp. compounded with their intended use in mind. Indoor or outdoor use is just one of the possible distinguishing criteria. The fine art of formulation extends to the question of what the respective weather conditions are like in the respective target market. Complex formulations are developed that must withstand standardized aging tests under regional conditions (heat, radiation intensity, humidity, biological activity, etc.), but also consumer expectations such as haptics, color, electrostatic properties, or smell and taste.

The art lies in using polymer blends and additives to give plastics different properties that are precisely suited to the respective conditions and purposes of use. There are extensive monographs and manuals (e.g., [18,19]) that describe hundreds of substances to help formula developers make the right choice. And there are university courses where you can learn all this in several semesters.

It is not uncommon for a formulation to contain not just a single additive, but up to a dozen or more in very different concentrations. Depending on the polymer, additives must be supplemented with auxiliary additives to enhance a desired effect or suppress or limit undesirable effects. It is also not unusual to use biocides or special stabilizers to ensure the longevity of additives in plastics in defined areas of application.

The additives are low molecular weight, i.e., they are much smaller than the polymers. As a rule, they do not form a strong chemical bond with the polymers of the plastic (although there are exceptions [20]), but are usually only incorporated via weak interactions between the polymer chains [21]. Figure 1, based on the PlastChem project [22], provides an overview of what the "chemical construction kit" currently offers for the production of plastics (compounding).

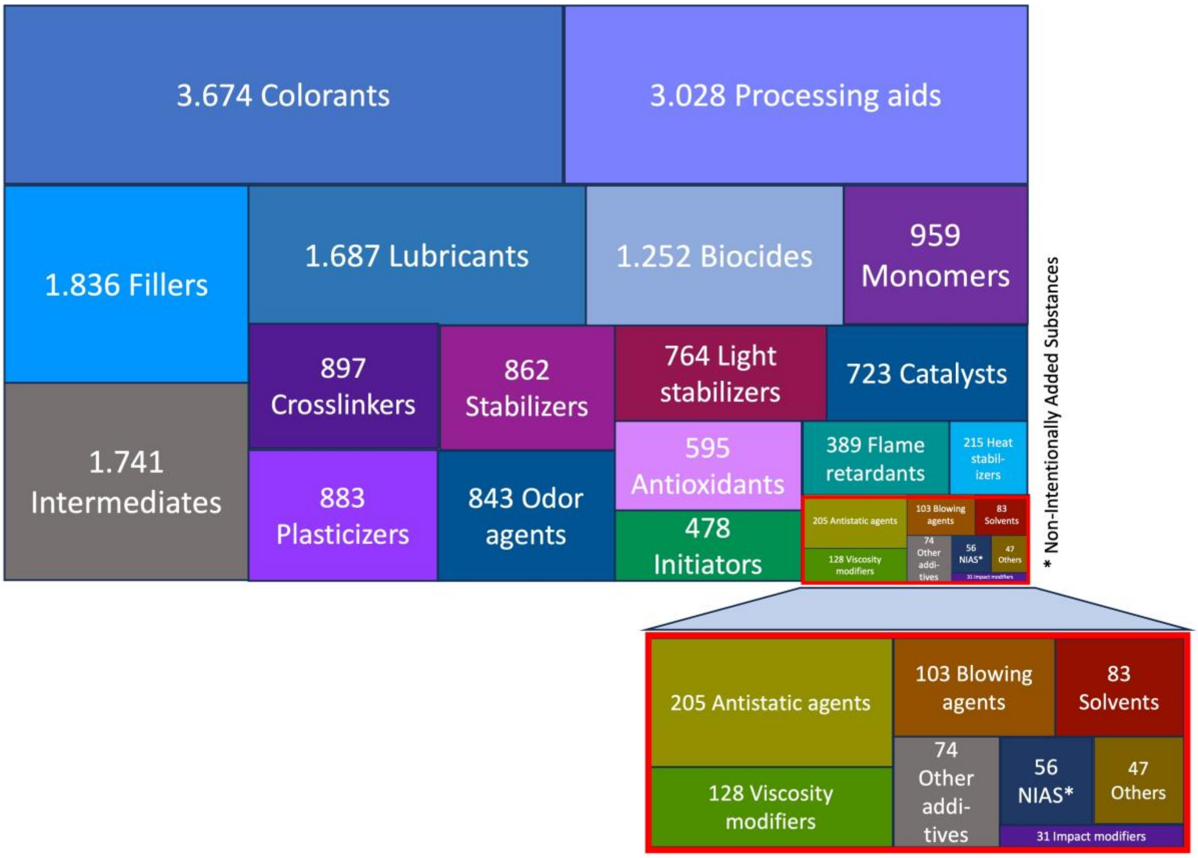


Figure 1: Overview of the functions of plastic additives and chemicals. Note: Many substances have more than one function (own graphic, according to [22])

2.4. Problematic dowry

Today's plastics recycling industry must address the developments outlined above regarding chemical diversity over the past decades. International databases are available that compile information on this diversity of additives as well as unwanted reaction products (see Table 1).

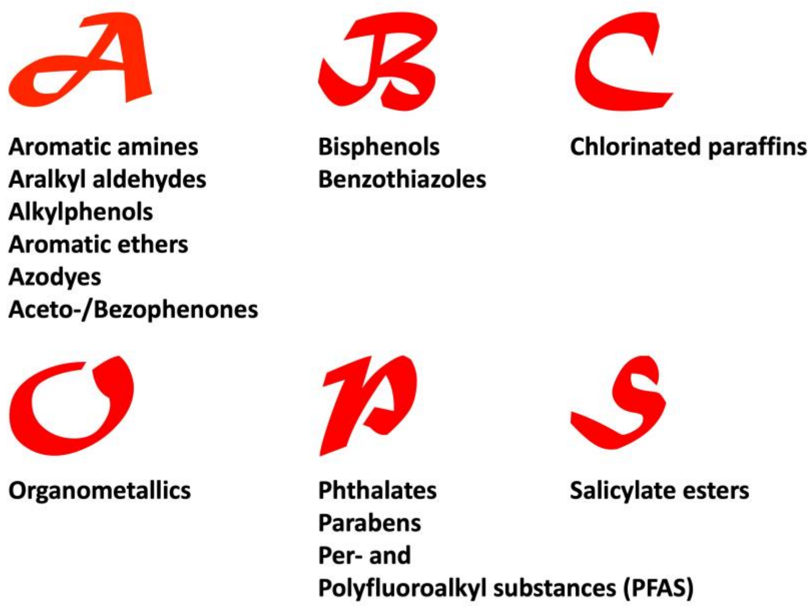
In summary, the following conclusions can be drawn from these databases:

- The group of substances used in plastic products comprises around 16,000 chemicals.
- For around 10,000 of these substances, basic data on their hazardousness is lacking.
- The experts involved in the PlastChem project have identified 15 priority groups and over 4,200 plastic chemicals of concern, of which around 3,650 are currently unregulated worldwide (see Figure 2).

Table 1: Comparison of the number of chemicals listed, evaluated, and classified as hazardous in PlastChem and previous databases [22]

Author [Ref.]	**Number of substances in plastic**	**Of which classified as hazardous**
Wiesinger et al. (2021) [23]	10,547	2,486
Aurisano et al. (2021) [24]	> 6,000	590
UNEP (2023) [25]	> 13,000	3,200
PlastChem (2024)	16,325	> 4,332; *of which currently 3,651 globally unregulated*

Figure 2: The primary groups of plastic additives and chemicals (own graphic based on 22])



According to Wagner et al. [22], these approximately 3,650 substances would need to be examined more closely for their hazardousness (PBMT – persistence, bioaccumulation, mobility, and toxicity) and substitutability. The general review procedures under REACH, POP, and others are ongoing; new findings on hazardous substances are published regularly. A current example is the classification of TNPP (tris(4-nonylphenyl, branched and linear) phosphite) itself, an important stabilizer for packaging films, as an SVHC (substance of very high concern), (NEW) regardless of its content of branched and linear 4-nonylphenol [26]).

Classification as an SVHC means that suppliers must provide their customers and consumers with information on the safe use of this substance if a product contains this substance in a concentration of more than 0.1% by weight. Consumers also have the right to ask suppliers whether the products they purchase contain this or any other substance of very high concern. The ECHA database SCIP (substances of concern in products) has been in existence for a few years now and is intended to create transparency in this area. However, as feared [27], it has so far proved to be of little use for waste management [28]. At the end of July 2025, the

European Commission announced that it was considering abolishing the SCIP database as part of a broader initiative to reduce the regulatory burden on EU companies caused by environmental regulations. The planned Digital Product Passport (DPP) (see section 4.4) could replace or integrate the previous complex information requirements such as safety data sheets (SDS), technical data sheets (TDS), and SCIP reporting requirements, enabling uniform data exchange along the entire value chain.

To date, a high number of unreported cases can be expected, particularly with regard to imports from non-EU countries. One slogan from the time of the struggle over REACH was: "No data, no market!" This should also apply in particular to the compounding of plastics for contact-sensitive applications, as is already stipulated for packaging in the EU Packaging Regulation 2025/40 [29].

As of December 2025, the database of the Baden-Württemberg State Agency for the Environment (LBUW) contains over 130 entries on SVHC substances, most of which are used as additives in plastics [30]. Twenty SVHCs alone have been newly added in the last four years. Table 2 shows which substances are most likely to be found in which kind of plastics.

Table 2: SVHCs that may be present in plastics – as of December 2025 ([30])

Material sub group	Substance (some short names)	CAS-Numbers
Poly-ethylene, PE	lead chromate molybdate sulfate red *(*C.I. Pigment Red 104); 2-(2H-benzotriazol-2-yl)-4,6-ditert-pentylphenol (UV-328); 2,4-Di-tert-butyl-6-(5-chlorbenzotriazol-2-yl)phenol (UV-327); diarsenic trioxide; tris(4-nonylphenyl, branched and linear) phosphite (TNPP) with ≥ 0.1% w/w 4-nonylphenol, branched and linear (4-NP); potassium hydroxyoctaoxo-dizincate dichromate; decabromodiphenylethane (DBDPE)	12656-85-8; 25973-55-1; 3864-99-1; 1327-53-3; -; 11103-86-9; 84852-53-9
Poly-propylene, PP	lead chromate molybdate sulfate red *(*C.I. Pigment Red 104); UV-328; UV-327; potassium hydroxyoctaoxo-dizincate dichromate; 2-(dimethylamino)-2-[(4-methylphenyl)methyl]-1-[4-(morpholin-4-yl)phenyl]butan-1-one; DBDPE	12656-85-8; 25973-55-1; 3864-99-1; 11103-86-9; 119344-86-4; 84852-53-9
Polystyrene, PS	UV-328; UV-327; HBCDD; diisobutyl phthalate (DIBP); 1,1'-[1,2-ethanediylbis(oxy)]bis[2,4,6-tribromobenzene] (BTBPE); 2,2',6,6'-tetrabromo-4,4'-isopropylidenediphenol (TBBPA); 2-(dimethylamino)-2-[(4-methylphenyl)methyl]-1-[4-(morpholin-4-yl)phenyl]butan-1-one; 2-(2H-benzotriazol-2-yl)-4-(1,1,3,3-tetramethylbutyl)phenol (UV-329); triphenyl phosphate	25973-55-1; 3864-99-1; 25637-99-4 (3194-55-6); 84-69-5; 37853-59-1; 79-94-7; 119344-86-4; 3147-75-9; 115-86-6
Polyvinyl-chloride, PVC	lead chromate molybdate sulfate red (C.I. Pigment Red 104); 1,2-benzenedicarboxylic acid, di-C6-10-alkyl ester; EC No. 201-559-5; DHNUP; UV-328; UV-327; UV-320; 4,4'-isopropylidenediphenol bisphenol A; DEHP; diarsenic trioxide; DBTC; DnHP; dipentyl phthalate; pentacosafluorotridecanoic acid; reaction mass of DOTE and MOTE; sulfuric acid, lead salt, dibasic; tetrabis(2-chloroethyl) phosphate; tribis(2-chloroethyl)	12656-85-8; 68515-51-5; 68648-93-1; 68515-42-4; 25973-55-1; 3864-99-1; 3846-71-7; 80-05-7; 117-81-7; 1327-53-3; 683-18-1; 84-75-3; 84-75-3; 131-18-0; 72629-94-8; 62229-08-7;

Material sub group	Substance (some short names)	CAS-Numbers
	phosphate; Tris(2-chloroethyl) phosphate; Trixylyl phosphate; BBP; DMEP; DBP; DIBP; Cadmium nitrate, [phthalato(2-)]dioxotributyl; Fatty acids, C16-18-, lead salts; 1-Methyl-2-pyrrolidone, lead; Dicyclohexyl phthalate (DCHP), dioxobis(stearato)tributy, pentabutyltrioxide sulfate, DOTE, ADCA; Tris(4-nonylphenyl, branched and linear) phosphite (TNPP) with ≥ 0.1% wt/wt 4-nonylphenol, branched and linear (4-NP); Cadmium sulfide, cadmium oxide, lead hydrogen arsenate, potassium hydroxyoctaoxo-dizincate dichromate; dibutylbis(pentane-2,4-dionato-O,O')tin; lead monoxide (lead oxide); Diarsenic pentaoxide; Dioctyl tin dilaurate, stannic, dioctylbis(coco-acyloxy) derivatives and all other stannic, dioctylbis(fatty acyloxy) derivatives, where C12 is the predominant carbon number of the fatty acyloxy unit; Medium-chain chlorinated paraffins (MCCP) (UVCB substances consisting of more than or equal to 80% linear chloroalkanes with carbon chain lengths in the range of C14 to C17); lead sulfate, basic; barium dibortetraoxide; Bis(2-ethylhexyl)tetrabromophthalate, covering any of the individual isomers and/or combinations thereof; 2-(Dimethylamino)-2-[(4-methylphenyl)methyl]-1-[4-(morpholin-4-yl)phenyl]butan-1-one; UV-326; UV-329; triphenyl phosphate; lead sulfochromate yellow; (C.I. Pigment Yellow 34)	12202-17-4; 12141-20-7; 115-96-8; 25155-23-1; 85-68-7; 117-82-8; 84-74-2; 84-69-5; 10325-94-7; 69011-06-9; 91031-62-8; 872-50-4; 7439-92-1; 84-61-7; 12578-12-0; 12065-90-6; 15571-58-1; 123-77-3; -; 1306-23-6; 1306-19-0; 7784-40-9; 11103-86-9; 22673-19-4; 1317-36-8; 1303-28-2; 3648-18-8, 91648-39-4; -; 12036-76-9; 13701-59-2; 119344-86-4; 3896-11-5; 3147-75-9; 115-86-6; 1344-37-2
Poly-carbonate, PC	UV-327; BPA; 4-tert-butylphenol; 1,1'-[1,2-ethanediylbis(oxy)]bis[2,4,6-tribromobenzene] (BTBPE); UV-326; UV-329; triphenyl phosphate	3864-99-1; 80-05-7; 98-54-4; 37853-59-1; 3896-11-5; 3147-75-9; 115-86-6
Polyacetal, POM	UV-328; DIBP	25973-55-1; 84-69-5
Polyamide, PA	lead dinitrate; C.I. Direct Black 38	10099-74-8; 1937-37-7
Polyethylene tere-phthalate, PET	2,2-Bis(bromomethyl)propane-1,3-diol (BMP); 2,2-Dimethylpropane-1-ol, tribromide derivative / 3-Bromo-2,2-bis(bromomethyl)-1-propanol (TBNPA); 2,3-Dibromo-1-propanol (2,3-DBPA)	3296-90-0 (BMP), 36483-57-5 and 1522-92-5 (TBNPA), 96-13-9 (2,3-DBPA)
Polyethylene ether, modified, PPE		
Poly-urethane, PUR	UV-328; 2,2'-Dichloro-4,4'-methylenedianiline; UV-320; Tris(2-chloroethyl) phosphate; Trixylyl phosphate; DIBP; 1-Methyl-2-pyrrolidone; Ethylenediamine (EDA); DIBP; diarsenic pentaoxide; 2,2-bis(bromomethyl)propane-	25973-55-1; 101-14-4; 3846-71-7; 115-96-8; 25155-23-1; 84-69-5; 872-50-4; 107-15-3; 84-

Material sub group	Substance (some short names)	CAS-Numbers
	1,3-diol (BMP); 2,2-dimethylpropane-1-ol, tribromo derivative / 3-bromo-2,2-bis(bromomethyl)-1-propanol (TBNPA); 2,3-Dibromo-1-propanol (2,3-DBPA); Bis(2-ethylhexyl)tetrabromophthalate, covering any of the individual isomers and/or combinations thereof; UV-329; Triphenyl phosphate	69-5; 1303-28-2; 3296-90-0 (BMP), 36483-57-5 and 1522-92-5 (TBNPA), 96-13-9 (2,3-DBPA); 3147-75-9; 115-86-6
Unsaturated polyesters, UP	UV-328; UV-320; lead nitrate; diarsenic trioxide; hexahydromethylphthalic anhydride and others; 1,3,5-tris(oxiran-2-ylmethyl)-1,3,5-triazine-2,4,6-trione (TGIC); 1,3,5-tris[(2S and 2R)-2,3-epoxypropyl]-1,3,5-triazine-2,4,6-(1H,3H,5H)-trione (β-TGIC), MOCA; 2,2-bis(bromomethyl)propane-1,3-diol (BMP); 2,2-dimethylpropan-1-ol, tribrom derivative / 3-bromo-2,2-bis(bromomethyl)-1-propanol (TBNPA); 2,3-dibromo-1-propanol (2,3-DBPA); UV-326; UV-329	25973-55-1; 3846-71-7; 10099-74-8; 1327-53-3; 25550-51-0; 19438-60-9; 48122-14-1; 57110-29-9; 2451-62-9; 59653-74-6; 101-14-4; 3296-90-0 (BMP), 36483-57-5 and 1522-92-5 (TBNPA), 96-13-9 (2,3-DBPA); 3896-11-5; 3147-75-9
Epoxy resins, EP	1,2-benzenedicarboxylic acid, di-C6-8-branched alkyl esters, C7-rich (DIHP), ethylenediamine (EDA), dicyclohexyl phthalate (DCHP), BPA, hexahydromethylphthalic anhydride, and others; 1,3,5-tris(oxiran-2-ylmethyl)-1,3,5-triazinane-2,4,6-trione (TGIC); 1,3,5-tris[(2S and 2R)-2,3-epoxypropyl]-1,3,5-triazine-2,4,6-(1H,3H,5H)-trione (β-TGIC), MOCA, 4-(1,1,3,3-tetramethylbutyl)phenol, ADCA, 4-tert-butylphenol, formaldehyde, oligomeric reaction product with aniline, phenol, alkylation products (mainly in the para position) with C12-rich branched alkyl chains from oligomerization, comprising all individual isomers and/or combinations thereof (PDDP); 2,2-Bis(bromomethyl)propane-1,3-diol (BMP); 2,2-Dimethylpropane-1-ol, tribrom derivative / 3-Bromo-2,2-bis(bromomethyl)-1-propanol (TBNPA); 2,3-Dibromo-1-propanol (2,3-DBPA); 2,2',6,6'-Tetrabromo-4,4'-isopropylidenediphenol (TBBPA); UV-326	2451-62-9; 59653-74-6; 25973-55-1; 101-14-4; 3864-99-1; 3846-71-7; 140-66-9; 80-05-7; (25550-51-0; 19438-60-9; 48122-14-1); 57110-29-9; 84-74-2; 107-15-3; 84-61-7; 107-15-3; 84-61-7; 80-05-7; 25550-51-0; 19438-60-9; 48122-14-1; 57110-29-9; 2451-62-9; 59653-74-6; 101-14-4; 140-66-9; 123-77-3; 98-54-4; 25214-70-4; -; 3296-90-0 (BMP), 36483-57-5 and 1522-92-5 (TBNPA), 96-13-9 (2,3-DBPA); 79-94-7; 3896-11-5
Fluoro-polymers, FP	APFO; henicosafluoroundecanoic acid; heptacosafluorotetradecanoic acid; PFDA and salts; PFOA; PFNA and its sodium and ammonium salts, PFHxS, pentacosafluorotridecanoic acid, PFOA, tricosafluorododecanoic acid, 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propionic acid, their salts and their acyl halides	2058-94-8; 3825-26-1; 376-06-7; (335-76-2, 3108-42-7, 3830-45-3); (375-95-1; 21049-39-8; 4149-60-4); -; 72629-94-8; 72629-94-8; 307-55-1; -

Risk and exposure analysis is a crucial aspect of the political regulatory process. Just because substances are hazardous does not necessarily mean that they pose a risk to humans. Are these hazardous additives even relevant? Are they not firmly enclosed in the plastic, meaning that there is no exposure?

In order to assess health risks, human exposure to harmful additives must be analyzed. Table 3, taken from a literature review on the use of recycled materials in consumer goods and potential chemical safety concerns [31], shows that many additives may cause human exposure due to the migration behavior of the substances.

Table 3: Migration risk and persistence in recycling, by analyte group, based on Danish EPA findings [31]

Analyte Group	Persistence in recycling	Migration risk
Heavy metals	Due to strong binding, expected to persist through mechanical recycling process. Mercury typically found in polyurethane, which cannot be mechanically recycled. The fate of mercury in feedstock recycling isn't known, but most mercury is expected to have evaporated by that point.	Typically strongly bound, therefore not expected to migrate. As a result, the "exposure to consumers must therefore be considered low". Mercury an exception: not chemically bound, will migrate and evaporate, leading to some exposure risk. This risk is judged to be small.
Perfluorinated chemicals	Only used in certain types of plastics, and the fate of these substances by recycling is unknown. They suggest that "recycling is not normally practised".	These substances are not chemically bound, meaning there is a risk of migration.
Flame retardants	The fate in recycling depends on the plastic. Plastics which can be mechanically recycled (including PVC, PP, PS) will retain flame retardants during recycling. Newer, alternative flame retardants are less studied, characterised by "a lack of knowledge regarding both applications and fate in the products as well as by subsequent recycling activities".	Migration risk depends on the substance. Reactive flame retardants are chemically bound, and are considered of less risk. Additive flame retardants (such as most BFRs) are not chemically bound and will migrate easily, "and may thus result in significant exposure of consumers".
Phthalates	The migration rate is low enough to assume the main part of the plasticiser added to the product will remain in it until end of life. If mechanically recycled, they will "also be present in recycled materials".	Migration of plasticisers to food well studied. Generally, all plasticisers "must be anticipated to migrate and the use in plastics should thus be considered a source of exposure to consumers".

Analyte Group	Persistence in recycling	Migration risk
Bisphenols	They judge that if Bisphenol A is present in mechanical recycling, it will remain in the plastic.	Based on its physical properties, it should be regarded as a semi-volatile compound, able to migrate out of plastics. With time, "the major part of the substance will probably be released by leaching to the surface followed by evaporation or removal by washing".
Formaldehydes	In mechanical recycling, unreacted formaldehyde will likely evaporate due to its low boiling point and the high vapor pressure. As a result, "the substance will most likely not be present in recycled materials".	Its physical properties suggest it should migrate strongly. This strong evaporation could lead to occupational exposure.

If these analyses of migration and exposure are confirmed, we would have a very big problem to solve, because plastics, unlike any other chemical carrier, are used extensively and often very close to humans—with measurable consequences. Human biomonitoring data in Europe show that, in terms of quantity, relevant additives are detectable in humans as "body burden" in concentrations that are sometimes cause for concern ([32], among others). For example, many phthalates, bisphenols, benzophenones, parabens, phenolic antioxidants, as well as older brominated and organophosphate flame retardants and polyfluorinated substances (PFAS) have been detected in human blood, urine, and tissue in various regions of the world. A study by the European Environment Agency [33] showed that most of the people tested in the EU in human biomonitoring had excessive levels of the plastic additive bisphenol A. Fluorinated additives are also viewed with concern: PFOS and PFOA are already banned as individual substances, and a ban on the entire group (PFAS) is currently being pursued in Brussels.

3. Plastics recycling

3.1. Preliminary remark

At first glance, recycling plastic waste does not appear to increase the exposure to additives or chemicals described above, as only the actual variety of substances already present re-enters the system. During recycling, all of the substances mentioned re-enter a product [34]. One might ask: since these substances are also contained in products made from virgin plastics, what is the problem with recycling?

As shown above, some particularly critical or high-risk substances are now banned and, for good reason, may no longer be used in virgin plastics. However, these so-called “legacy chemicals” are still contained in products that continue to be used in the technosphere (or migrate from them into the environment). Whenever plastics contaminated with these substances are recycled, they re-enter the plastics cycle with the recyclate. For this, the authors use the term **"risk cycle"** [8], based on the EU project RISKCYCLE (Risk-based management of chemicals and products in a circular economy at a global scale [35]). Which areas of application are particularly relevant for the risk cycle? Since the introduction of REACH [36] and the POPs Regulation in Europe [37], numerous bans and restrictions have been imposed on additives that come into direct or indirect contact with humans via plastic products [38,39]. It can be assumed that these "legacy substances" are the substances that pose the greatest risks, that's why they were banned. Compliance with these limit values is therefore of utmost importance from a health perspective compared to the other risks posed by plastic additives. Table 4 provides an overview of the substances that fall into this category.

Table 4: Legacy additives – substances whose use as additives is prohibited or regulated

Function	Substance group	Substance(s)	Effect/risk
Plasticizers	Phthalates	DEHP, DBP, BBP, DIBP	hormonal effect → reproductive hazard
Flame retardants	Halogen compounds	Polybrominated and polychlorinated compounds, chlorinated paraffins (CP)	carcinogenic, bioaccumulative, developmental neurotoxic effects
Stabilizers	Heavy metals	cadmium, lead, tin	nephrotoxic, carcinogenic
UV-Stabilizer	Benzo-triazole	UV-328 (= 2-(2H-benzotriazol-2-yl)-4,6-ditert-pentylphenol)	harmful to the liver and kidneys, endocrine effects
Surface treatment, water, grease, and dirt repellency, as well as high temperature and chemical resistance, processing aids	PFAS	In particular, PFOS, PFOA, and their salts	Possibly carcinogenic, damages the immune system, concerns regarding endocrine effects
Colorants for plastics and especially textiles	Organic pigments	Certain azo dyes (form aromatic amines) such as benzidine and benzidine-based dyes, p-aminoazo-benzene, 4-chloroaniline, 2-naphthylamine, and many more; carbon black (in case of high contamination with PAH)	Possibly carcinogenic
Biocides, insecticides, especially for textiles	Organo-halogen compounds	Lindane, chlorobenzenes such as HCB, chlordecone, various chlorinated phenols such as PCP, triclosan, dimethyl fumarate (DMFu), TBT, etc.	Mutagenic, carcinogenic, or endocrine disrupting, depending on the substance

For which areas of application or plastic products is Risk Cycle highly relevant? The hazards of risk cycle are particularly high for recycled products that come into close contact with humans.

3.2. Children's toys

The most relevant are certainly recycled products that come into direct contact with people's mouths or skin. Children's toys are therefore subject to particularly high requirements that must be observed [40], because in addition to direct contact and the sucking and licking behavior of small children, the special sensitivity of the developing child's organism must also be taken into account [41]. In 2025, the EU Commission once again significantly tightened the requirements for the absence of harmful substances in children's toys by means of a regulation [42]. In addition to substances with CMR properties, substances that damage the endocrine system, substances with specific organ toxicity, and substances that cause sensitization of the respiratory tract or skin are also prohibited. The intentional use of per- and polyfluoroalkyl substances (PFAS) [43] and the most hazardous types of bisphenols will also be prohibited in the future. A ban will also apply to allergenic fragrances in toys for children under three years of age and in toys intended to be placed in the mouth.

Furthermore, Annex VI introduces a digital product passport, which must also contain a list of the allergenic fragrances listed in Annex II, provided that these are present in the toy or any of its components in concentrations exceeding 10 mg/kg. With the mandatory CE marking (Conformité Européenne), the manufacturer also confirms that the toy meets the essential requirements of the EU directives regarding safety, health, and environmental protection, including those listed in Annex II of the regulation for heavy metals, N-nitrosamines and N-nitrosatable substances, as well as certain flame retardants, plasticizers, and monomers. This should mean that **the use of recycled plastics in children's toys will no longer be a legal option** in the future.

Even without the use of recycled materials, monitoring children's toys is not easy. Just a few years ago, a study of consumer products and children's toys containing black plastics from all continents of the world yielded very worrying results [44]. More than 60% of the products analyzed had dioxin levels of more than 1 µg TEQ/kg. The authors thus confirm their own older research results [45,46,47]. And due to the increasing imports of cheap plastic goods from China via online platforms, some highly polluting products are ending up in children's hands. According to the EU Commission, around twelve million parcels arrived in the EU every day in 2024 – a significant increase compared to the previous two years [48]. In view of this tsunami of parcels, especially from China, the enforcement of chemical legislation in EU member states is overwhelmed and unable to ensure adequate health protection.

3.3. Food Contact Material (FCM)

Polyethylene (PE) is a plastic that is widely used in food packaging and similar applications (hereinafter referred to as the food contact material sector, FCM). In a meta-study on PE in the FCM sector, British scientists evaluated 116 studies that investigated the migration of additives into food. They found 211 substances that had migrated from PE food packaging into food. Only 25% of these substances were permitted in the EU for the FCM sector at the time of publication (2023) [49]. A further review of 470 scientific studies on plastic packaging for food shows that of 1,346 chemicals examined, 1,086 can migrate into food under certain conditions [50].

The EU has imposed numerous restrictions and requirements on FCM plastic packaging for over ten years. For example, a positive list has been in place for the manufacture of FCMs for many years [51]. Only substances listed here may be used as additives for plastic FCMs. Since 2022, the use of recyclates from post-consumer waste has no longer been permitted [52,53,54]. The only exception is for plastic waste such as PET bottles. "… mechanical PET recycling and product loops in a closed and controlled chain may be considered as suitable recycling technologies to recycle waste plastic into plastic meeting the requirements" concerning FCM [52]. The input for PET recycling may contain a maximum of 5% of materials and objects that have come into contact with non-food materials or substances [55].

The FCM regulation also covers packaging that may come into contact with foodstuffs according to "foreseeable conditions of use".[4] Therefore, our precautionary position is that packaging should comply with the FCM standard overall.

The FCM regulations are relatively strict. Among other things, only additives that comply with defined migration limits are permitted [51]. Furthermore, recycling facilities for FCM are subject to strict requirements and controls. Since it is not possible in practice to ensure that recycled materials comply with food law requirements, the EU focuses on the requirements for the respective recycling facilities. Currently, two technologies are considered suitable: mechanical PET recycling and recycling from a closed and controlled recycling chain [53,56]. A "high degree of purity" was required for recycled materials in 2025 [57]. The ban on bisphenol A in food packaging, which was also adopted in 2025, alone makes it clear how difficult this market has become for the use of recycled materials [58]. **We therefore conclude that FCM should not use recycled materials of unclear origin.**

3.4. Indoor materials

In temperate climates, people spend more than 90% of their lives indoors. Therefore, indoor materials must be assumed to be subject to intensive consumer contact. Substances that are now banned (e.g., polybrominated diphenyl ethers, PBDE) are finding their way back to consumers via recycling, e.g., in the backing of carpets [59], in concentrations (see Table 5) that are in some cases far higher than those permitted for new materials [37]. For example, plastics used as part of indoor consumer products (appliances [60], furniture, floor coverings [61,62], building materials) can contain high concentrations of pollutants and cause emissions through evaporation (see human biomonitoring [32] and [63,64]).

Table 5: Summary of PBDE values in 26 carpet backings manufactured (with) recycled material compared to the EU's low POP limits for new material (10 ppm in each case) [59]

Polybrominated diphenyl ethers	No. of samples containing specific BDE	Range (ppm)	No. of samples >10 ppm
TetraBDE	19 (73%)	1–398	13 (50%)
PentaBDE	19 (73%)	1–732	13 (50%)
HexaBDE	14 (54%)	1–81	12 (46%)
HeptaBDE	10 (38%)	1–5	0 (0%)

[4] "… can reasonably be expected to be brought into contact with food or to transfer their constituents to food under normal or foreseeable conditions of use" (Regulation (EC) No 1935/2004, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:338:0004:0017:en:PDF)

In the past, leather, for example, was treated with a number of substances that are now banned: chromium, alkylphenols, trichlorophenol, PCP, and special azo dyes [35]. UV-328 (CAS 25973-55-1) is a widely used UV absorber from the phenolic benzotriazole group that protects plastics and coatings from light-induced degradation. More recently, PFAS substances have been added to this list. In the past, many particularly critical substances such as heavy metals, defined flame retardants, and plasticizers [35] were used in plastics in electrical appliances. Plastic waste from this sector is among the most heavily contaminated materials. For home textiles, see also the next chapter.

High concentrations of phthalates and phthalate substitutes are found in house dust, even though many of these substances have been banned for years. In 2024, the German Federal Environment Agency issued a clear warning[5] when it published the results of a recent study of urine samples from kindergarten children in North Rhine-Westphalia [65,66]. **Overall, therefore, the use of recycled materials for indoor products cannot be recommended.**

3.5. Textiles and footwear

Almost 70% of all textiles are made from synthetic fibers. There is probably no plastic product that comes into closer contact with humans than textiles. Of course, the intensity of contact depends on the type of apparel (outerwear, underwear) and how long it is worn for.

Textiles are chemically treated – a number of the substances used for this purpose have now been banned. In the past, for example, flame retardancy was a common treatment for textiles [67,68,69]. Organotin additives were also incorporated into the fabric to reduce the formation of odors caused by sweat. PFAS was used for surface treatment. Triclosan and nanosilver can be found in textiles as problematic biocides [70]. Black textiles require particular attention because the dye used (carbon black) may be chemically contaminated. Furthermore, some azo dyes pose risks (release of amine). Dyes may also contain heavy metals [71].

In its 2012 statement on apparel [72], the German Federal Institute for Risk Assessment (Bundesinstitut für Risikobewertung, BfR) provides an overview of several classes of auxiliary and finishing agents for apparel that are not related to dyeing (Table 6) and of the main dyes and auxiliary agents used in dyeing (

Table 7).

The problem of the increasing volume of waste textiles and shoes, the growing pollution of the environment with synthetic textile waste, and the current resource-inefficient waste management of this waste have prompted the EU to take action. In October 2025, the revised EU Waste Framework Directive, with a focus on textiles, came into force [73]. All member states are required to introduce their own Extended Producer Responsibility (EPR) system for textiles and shoes in accordance with common rules applicable throughout the EU. Under these systems, textile and footwear manufacturers pay a fee for each product placed on the market. This fee finances collection systems and the management of collected textiles, including their reuse, preparation for reuse, recycling, and disposal. This directive aims in particular to strengthen textile recycling (fiber to fiber) and to combat the practices of 'ultra-fast fashion' and 'fast fashion' [74]. The specific requirements, including those relating to

[5] "You shouldn't find a substance like this in the body, but we do. ... It's a problem of considerable magnitude." ("So einen Stoff dürfte man nicht im Körper finden und wir finden ihn. … Es ist ein Problem größeren Ausmaßes." https://www.mdr.de/nachrichten/sachsen-anhalt/gefaehrliche-weichmacher-in-urin-umweltbundesamt-100.html

substances of concern (risk cycle), are to be regulated in the EU Ecodesign Regulation, which is currently being implemented. **Here too, it should be stipulated that fibers contaminated with prohibited substances may not be recycled.**

Table 6: Some categories of auxiliaries and finishing agents for garment textiles without reference to dyeing [72]

Name	**Chemistry**	**Comments**
Agents for improving crumpling and wrinkling behaviour	*N*-Methylol derivatives (formaldehyde)	Shape stability, "high grade finishing"
Catalysts for crumpling and wrinkling-free finish	Dialkylated tin derivatives	
Gripping agents	e.g. polymers	Up to 20% of textile product weight
Flame retardants	e.g. organophosphates	Protective clothing
Anti-microbially active agents	Biocides	Footbed, socks (sanitised)
Phagodeterrents	Permethrin	Preservation (transport, storage of uniforms)
Waterproofing agents	Paraffins, fluoropolymers	Water, oil and dirt repellent
Anti-felting finish	Polymers	Wool
Conditioning agents	Oils, greases	Surface enhancement
Lustering finishing agents	Waxes, paraffins	
Coating agents	Polymers	

Table 7: Dyes and auxiliaries for dyeing [72]

Name	**Chemistry**	**Dyeing principle, function**
Dye		
Reactant-type dyes	Water-soluble	Covalent binding to the fibres
Disperse dyes	Lipophilic azo dyes	Balanced distribution, carriers, chemical fibres
Acid and base dyes		Binding via ion exchange
Mordant agents		Fixation via chromium salts
Direct dyes	Water-soluble	Deposition in cavities
Vat dyes	Anthraquinones	Redox dyeing process, high degree of fastness in use
Sulphur dyes		
Development dyes (naphthols)	Azo dyes	Diazotised amine, coupled on fibre

Name	Chemistry	Dyeing principle, function
Pigments	Azo dyes, anthraquinones	Not readily soluble
Dyeing auxiliaries		
Dye accelerators (carriers)	Aromatics	Chemical fibres, disperse dyes
Levelling agents	Surfactants	Uniform coloration
Crease prevention agents	Polyglycol ethers	
After-treatment agents	Surfactants, resins	Colour fastness
Binding agents	Copolymers	Pigment dyeing
Thickening agents	Copolymers	Pigment printing
Dispersing agents	Polymers, surfactants	Pigment dyeing
Fixation accelerators	Oxethylates	Pigment printing

Particularly relevant to the textile sector are the now banned additives PFOS and PFOA [75] and their later substitutes from the group of polyfluorinated alkyl substances (PFAS), which are used to make fabrics water-repellent, as well as triclosan and hexabromocyclododecane (HBCDD), which were used as biocides or flame retardants [35]. In the authors' opinion, the material recycling of textiles of unclear origin cannot be recommended.

4. Possible solutions

4.1. Higher limits for recycled products?

The NGO Health and Environment Alliance (HEAL) demands: "Regulations on recycled materials should be the same as for virgin materials" [76, p. 22]. Or “Zero Waste Europe” also takes a clear stance: "In a clean and safe circular economy, all materials and products should be free from harmful chemicals in order to ensure their safety for both primary and secondary uses" [16]. The EU Commission also agrees with this in principle [77], but adds: "However, there may be exceptional circumstances where a derogation to this principle may be necessary. This would be under the condition that the use of the recycled material is limited to clearly defined applications where there is no negative impact on consumer health and the environment, and where the use of recycled material compared to virgin material is justified on the basis of a case by case analysis."

In recent years, the EU Commission has repeatedly raised the limit values for recycled materials. Table 8 shows selected examples.

The authors share the view of various NGOs that the permitted concentrations of hazardous or concerning substances in recycled materials must not be higher than for virgin plastics.

Table 8: Selection of regulations where higher burdens for recycled materials were considered acceptable by the EU

Substance	Scope of application or products	Year
Lead	PVC products containing recycled rigid PVC, if the lead concentration is less than 1.5% by weight of the **recycled rigid PVC**, until 28 May 2033: a) profiles and sheets for exterior applications in buildings and civil engineering works, excluding decks and terraces; b) profiles and sheets for decks and terraces, provided that the recovered PVC is used in a middle layer and is entirely covered with a layer of PVC or other material for which the concentration of lead is lower than 0.1% by weight; c) profiles and sheets for use in concealed spaces or voids in buildings and civil engineering works (where they are inaccessible during normal use, excluding maintenance, for example, cable ducts); d) profiles and sheets for interior building applications, provided that the entire surface of the profile or sheet facing the occupied areas of a building after installation is produced using PVC or other material for which the concentration of lead is lower than 0.1% by weight; e) multi-layer pipes (excluding pipes for drinking water), provided that the recovered PVC is used in a middle layer and is entirely covered with a layer of PVC or other material for which the concentration of lead is lower than 0.1% by weight; f) fittings, excluding fittings for pipes for drinking water.	2023 [78]
Cadmium	… shall not apply to: – mixtures produced from PVC waste, hereinafter referred to as "**recovered PVC**", – mixtures and articles **containing recovered PVC** if their concentration of cadmium (expressed as Cd metal) does not exceed 0.1% by weight of the plastic material in the following **rigid PVC applications**: (a) profiles and rigid sheets for building applications; (b) doors, windows, shutters, walls, blinds, fences, and roof gutters; (c) decks and terraces; (d) cable ducts; (e) pipes for non-drinking water if the recovered PVC is used in the middle layer of a multilayer pipe and is entirely covered with a layer of newly produced PVC in compliance with paragraph 1 above.	2011 [79]

Substance	Scope of application or products	Year
DEHP (Diethylhexyl phthalate)	Approved use: • Formulation of **recycled soft poly(vinyl chloride) (PVC)** containing DEHP in compounds and dry-blends. • Industrial use of **recycled soft PVC** containing DEHP in polymer processing by calendering, extrusion, compression and injection moulding to produce PVC articles except: toys and childcare articles; erasers; adult toys (sex toys and other articles for adults with intensive contact with mucous membranes); household articles smaller than 10 cm that children can suck or chew on; consumer textiles/clothing intended to be worn against the bare skin; cosmetics and food contact materials regulated under sector-specific Union legislation.	2016 [80]
HBCDD (Hexabromo-cyclododecane)	• POPs regulation, Annex I, Part A: Specific exemption on intermediate use or other specification: 2. **Expanded polystyrene articles** containing hexabromocyclododecane already in use in buildings before 21 February 2018 in accordance with Commission Regulation (EU) 2016/293 (5) and Commission Implementing Decision No 2016/C 12/06 (6), and **extruded polystyrene articles** containing hexabromocyclododecane already in use in buildings before 23 June 2016 may continue to be used. Article 4(2), third and fourth subparagraphs shall apply to such articles. • POPs regulation, Article 7 para 4: (a) **waste** containing or contaminated by any substance listed in Annex IV may be otherwise disposed of or **recovered** in accordance with the relevant Union legislation, provided that the content of the listed substances in the waste is below the concentration limits specified in Annex IV; concentration limit in Annex IV for HBCDD: 1 000 mg/kg, subject to review by the Commission by 20 April 2019.	2019 [37]
Nonylphenol ethoxylate (NPE)	1. Shall not be placed on the market after 3 February 2021 in textile articles which can reasonably be expected to be washed in water during their normal lifecycle, in concentrations equal to or greater than 0,01% by weight of that textile article or of each part of the textile article. 2. Paragraph 1 shall not apply to the placing on the market of **second-hand textile articles** or of new textile articles produced, without the use of NPE, **exclusively from recycled textiles**.	2016 [81]

Substance	Scope of application or products	Year
PBDE (poly-brominated diphenyl ether)	a) Limit value for the sum of tetra-, penta-, hexa-, hepta-, or decaBDE: **10 mg/kg** upon entry into force of this Regulation where they are present in mixtures or articles, except for food contact materials subject to Regulation (EC) No 1935/2004; b) by way of derogation from point (a), **500 mg/kg** upon entry into force of this Regulation, **350 mg/kg** as of 30 December 2025 and **200 mg/kg** as of 30 December 2027 where they are present in mixtures or articles containing or **made of recovered material** containing tetra-, penta-, hexa-, hepta- or decaBDE, **except for food contact materials** subject to Regulation (EC) No 1935/2004; c) by way of derogation from point (a), **500 mg/kg** upon entry into force of this Regulation, **350 mg/kg** as of 30 December 2025 and **10 mg/kg** as of 17 May 2027 where they are present in **toys** subject to Directive 2009/48/EC, or in any **product facilitating children's** seating, sleep, relaxation, hygiene, changing and general body care, feeding, sucking, transportation and protection, containing or made of **recovered material** containing tetra-, penta-, hexa-, hepta- or decaBDE, except for food contact materials subject to Regulation (EC) No 1935/2004.	2025 [37]
PFAS (per- and polyfluoroalkyl substances)	Of the **p**er**f**luorinated and polyfluorinated **a**lkyl substances (PFAS), PFOS (**p**er**f**luoro**o**ctane **s**ulfonic acid) and PFOA (**p**er**f**luoro**o**ctanoic **a**cid) are particularly critical [75]. PFOS and PFOA are both considered POPs and were largely banned in the EU in 2010 and 2020 [82,83]. Other polyfluorinated alkyl substances have been used as substitutes, but their hazardousness is unclear. The entire group of PFAS has therefore been subject to closer scrutiny [84]. For example, Article 5 of the recently adopted EU Packaging Regulation [29] imposes strict restrictions on PFAS. Whether there will be any exemptions for recycled materials is currently under discussion. The ECHA has already made such a proposal for textiles, which would postpone the entry into force of the restrictions on recycling for up to 13.5 years [43,85]. In the regulatory dossier recently submitted by ECHA, it is proposed that recycled plastics be exempted from compliance with the specified PFAS limits for the entire PFAS group for the next 23.5 years [43]. However, FCM and children's toys are excluded from this exemption. The EU Commission is expected to make a final decision on the dossier in 2027.	2025 [43,85]

4.2. No use of recycled plastics in consumer products?

Due to the intensive consumer contact described above, we recommend that, until further notice, no recycled materials from post-consumer plastic waste be used in children's toys, FCM/packaging, indoor consumer products, and textiles. Our recommendation will certainly provoke opposition. We therefore summarize below the studies known to us from recent years that have found high levels of hazardous or prohibited pollutants in recycled materials [e.g., 49,59,86,87,88,89,90,91,92,93,94]. Numerous other scientific publications are also documented in publications by IPEN [12,45,95,96,97,98,99] and GREENPEACE [100] in particular.

Is it likely that such problems will ease in the coming years as the amount of old plastics contaminated with banned substances gradually decreases? The answer depends, of course, on the type of plastic items and their respective "lifespan". The service life varies from less than a month for disposable products, several months for packaging, several years for electrical appliances, and up to 50 to 100 years (or longer) for components such as windows, profile boards, walls, or pipes. Therefore, in theory, relief for disposable products or packaging would be expected sooner than for most other products. However, as the evaluation of substances and additives used in packaging is not yet complete (see section 3.3), this argument cannot be accepted across the board. The work plan of the European Chemicals Agency (CoRAP – Community Rolling Action Plan [101]) alone shows that substance evaluation is still in full swing.

The evaluation of (existing) substances under REACH has been ongoing for around 20 years, which immediately raises another question: When will there be clarity regarding the evaluation of substances that have not yet been conclusively evaluated? The answer to this question points to the shortcomings of the current REACH system. The submission of substance dossiers, which has been taking place since 2007, has revealed glaring data deficiencies. Furthermore, the substance evaluation by the Chemicals Agency took far too long, as did the authorization and bans. No wonder, then, that the EU Commission itself sees the need for a REACH reform and has announced a proposal for an amendment. But ideas about what this reform should look like vary widely [102]. All in all, REACH has identified several hundred substances over the last 20 years that we should (or must) avoid in plastics, but the complete processing of the chemical diversity will only be largely completed in a few years, provided that the amendment accelerates the work processes. Therefore, there is still no reason to relax on the issue of the risk cycle.

Another argument focuses on the specific situation with packaging plastics. It is pointed out that the use of particularly problematic additives has tended to occur in durable products such as those used in the construction sector. Today's packaging in particular is less problematic, partly due to the new FCM requirements. However, as shown above, today's packaging and its recyclates are not “clean.” This is also demonstrated by the recently enacted EU Packaging Regulation [29], which in Article 5 (1) limits the presence of additives and other substances of concern in packaging, but also in recyclates, to a minimum and which in para 2 announces a report for the end of 2026 on which substances of concern are relevant. In autumn 2025, the ECHA conducted an investigation on behalf of the EU Commission to determine which substances are used in packaging plastics [103]. The initial results are to be submitted to the Commission by March 20, 2026 [104].

Another development in recent years will also keep the topic of the “risk cycle” and the need for a moratorium on the agenda: online platforms from China. Many of the cheap plastic items supplied from there are contaminated with hazardous substances that are banned in the EU [105,106,107,108]. These products are fast-moving and quickly become waste.

And given this unclear risk situation, the highest priority is to ensure that at least the prohibited substances are not "recycled". This is our central justification for the current solution strategy: **No use of recycled plastics in consumer products.**

4.3. Avoiding "regrettable substitutions"

Nor can we be sure that the substitution of hazardous or concerning substances with "better" substances has always been successful. The long "skid-marks" in the "risk cycle" is also due to the fact that chemical regulation has been too hesitant in the past and that substitutes have not always been or are not always less problematic. In this case, there are many reasons to regret the substitution in the end ("regrettable substitution" [109, 110]). It is particularly problematic when the substitute is selected from the same chemical group (e.g., ortho-phthalates or PFAS). The so-called single-substance approach taken by the EU to date and the replacement of well-tested substances with related but little or less well-studied substances has therefore perpetuated the issue of "chemical legacy" to the present day [111].

Strategically, therefore, a different approach would be more effective, one that is currently being promoted by individual EU member states specifically for the 10,000 or so perfluoroalkyl and polyfluoroalkyl substances (PFAS). This new approach is known as “grouping” and can, of course, also be applied to other groups of substances. This approach has been advocated for many years by the scientific community [112,113,114,115] and also by NGOs [116]. The EU Commission has also opened up to the group approach as part of its "Chemicals Strategy for Sustainability" (CSS) [77,117]. This approach was already applied in the PFAS Regulation [118] that came into force on October 10, 2025 (for textiles, leather, furs and hides, paper and cardboard as FCM, cosmetic products, and firefighting foams).[6]

4.4. Waiting for the digital product passport (DPP)

Mechanical and material recycling are not only confronted with the risk cycle problem. In practical terms, recyclers also have little access to reliable information that would enable them to assess the additives in their waste input. This is unsatisfactory in terms of good practice, because the manufacture of a high-quality product requires, among other things, sufficient additives. But how can this work if the recycler has no information about the additives in their

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[6] Undecafluorohexanoic acid (PFHxA), its salts and PFHxA-related substances
a) having a linear or branched perfluoropentyl group with the formula C_5F_{11}- directly attached to another carbon atom as one of the structural elements; or
b) having a linear or branched perfluorohexyl group with the formula C_6F_{13}-.
The following substances are excluded from this designation:
a) C_6F_{14};
b) C_6F_{13}-C(=O)OH, C_6F_{13}-C(=O)O-X’ or C_6F_{13}-CF_2-X’ (where X’ = any group, including salts);
c) any substance having a perfluoroalkyl group C_6F_{13}- directly attached to an oxygen atom at one of the non-terminal carbon atoms.
… 9. For the purposes of this entry, PFHxA-related substances are substances that, based on their molecular structure, are considered to have the potential to degrade or be transformed to PFHxA.

goods? This is one reason why, as a result, the current practice is preferably downcycling, where quality is less important. For recycling at the same level, the recycler must essentially be placed in the same situation as the compounder of virgin plastics. They need to know what additives have been added to their material and can then use the above-mentioned "chemical construction kit" to produce the quality required for the respective application.

With the new Ecodesign for Sustainable Products Regulation (ESPR) [119], information on the additives or substances of concern used, including their respective concentrations, is likely to be passed on in future throughout the product processing chain, right up to the recycling stage. The digital product passport[7] is the key tool for this transfer of information. According to Article 7 (5), the DPP must contain at least the following information:

(a) the name or numerical code of the substances of concern present in the product, as follows:
    i. name in the International Union of Pure and Applied Chemistry (IUPAC) nomenclature, or another international name when IUPAC name is not available;
    ii. other names, including usual name, trade name, abbreviation;
    iii. European Community (EC) number, as indicated in the European Inventory of Existing Commercial Chemical Substances (EINECS), the European List of Notified Chemical Substances (ELINCS) or the No Longer Polymer (NLP) list or the number assigned by the European Chemicals Agency (ECHA), if available and appropriate;
    iv. the Chemical Abstract Service (CAS) name and number, if available;
(b) the location of the substances of concern within the product;
(c) the concentration, maximum concentration or concentration range of the substances of concern, at the level of the product, its relevant components, or spare parts;
(d) relevant instructions for the safe use of the product;
(e) information relevant for disassembly, preparation for reuse, reuse, recycling and the environmentally sound management of the product at end-of-life.

According to Article 2, point 27, "substances of concern" include

- substances on the "candidate list" according to the REACH Regulation (1907/2006) (SVHC),
- substances classified as particularly hazardous according to the CLP Regulation (1272/2008),
- organic pollutants classified as persistent according to the POPs Regulation (2019/1021), and
- a substance that negatively affects the reuse and recycling of materials in the product in which it is present (new category).

A DPP containing the aforementioned information would ensure the necessary transparency for recycling in the future. This would eliminate the need for the moratorium on the use of recycled materials, we recommended above, at least for "fast moving" consumer products such as packaging.

Until this regulation comes into effect, representative, comprehensive laboratory monitoring of recycling activities, particularly of output materials (products), could avoid the moratorium

[7] Resp. the digital material passport (DMP)

during the transition period, too. The industry is working on its own solutions to help plastic recyclers efficiently monitor substances of concern in their products in accordance with legal requirements. Plastic Recyclers Europe (PRE) offers a voluntary industry standard [120], which is not publicly available, however. According to PRE, the PRE 1000 standard comes with an online tool that lists every substance of concern, along with information on the thresholds in legal regulations such as REACH, POP, CLP, etc., and details on whether the substance in question is likely to be present in plastic waste and, if so, how likely.

5. Conclusion

Today's practice of material recycling of plastics is mainly what is known as downcycling and is therefore a waste of (carbon) from the perspective of resource conservation and climate protection.

Material recycling at the same level should be suspended for contact-sensitive products until further notice (moratorium) because the risk of introducing prohibited additives into new products is too high (risk cycle). It is often argued that this risk for “fast-moving” plastic products will be reduced in the coming years as contaminated products are phased out. We show that material assessment is far from complete. Although European chemicals policy has made significant progress since the introduction of REACH (2007), the discussion about the need for a REACH amendment also shows that much of the work still lies ahead [102]. We must therefore expect more bad news in the coming years regarding plastic additives that are commonly used today. [8] Another risk is the unregulated imports from online platforms (12 million packages a day), some of whose products are contaminated with additives that are banned in the EU and will contaminate the entire pool of plastic waste.

In the short term, **representative, comprehensive laboratory monitoring**, particularly of recycled materials and output materials (products), could help. The industry offers a wide range of solutions in this area.

In the medium term, the planned **digital product passport**, which is intended to document the chemical composition of products, would also help to enable high-quality recycling (see Article 2 (27) of the Ecodesign Regulation). Additives have been and continue to be needed to give polymers the properties that have made plastics so successful as a material. And we will continue to learn that the innovations of the future also depend on these substances. So, there will be no "no, thank you" strategy for additives in plastics. Polymers without additives, as we have known for 75 years now, do not work. So the only possible answer is to have all additives tested in accordance with legally established regulations. Unfortunately, we are still not there yet. To speed up substance evaluations, there are proposals (grouping, hazard-based assessment, generic risk analysis), but these are viewed critically by industry.

Even if the REACH processes are accelerated significantly in the coming years, it will not be possible to eliminate harmful substances from products entirely; however, the risks will gradually be reduced. The circular economy will therefore have to live with the risk cycle for the foreseeable future. But are the EU's attempts to keep recycled materials marketable by

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[8] See the TNPP example mentioned above, a very common additive for packaging films, which was recently classified as an SVHC [ECHA, 2025].

raising limit values the right way forward? In our view, allowing recycled materials to contain ten or a hundred times more pollutants than new materials is not an adequate solution. This shifts risks and responsibilities and covers up the problem. Conflicting goals, such as strengthening the circular economy on the one hand and reducing the dissipation of hazardous substances on the other, cannot always be resolved. Johansson [121] therefore proposes as a solution to abandon the win-win paradigm of circular economy rhetoric and to adopt a more open and flexible approach. He proposes a "reflexive circular economy" that can withstand conflicting goals, i.e., one that does not suppress the data and facts we have compiled here, but rather processes and redesigns them. A reflexive understanding also allows for setbacks and waste that cannot be recycled (in terms of materials) but must be disposed of (means incineration / waste-to-energy).

In this understanding, a moratorium on the use of recycled materials in contact-sensitive applications is not a "toxic" attack on the circular economy, but rather a temporary solution until greater transparency is established throughout the entire value chain. And as if this had been heard, at the end of 2025, the EU Commission opened a consultation process for its proposal on plastic recycling, which ran until January 26, 2026 [122,123]. According to this proposal, recycled materials and products made from recycled materials must in future comply with all relevant material law requirements that virgin plastics must also comply with. This is to be ensured by close-meshed, comprehensive laboratory monitoring of both the input and, in particular, the output of recycling, and the results are to be documented electronically and made available to the entire value chain. If adopted, the proposal will create significantly more transparency.

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