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DISCUSSION

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# How should we deal with the interfaces between chemicals, product and waste legislation?

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**Abstract**

**Background:** In the 7th Environment Action Programme, the European Commission targets two essential goals in the handling of substances and materials known by the buzzwords "non-toxic environment" and "circular economy". There are numerous interfaces in product, waste and chemicals legislation in these two areas. This leads to conflicting objectives, e.g. with regard to the classification of waste in analogy to chemicals as well as at the border between waste and secondary raw materials that are further processed into products.

**Results:** We investigate how these conflicting objectives can be mitigated or resolved. In our view, it is necessary to provide operators in the waste management sector with considerably more information on the composition of used products than before; this should include not only hazardous substances but also materials that interfere with the recycling process as well as recyclable or valuable materials. Waste management legislation largely follows risk considerations—a 1:1 transfer of hazard classifications of chemicals and products to waste management would be counterproductive to achieving the Commission's objectives. In the case of contaminated secondary raw materials, their input into products can be justified in specific cases. However, this requires a risk assessment that includes in particular physicochemical factors, patterns of utilisation and controlled collection routes. Internationally recognised lists of secondary materials are an important condition for determining end-of-waste status and thus for increasing material recycling.

**Conclusions:** A common guiding principle for chemicals policy and waste management is urgently needed.

## "Circular economy" and "toxic free environment": contradicting goals?

With its 7th Environment Action Programme (EAP) of November 2013, the European Commission declared two overarching goals with respect to chemical safety and waste management that are to be achieved simultaneously by 2020: "Non-toxic environment" and "circular economy". Regarding "non-toxic environment", the aim is to safeguard [1] public health and environmental integrity by reducing hazardous substances in the environment, *inter alia* endocrine disruptors, nanoparticles, pesticides and hazardous chemicals in products. The Commission intends to achieve this inter alia by "non-toxic material cycles" This points to the Commission's second important objective of "circular economy" (further information in Additional file 1: S1).

Both goals come into conflict if the two keywords "non-toxic environment" and "circular economy" are taken literally. How can toxics in recycled products be avoided if primary products contain ingredients that are no longer permitted? How can material cycles be closed if products contain a multitude of substances and additives that can only be separated with high energy input, if at all? This conflict is not new. When negotiating the Stockholm Convention on Persistent Organic Pollutants (POPs) it was discussed how to deal with products containing POPs when becoming waste. Since POPs are considered to be not manageable, in Article 6 of the Convention stipulates that POPs containing wastes are

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"disposed of in such a way that the persistent organic pollutant content is destroyed or irreversibly transformed" [2]. The EU POPs regulation 850/2004 therefore lists very low limit values for POPs content in waste. However, this strict provision cannot be the pattern for all hazardous contaminants in waste [3]. An estimation of the risks considering the likely exposure is necessary when assessing secondary raw materials to find the right balance between resource conservation and chemical safety. The problems with these conflicting goals already start with the definition and the scientific basis of "non-toxic" and "material cycles":

- The REACH regulation [4] does not know the term "non-toxic". The aim of REACH is rather to make sure that sufficient data are available on substances so that their risks to human health and the environment can be assessed and, as a result, safe handling can be ensured. Substances of very high concern (SVHC) are to be substituted and therefore may only be used with temporary authorisation (see Chapter 4).
- The Waste Framework Directive (WFD)—a major step towards achieving the goal of a circular economy—was amended in 2018 [3] but does not define the terms "circular economy" or "material cycles". It only defines a waste hierarchy that favours re-use and recycling.

In a study that explores how to achieve the goal of a "non-toxic environment" [5], the European Commission lists a number of chemicals-related challenges and possible measures to reduce exposure to (toxic) chemicals in addition to REACH obligations. These include the substitution of hazardous chemicals. However, it is not possible to dispense completely with hazardous substances. In many cases, the hazard (e.g. corrosive, oxidising or flammable properties) is closely linked with the intended function. Moreover, an environment without toxins is not realistic because of naturally occurring toxicants. In addition, the toxicity of a substance depends, among other parameters, on its concentration, i.e. on the level of exposure. The objective of a "non-toxic environment" should therefore be understood as a policy vision in the sense of reducing risks from hazardous substances (synthetic or natural) as far as possible.

What is meant by "circular economy" or "material cycles"? The term "circular economy" is used frequently but interpreted very differently. The Commission introduced the term as part of its resource strategy [6] as a synonym for "sustainable materials management" with a special focus on the handling of non-renewable resources such as minerals and metals. Most authors understand circularity as a system of closed cycles. The discussion was influenced by studies that stated as their goal: "The circular economy aims to design out waste,... products are designed and optimised for a cycle of disassembly and re-use,... consumables are made of biological ingredients or 'nutrients' that are at least non-toxic and possibly even beneficial, and can safely be returned to the biosphere" [7, 8]. Combined with the prediction of a "trillion-dollar opportunity with huge potential for innovation, job creation and economic growth", this undoubtedly fuelled the political discussion, so that the amendment to the WFD was overloaded with high expectations regarding the recycling of materials from waste back to product.

From a scientific perspective, material cycles cannot be closed completely due to the second law of thermodynamics. Most products are not pure but "contaminated" for technical reasons with various substances, such as alloy components, stabilisers, plasticisers, colorants, etc. Moreover, the components or materials of many products cannot be easily disassembled because they are irreversibly bonded. This may require a higher energy input for recycling or prevent it completely for chemical reasons, as we know from metallurgy: many alloy metals "disappear" into the steel during steel scrap processing without being recovered, resulting in lower quality of the steel. In addition to these obstacles, many products that end up in municipal waste after use contain various substances classified as hazardous. This is usually due to two circumstances:

- A component of the product has been identified as hazardous during the period of use, e.g. under REACH as a substance of very high concern (SVHC), such as di-2-ethylhexyl phthalate (DEHP) as plasticiser in PVC, or as a persistent organic pollutant (POP) in the Stockholm Convention, such as hexabromocyclododecane (HBCD), which was previously used as a flame retardant in polystyrene.
- A substance has already been known to be toxic at the beginning of its lifecycle, but its substitution has only recently become possible (example: replacement of mercury coin cells by Hg-free batteries).

In many cases, the added component cannot be simply avoided but instead is needed to maintain function. At best, the problematic component can be substituted by a less toxic one. This poses a dilemma when re-using products or recycling a defined waste fraction (stages 2 and 3 of the waste hierarchy according to WFD): to allow the respective pollutant to continue to circulate and keep it in the secondary material—if it cannot be separated completely—or dispose of it safely as hazardous waste. This is declared in the WFD as follows:

"Therefore, in line with the 7th Environment Action Programme, which calls for the development of non-toxic material cycles, it is necessary to promote measures to reduce the content of hazardous substances in materials and products, including recycled materials, and to ensure that sufficient information about the presence of hazardous substances and especially substances of very high concern is communicated throughout the whole lifecycle of products and materials. To achieve those objectives, it is necessary to improve the coherence among the law of the Union on waste, on chemicals and on products ..." ([3], preliminary note 38).

This is a good and correct resolution, but it cannot solve all problems mentioned above and has to be substantiated. Waste processors are left alone with the question of how to deal with such waste. They are even confronted with varying regulations in different countries regarding the hazardous properties of products, a lack of market surveillance and missing information on the constituents and contaminants of discarded products, in particular concerning imported articles.

The goal of either re-using or recycling all waste as a priority or returning it to the biosphere if it is degradable can only be partially achieved due to the above-mentioned problems and simply because of the large number of products with numerous components. The re-use and recovery rates of 55% for municipal waste in 2025 (65% in 2035) already set out in the new WFD represent an extremely ambitious target. "Non-toxic material cycles" are therefore a desirable but certainly only partly realisable ideal. There is no doubt that we should take all possible efforts to achieve the following:

- To remove substances identified as hazardous from products
- Where this is not possible, to label these products accordingly and manage them safely and separately from other material flows
- If technically possible as well as energetically and economically feasible, to promote the recovery of resources with the aim of removing pollutants from existing material flows as far as possible
- To produce materials for inferior uses (downcycling) if the pollutant load cannot be sufficiently reduced for the original use.

As a result, limit values are necessary for (potentially) hazardous substances in both primary and secondary materials. Is such an approach also applicable to waste? How can the interface between product and chemicals legislation and waste management be designed? The European Commission is also asking itself these questions [9]. The Council recently reminded the Commission (Council conclusions on "Towards a Sustainable Chemicals Policy Strategy of the Union", 10279/19, Brussels, 20 June 2019) of addressing the "management of substances of concern in recovered materials under REACH aiming at non-toxic material cycles and the better alignment of chemicals, products and waste policy to stimulate a market for high-quality secondary raw materials which uses are safe for human health and environment." In the following, we examine the "fate" of a chemical or a material on its way from production to product to waste and the secondary product generated from it and try to give answers to the Commission's questions.

## Substance → product → waste→ product: how can we obtain a holistic view?

Concerning the interfaces on the way from raw material to a product that is discarded as waste after use and the following generation of a secondary product from this waste, there are roughly two different legal areas to be considered: chemicals and product legislation (substances, materials, mixtures or articles[1]) on one hand and waste legislation on the other. Products are manufactured, marketed and used within the framework of chemicals and product legislation. As soon as products or objects are discarded (Article 3 (1) WFD [3]), they acquire waste status at the end of their use phase.

The corresponding waste is collected, transported and treated within the framework of waste and recycling management. Treatment depends on the waste hierarchy (Article 4 (1) WFD [3]): in addition to the overall prevention of waste, the treatment options are re-use, material recycling with the generation of marketable secondary raw materials, other recovery options, such as energy recovery from waste, or the safe disposal of non-recyclable waste as the last alternative. In the case of re-use or recycling to secondary raw materials, products made from waste are obtained.

As a result, the following two interfaces should be considered:

- The transition from product to waste
- The transition from waste to (secondary) product.

Chemicals and product legislation regulate the handling of substances, materials and articles during their

[1] The term "product" is used in two different ways: In some products the chemical composition determines its function (e.g. biocidal products, medicinal products, paints). In chemicals legislation they are called mixtures. Other products are called articles. According to REACH Article 3 (3) "Article means an object which during production is given a special shape, surface or design which determines its function to a greater degree than does its chemical composition". (Examples: plastic products, toys, electric products).

lifecycle stages of manufacture and intended use. Waste and recycling management rules become effective when substances or objects are discarded and remain so until a new (secondary) product has been produced (end-of-waste status).

Both areas of legislation aim to protect humans and the environment from harmful effects. To this end, the same evaluation principles and instruments are applied, but sector-specific provisions are also in place. Classification and labelling in line with chemicals legislation are based on (experimentally determined) hazard characteristics, whereas waste law, on the other hand, usually implicates risk considerations.[2]

The REACH regulation [4] as the central legal norm of chemicals legislation contains a general exception for waste. Article 2 (2) states: "Waste as defined in Directive 2006/12/EC of the European Parliament and of the Council [precursor of the current WFD] is not a substance, mixture or article within the meaning of Article 3 of this Regulation".

REACH does not regulate all materials that are subject to waste legislation. However, materials that leave the waste regime as (secondary) products will again be subject to the provisions of REACH. With regard to products that are no longer waste, Article 2 (7) of the REACH regulation contains the important exception that substances resulting from recovery processes which are identical to already registered substances need no registration. Furthermore, some substances and materials which are usually recycled in large quantities, such as glass, paper or compost, are exempted from registration obligation (annexes IV and V). Only if these exemptions do not apply secondary products from waste are subject to registration under the REACH regulation. Products generated during energy recovery from waste, such as gypsum and hydrochloric acid, are not excluded from registration either.

While the point when a product becomes waste is clearly defined (see above), the transition from waste to product (end of waste) is neither clearly defined in REACH nor in the WFD (see Chapter 5).

The Classification, Labelling and Packaging Regulation (CLP) [10] adopts from REACH the general exemption for waste. It sets out in detail the rules for classifying substances and mixtures according to their hazardous properties. Substances to be labelled are called hazardous substances. Articles (with the exception of explosive articles) are not to be classified and labelled. The CLP regulation is based on the rules of the 'globally harmonized system' (GHS) for classification and labelling of substances and mixtures [11], which is gradually being implemented worldwide. Responsible for classification and labelling are the manufacturers, importers and users of substances and mixtures, who submit their respective classifications (of substances) to the European Chemicals Agency (ECHA) for publication in a list. Uniform and harmonised classification is only intended for special substances (e.g. pesticides) and, among others, for carcinogenic, mutagenic or reprotoxic (CMR) substances. Classification of mixtures is usually derived from the classification of the individual components, whereby concentration limits determine below which concentration a corresponding classification is unnecessary. Therefore, a lower risk is taken into account for low exposure. Otherwise, classification is based solely on hazard criteria and does not include other aspects such as reduced bioavailability in solid matrices.

Waste and recycling management constitute a separate legal area. Besides the protection of human health and the environment, the reduction of the overall impacts of the use of natural resources plays an important role (Article 1 WFD) [3]. Although the classification of waste is based on rules governing chemicals, above all the CLP regulation, it differs considerably and contains numerous deviations. In addition to substances and mixtures, waste classification also applies to used articles that become waste. Annex III of the WFD lists the properties which render waste hazardous. The hazard criteria refer to the criteria of the CLP regulation and its concentration thresholds but with deviations depending on the nature of the waste. This includes, for example, a change in hazard criterion HP 13 (sensitization), for which a different concentration limit applies. Furthermore, Annex III contains the waste-specific hazard properties HP 9 "Infectious" and HP 15 "Waste capable by any means, after disposal, of yielding another substance, e.g. a leachate, which possesses any of the characteristics listed (in this annex)", which are not found in chemicals legislation. The waste classification system of the WFD is basically based on substance-inherent hazardous properties. The European Waste Catalogue (EWC) 2014/955/EU [12] lists the different kinds of waste and classifies them as hazardous if one of the hazard criteria mentioned above applies. It is enforced in the Member States, e.g. in Germany by the "Abfallverzeichnisverordnung" (AVV) [13].

However, concerning transboundary shipment of waste, Regulation 1013/2006/EC (WSR) [14], also includes elements of a waste-related risk assessment in the sense of the OECD risk approach, which, in addition to quantifying exposure, also takes into account the type

[2] The term 'hazard' describes the properties of a substance which may cause harm to humans or the environment. 'Risk' additionally considers the likelihood of the occurrence of harm and its severity. It takes into account the concentration/dose to which humans or the environment may be exposed.

of waste management measures and the associated technical effort and financial cost.

To classify waste correctly, information is needed on the hazardous properties of the substances contained. Moreover, if waste is intended to be recycled into secondary raw materials, a holistic view is needed. However, this is obstructed by a loss of information along the path from chemical to product to waste. We therefore examine in the following two chapters the question of whether a uniform classification of substances and waste is advantageous and what information is needed at the product/waste interfaces.

## Does a holistic view of the material flow also mean identical classification criteria at each level?

In its Communication addressing the interface between product, waste and chemicals legislation (see Chapter 1), the Commission asks [9]: "Should we further align the rules on hazard classification so that waste would be considered hazardous according to the same rules as products?"

As explained above, the CLP regulation with its UN-wide harmonised terminology, hazard pictograms and hazard and precautionary statements provides the basis for the classification of hazardous substances and mixtures. The corresponding classifications must be labelled on the packaging and indicated in the safety data sheets. As waste is excluded from the CLP and REACH regulations, operators of waste treatment plants do not have comprehensive information on how to handle a substance or mixture during the disposal phase. Although the waste classifications according to EWC are based on the CLP regulation, they also contain deviations.

Two special cases should be mentioned:

Special provisions apply to waste containing persistent organic pollutants (POPs), for which production bans or restrictions on use are laid down in the Stockholm Convention [15]. The very low concentration limits listed in Annex IV of the EU POPs Regulation 850/2004 [2] are applied for the classification of waste as hazardous (see also the provisions in the EWC). This includes, among other obligations, the requirement to keep waste separately, prohibition of mixing as well as proof and registration obligations.

In German occupational health and safety legislation, numerous rules on the classification of hazardous substances are implemented in practice by Technical Rules for Hazardous Substances (TRGS) [16]. TRGS 201 thus describes the procedures for the classification and labelling of hazardous substances and is also intended to help employers to classify and label themselves their intermediates, substances and mixtures that are not classified and labelled by a supplier (e.g. products synthesised in the company or intermediates). Compared to the provisions of the CLP regulation, this TRGS contains simplified procedures for internal classification and labelling. However, it also applies, without prejudice to waste legislation, to the application of the classification and labelling provisions to waste, insofar as such waste contains hazardous substances and is used further. This takes particular account of the requirements of occupational health and safety for employees in waste treatment plants.

Substances or mixtures are considered as waste if there is a willingness or obligation to dispose of them. They must then be labelled in accordance with Annex III of the WFD and TRGS 201. Examples can be found in Chapter 14 of the EWC "Waste organic solvents, refrigerants and propellants" and subgroup 14 06 "Waste organic solvents, refrigerants and foam/aerosol propellants". An example is given in Box 1.

**Box 1: Classified and hazardous waste requiring labelling according to the EWC [17]**

| | | |
|---|---|---|
| 14 06 02* | Other halogenated solvents and solvent mixtures | These liquid solvents and solvent mixtures originate, for example, from waste disposal, chemical or metal processing industries. Examples are cold cleaners and paint strippers containing chlorinated solvents such as tetrachloroethylene (PER). PER is classified as carcinogenic (group 2) and hazardous to the environment. Some chlorinated solvents, e.g. dichlorobenzenes, are also hazardous to the environment. Tetrachloromethane (Tetra), which is toxic and also classified as carcinogenic (Group 2), or 1,1,2,2-tetrachloroethane, which is very toxic, are further examples of this type of waste. The flash point of solvent mixtures is often between 0 °C and 21 °C, so that they are classified as highly flammable. |

The classification of waste according to the WFD is subject to the responsibility of the waste producer, since it can be assumed that he is the only one who has sufficient information on the safe handling and composition of the respective waste. Waste is generally assumed to be a contaminated mixture or complex product that requires suitable waste treatment in accordance with Annexes I and II of the WFD. If such waste materials are generated during production—as may be the case with the example presented in Box 1—their composition is usually relatively easy to document and in certain cases should be comparable with primary products (except in the chemical and pharmaceutical industries). With regard to post-consumer waste, in most cases composition can only be determined by means of extensive analyses and can vary considerably from batch to batch (e.g. mixtures of waste wood, mixed construction waste). Since such extensive analyses are very costly, the correct classification and subsequent treatment of such waste can only be achieved by collecting all available information.

The transfer of information from waste producer to waste processor is indispensable for correct classification in accordance with the EWC and further treatment of the waste. Even without this information, existing waste legislation requires classification according to the (assumed) substance-inherent hazard characteristics.

When reflecting on the classification of waste, it is helpful to look at an alternative waste classification system: The Waste Shipment Regulation (WSR) [14] implements the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal into Community law. Waste for shipment is classified on Green and Amber Lists. If a waste material is placed on the Amber List, export or import notification is required. In contrast to the EWC, this system is substance-based, the lists are not exhaustive and the entries in the lists are subject to a waste-related risk assessment. This deviates from the WFD procedure. As a consequence, wasted catalysts from car are on the Green List of the Basel Convention, though they are classified as hazardous in the EWC.

It is also helpful to take a look at the waste list used in Switzerland, the FOEN (Federal Office for the Environment) ordinance on lists of waste [18]. This is based on the EWC but also contains almost 40 additions and amendments based on a waste-related risk assessment (further information in Additional file 1: S2).

The two given examples—Green and Amber List according to the WSR and the Swiss Ordinance on Lists relating to the Movement of Wastes—demonstrate that the classification of substances and mixtures according to the CLP regulation is only suitable for waste management purposes if it is complemented by a mandatory waste-related risk assessment. Such an approach is not unusual, since other systems based on the GHS for the classification and labelling of chemicals, such as the transport of dangerous goods, are also governed by the GHS but do not implement all the provisions of the CLP regulation. The Commission's question "Should we further align the rules on hazard classification so that waste would be considered hazardous according to the same rules as products?" [9] can therefore only be answered with a clear "No". The current status of harmonisation should not be altered.

## Which product information on substances of concern is required in the application phase?

The Commission would like to know the added value of introducing a mandatory EU information system to inform waste management and recovery companies about substances of concern.[3] It also asks about its applicability to imported articles.

### Which product information must be available for use?

If a substance or mixture has hazardous properties according to the CLP regulation, a safety data sheet (SDS) must be provided to downstream users in accordance with the REACH regulation. This obligation covers substances (or mixtures) that are classified as hazardous according to the CLP, as well as chemicals that are 'persistent, bioaccumulative and toxic' (PBT) or 'very persistent and very bioaccumulative' (vPvB) or are included in the Candidate List of 'Substances of Very High Concern' (SVHC). Each SDS contains, among others, information on identity, hazards and measures to control these hazards. The SDS is to be made available to all downstream users of the respective substance. If a downstream user produces a mixture that contains a hazardous substance, he must compile an SDS for it, taking into account the information provided by the manufacturer/importer, and make this SDS available to his customers. A SDS must also contain information on disposal (No. 13).

Transmission of the information contained in the SDS, as a rule, ends with the downstream user of substances or mixtures. However, in the case of compliance with substance-related provisions of product law (e.g. toys or construction products), Art. 33, Annex XIV ("candidate list") or Annex XVII of the REACH regulation, the manufacturer must inform his customers that the products comply with the restrictions laid down therein (e.g. wood products containing arsenic). This obligation covers also importers regarding SVHCs or restricted substances. The lack of dissemination of information is particularly unfortunate in the case of articles which contain hazardous substances that might be released (e.g. batteries, cartridges), if products are made out of recycled substances. As a rule, waste handlers do not receive information on the identity and hazardousness of waste constituents. To make matters even more complicated, waste can also contain contaminants that entered the product during its service life or through cross-contamination in waste mixtures (for details see "Sources of contaminants in secondary raw materials").

[3] The Commission's understanding of substances of concern includes, in addition to SVHC, hazardous substances listed in Annex XVII of the REACH regulation and in Annex VI of the CLP regulation.

#### Substances of very high concern (SVHC)—meaning for articles

In the case of SVHC, further information obligations exist under the REACH regulation. The list of SVHC for which authorisation is required (REACH Annex XIV) currently contains 43 entries, including bisphenol A, some flame retardants (HBCD, polybrominated diphenyl ethers, etc.), perfluoro octane sulfonate, phthalates, heavy metals such as lead, cadmium and chromium (VI) or various polycyclic aromatic hydrocarbons (PAH) [19]. All substances identified as SVHC remain on the Candidate List even after inclusion in Annex XIV. According to Article 59 (1) REACH, this is important for the obligations according to Article 7 (2), Article 31 (2) point c and Article 33 REACH. As of July 12th, 2019, another 154 substances are on the Candidate List [20] for inclusion in this Annex ("Authorisation List"). It can be assumed that numerous other substances will be added to the Candidate List in the coming years. If substances are processed into complex end products (e.g. a dye in a finished plastic product, flame retardants in an insulating material), information on the "substance(s) of very high concern" contained must be passed on through the supply chain to ensure safe handling. For example, suppliers (manufacturers and importers) of articles are obliged to inform their customers if these products contain a candidate substance in a concentration of more than 0.1% to enable them to use the article safely. As a supplier of products, traders must also make this information available to end consumers on request. Following a ruling of the European Court of Justice (ECJ), the reference value of 0.1% has to be calculated for each single article in a product (e.g. handles) and not for the product made up of more than one article (e.g. passenger car with thousands of different articles) [21]. With regard to waste management, it is quite apparent: Information that does not reach the consumer will certainly not reach the recycling company. Construction waste accounts for a large proportion of total waste. However, for such waste types the information on the content of substances of concern is extremely deficient (further information in Additional file 1: S3).

#### What information should be available to the waste management sector?

In the recycling business, the quality of the input material determines the qualities and possible applications of the recycled materials produced. Clean and sorted production waste is usually processed using the usual processing methods. However, if the starting material consists of mixed or contaminated materials (e.g. a lot of post-consumer waste types), usually only low-quality recyclates can be produced by means of material recycling. This means that the product containing secondary materials often no longer meets the requirements of the original product (cf. "Regulations for contaminants in products"). In addition, analyses are not usually carried out on SVHC and other hazardous substances. As a consequence, the recyclate produced from these types of waste cannot be returned easily to the production process of the initial product. Because of these problems, various regulations—depending on intended application and product—must be taken into account if new products made from recycled materials are to be "placed on the market": e.g. REACH regulation, Stockholm Convention/EU POPs Regulation, Directive on Restrictions to Hazardous Substances in Electrical and Electronic Equipment (RoHS), Toy Safety Directive, European Packaging Directive or the Food Law, which set application restrictions with regard to the composition of substances. There are also specifications from national legislation and standards for products. As a result, analysis costs when using secondary raw materials are higher than for primary raw materials because important information from the previous use phase is missing. On the other hand, specifications remain the same—as a rule—as for using primary raw materials.

However, the measure according to Article 9 WFD with the implementation of an "ECHA database" of products containing SVHC does not go far enough: it should cover also other substances of concern—as defined in the Commission paper [9]. Moreover, it will be important in future that the information in the safety data sheets is available not only in the product chain but also for waste recyclers. The new ECHA-database must be available for all the waste recyclers being aware that SDS is only created for substances and mixtures. Therefore SDS should be also published normally on internet platforms by manufacturers. These two information channels (ECHA database, published SDS) would lead to less necessary analysis in the waste management sector.

This would facilitate also the possibility to separate (sector-specific) waste streams and feed them into specific treatment processes that allow more efficient sorting and removal or decontamination of materials containing (unacceptable) levels of substances of concern. Knowledge of the composition and properties of waste streams helps to identify potential recyclables and the selection of suitable treatment methods.

Recycling of substances from used products in waste can fail not only because of substances of concern but also because of other problems, including non-hazardous substances, which represent a technical obstacle. For hazardous substances and mixtures with safety data sheets (SDS) the information on interferences with a recycling process may be specified mandatorily under No. 13 (Information on disposal). The information base

**Table 1 Examples for substances restricted for use in the EU and their probable return via imported construction products [25]**

| Substance | Areas of use/products |
|---|---|
| Hexabromocyclododecane (HBCD) | Flame retardant, especially for XPS and EPS |
| Bis(2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP), butylbenzyl phthalate (BBP) | Plasticisers in plastics, especially PVC |
| Organotin compounds | Stabilisers in PVC plastics |
| Pentabromodiphenyl ether | Flame retardant, among others for polycarbonate and polyurethane |
| Pentachlorophenol (PCP) | Wood preservative |
| | Leather conservation |
| Lead carbonate, lead sulphate | Mainly pigments |
| Chromates (VI), dichromates, chromium trioxide | Corrosion inhibitor |
| | Production of batteries and stainless steel |
| | Tanning of leather |
| | Pigments |
| | Surface treatment (chrome plating, e.g. screws, electrical appliances) |
| | Wood stain |

of waste handlers and recyclers should therefore be as comprehensive as possible. For the recovery of substances or materials from waste, a binding information system for essential product flows is needed. This system would have to be provided by manufacturers and importers. Waste management companies would then be able to obtain information from these (digital) platforms and already have an important indication of which products and components contain potentially hazardous or interfering substances. Examples include the new Information for Recyclers Platform (I4R) online platform for electrical and electronic equipment [22], International Dismantling Information System (IDIS) [23] and International Material Data System (IMDS) [24] of the automotive industry. These examples can also constitute a basis for other sectors but must be expanded to include information on substances of concern. In every case there is an urgent need to further develop means for traceability and to exchange information on treatment technologies.

The information transfer along the product chain to the waste manager is particularly problematic when the SVHC are prohibited during the use phase of a product (example: Tris(2-chloroethyl)-phosphate—TCEP) or stronger limit values are set after the production of the product (example: PAH in tyres). Further information can be found in Additional file 1: S4.

Imported articles, for which the necessary information is usually unavailable, are likely to pose a particular problem. Imported substances and mixtures are subject to the same requirements under REACH, including the restrictions under Annex XVII and the information requirements on SVHC for imported articles. This is a subject of enforcement, including market surveillance. Table 1 shows a selection of substances restricted for use in the EU and their probable return via imported construction products.

## From waste back to products: what contamination can be allowed?

EU legislation marks a path from waste back to product: the "End of Waste" (EoW) procedure was introduced in the EU with the amendment of the WFD in 2008 (Article 6). It empowers the Commission to specify EoW criteria for a number of waste fractions. Harmonised EoW regulations provide a "Schengen zone for waste" [26]. The relevant EoW regulations include criteria concerning the quality of waste suitable for recovery and which requirements must be met by the recyclate. Compliance with the EoW criteria means no more waste-related obstacles to the transboundary transport of goods. As there are currently only three EoW regulations (see below), the Commission asks: "How and for which waste streams should we facilitate more harmonisation of end-of-waste rules?" This is why achieving "product status" should increase acceptance of secondary material or products made from secondary raw materials. Concerning the higher recycling rates for some important types of waste required by the Circular Economy Package, the Commission asks: "How do we reconcile the idea that waste is a resource that we should recycle and, at the same time, ensure that waste that contains substances of concern is only recovered into materials which can be safely used? Should we allow recycled materials to contain chemicals that are no longer allowed in primary materials? If so, under what conditions?" [9].

### EoW regulations

The basic requirements for EoW status are (Article 6 (1) WFD) [3]:

a) "the substance or object is commonly used for specific purposes
b) a market or demand exists for such a substance or object;
c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products;
d) the use of the substance or object will not lead to overall adverse environmental or human health impacts."

To date, regulations for iron, steel and aluminium scrap (Council Regulation (EU) 333/2011), copper scrap (715/2013) and glass cullet (1179/2012) have come into force. The market mechanism of the EoW regulations can be explained using the example of steel scrap: the scrap industry should supply steel mills and foundries with a secondary raw material in accordance with clients' specifications. The list of scrap types [27] serves as a basis here because it contains a number of quality criteria that are relevant to practical applications. Scrap can be roughly divided into steel scrap, scrap iron and electrical scrap. Scrap metal contains one or more common non-ferrous metals, such as copper, zinc, tin, aluminium, lead and brass. Scrap recycling is of high ecological and economic interest for conserving resources and reducing energy consumption. There is an interest in the scrap industry to trade scrap outside the waste regime, as some customers—i.e. steelworks or metal works—only accept scrap as a "product".

Some EU countries are known for the fact that "scrap as waste" has practically no chance anymore (e.g. Italy); in other Member States, EoW status is of minor importance. The EoW regulation [28] defines requirements that must be met to achieve product status: documentation of "a quality management system suitable to demonstrate compliance with the criteria … including … control of waste used as input for the recovery operation, … monitoring of the treatment processes and techniques, … monitoring of the quality of scrap metal resulting from the recovery operation, … feedback from customers concerning compliance with scrap metal quality …" (Article 6). The main criterion is the percentage of impurities ("foreign materials") in iron and steel scrap (not more than 2%) as well as the requirement that the scrap should be "free of visible oil, oily emulsions, lubricants or grease except negligible amounts that will not lead to any dripping" and should not contain any radioactively contaminated scrap (Article 3 and Annex I). By contrast, the list of scrap types contains a multiple of quality characteristics. However, the limitation of impurities content to 2% already means that only a small part of scrap fractions ceases to have waste status; these are mainly new scrap from production, punching, etc. This similarly applies to copper scrap with a maximum of 2% or aluminium scrap with a maximum of 5% foreign material content. Furthermore, copper scrap is not allowed to contain PVC to prevent the formation of highly toxic polychlorinated dioxins and furans. A tolerance of at most 0.2% of organic material was introduced for glass cullet. In addition, the EoW regulations exclude substances listed in Annex IV of the POPs regulation above certain "concentration limits" (Commission Decision 2014/955/EU). To obtain product status, the material in question as an aggregate must not exhibit any hazardous properties according to Annex III of the WFD.

In practice, no complex analyses are carried out. The regulation states: "Qualified staff shall carry out a visual inspection of each consignment. Where visual inspection raises any suspicion of possible hazardous properties, further appropriate monitoring measures shall be taken, such as sampling and testing where appropriate. The staff shall be trained on potential hazardous properties that may be associated with iron and steel scrap and on material components or features that allow hazardous properties to be recognised." It is therefore theoretically possible to overlook SVHC where the content is $\geq 0.1\%$. With the material groups regulated up to now, larger quantities of organic substances are not to be expected, especially since the EoW regulations for scrap exclude oil phases (see above). In the case of inorganic SVHC—cadmium, lead or their compounds may be considered—this question can be answered if the scrap origin is known. For other types of material, an "SVHC screening" means time-consuming and costly work (see also Sect. "What information should be available to the waste management sector?").

Further material groups have been examined with a focus on EoW criteria:

Used paper and cardboard: there is a list of over 50 types of recovered paper used on the European market [29]. The JRC proposed a content of more than 1.5% foreign matter ("any material different from paper, which is present in waste paper, and can be separated using dry sorting techniques"), including coated paper and board as a quantitative EoW criterion for recovered paper [30]. This EoW criterion for waste paper failed, among other reasons, due to the resistance of manufacturers of cardboard packaging coated with plastic film. The waste management sector criticised the criterion as being too harsh in comparison with the usual impurities in waste paper collections from residential areas.

For used plastic products, there are no uniform European grades; the EN standards available for the main plastic grades mainly serve to identify the different polymers. According to a study by the JRC [31], used plastics can be classified on the basis of completely different criteria, by type of polymer, physical condition and recycling status as well as by origin or previous use. This results in a large number of possible combinations. It is therefore not surprising that the French and British national EoW classifications for used plastics, for example, do not show any relevant intersections. JRC proposed a maximum content of non-plastic materials of 2%. Moreover, the recycled plastic material "shall not be classified as hazardous following the definitions in Article 3 and Annex I of Regulation EC/1272/2008 (CLP), shall

**Table 2 Potential contaminants in products and their origins**

| Origins of potential contaminants in products | Types | Examples |
|---|---|---|
| Case I: contaminant is regularly present in one or more (primary) raw materials | Toxic metals in commodity metals | Traces of Cd in Zn metals and alloys |
| | Actinoids in minerals | Uranium salts in phosphate rock (phosphorites) |
| | Pesticide residues | Food |
| | Plastic particles ("microplastics") | Textiles |
| Case II: contaminant has been used as additive to the final product | Plasticisers | DEHP in soft PVC |
| | Flame retardants | PBDEs in hard plastics, HBCD in polystyrene |
| | Stabilisers for plastics | Cd stearate in PVC |
| | Pigments | Lead pigments in pottery |
| Case III: "in situ" formed contaminants | Thermodynamically stable molecules formed during manufacturing at high temperature | Polychlorinated dioxins and dibenzofurans, PAHs (see also Additional file 1: S4) |
| Case IV: contaminant originating from the application/use phase | Decomposition products | Ageing phenomena of soft PVC |
| | Degradation products | Mycotoxins from rotten food (residues …) |
| | Adhesive contaminants | Lubricants on metals |
| | Chemicals added during use | Inks in printed paper |

meet the conditions of commercialisation of substances of very high concern (SVHC) laid out in Article 56 of Regulation EC/1907/2006 (REACH), shall meet the prescriptions about the restriction of the commercialisation of persistent organic pollutants …". Post-consumer waste plastic fractions would therefore have no chance of ceasing to be waste because of contaminants.

For other waste streams, there are only national regulations such as a British EoW for "non-packaging plastics" [32]. The "circular economy policy" was behind a new task for the European Commission (included in the WFD amendment in 2018) of examining national EoW regulations for potential harmonisation (Article 6 (2)) and the addition of a paragraph 5 obliging the distributor of an EoW product not yet on the market to ensure "that the material meets relevant requirements under the applicable chemical and product related legislation" and additionally to comply with the EoW conditions (Article 6 (1)) already in force.

### Sources of contaminants in secondary raw materials

Pollutants in products

- may either already be included in the basic material (case I), or
- intentionally added during the manufacture/formulation of final products (case II), or
- have been unavoidably and/or unintentionally generated and not been eliminated for technical, economic or other reasons (case III) or
- were added intentionally or by chance during the use phase (case IV).

Table 2 shows examples of the different cases mentioned above. It can be seen that even apparently non-critical starting materials for waste, such as food leftovers or textiles, can contain traces of substances that contaminate a secondary product—compost or recycled fibres (case I). The additives (case II) are often substances that were considered non-critical in earlier years but are now subject to restrictions in accordance with REACH, RoHS etc. Case III is relatively rare because attempts are made to avoid such effects through appropriate process management. In many cases, products that become waste at the end of their useful life differ significantly from new products. They are damaged, worn out, aged or altered by surface treatment (adhesive, paint, etc.) or due to the influence of UV radiation or heat, mechanical stress, contact with solvents or plasticiser migration. They may therefore contain—in the sense of case IV—other substances not used or produced during production. This includes products such as newsprint or magazine paper, in which inks and residues of the mineral oils used for printing constitute an integral part of the paper.

Another problem arises when processing waste: the secondary material obtained is not always produced from a defined earlier product but also from a mixture of (possibly also heavily contaminated) products. This may often result in the secondary material containing a number of substances from different applications, e.g. plastics from used cars or electronic equipment. The above-mentioned contaminated waste papers are mixed with other waste papers during collection from households. The same applies to the demolition of buildings, e.g. pigments in plaster or on bricks and wallpaper cannot be separated from adhesives and the respective building materials.

A comparison of Table 2 with the usual requirements of the EoW regulations (see "EoW regulations") shows that it is extremely difficult to develop EoW criteria to exclude all possible loads in a material or product on the one hand and to limit the cost of analysing the recyclates at an economically acceptable level on the other, i.e. not to exceed the costs for primary materials. Even if a secondary material complies with the criteria of the EoW regulation (Article 6 (1) WFD, see "EoW regulations"), the secondary material may contain more (or possibly less) pollutants than the primary material.

In the case of imported products, it is often not known whether they contain substances of very high concern. As a consequence, this cannot be excluded for the secondary raw material produced from them—unless enormous analytical effort is undertaken. It should be noted that there is a gap in REACH as far as imported articles are concerned. In its conclusions from 26 June 2019 the Council of the EU "underlines that additional efforts will be necessary to create a proper level playing field for imported articles … by restricting the use of SVHC in imported articles where such use is not authorised in the EU …. and requests the Commission to study options to facilitate the work of customs authorities…." (See "Circular economy" and "toxic-free environment" - contradicting goals?).

### Regulations for contaminants in products

If former waste achieves "product status" by meeting EoW criteria, then substance-specific and/or product-specific regulations apply. There are a number of product-specific regulations, especially in the case of toys, electrical and electronic equipment, machinery, medical devices, personal protective equipment as well as in Annex XVII of the REACH regulation. There are limit values for certain substances in the regulations for special product groups, especially in the RoHS Directive (Pb, Hg, Cd, Cr–VI, Cd, PBB, PBDE) and the Toy Safety Directive. According to the latter directive, toys may not contain any CMR substances listed in REACH or any allergenic substances listed individually; the migration of numerous metals is therefore subject to threshold values (Annex II of the Directive). There are also individual provisions for certain substances, which are intended to avoid their exposure to humans and the environment through products—irrespective of the origin of the raw materials. These include, for example, Cd and its compounds and products containing Cd. The current SVHC list includes Cd itself and eight of its compounds, partly because of their carcinogenic potential. Cd and its compounds may only be used in specific applications (e.g. NiCd batteries, CdTe photovoltaic modules). Due to a threshold value of 100 ppm, the use of Cd in plastics has (de facto) been prohibited since 10 January 2012 (see also "Is exposure risk an adequate criterion for the assessment of a secondary material?"). Other recent examples are various phthalates that shall no longer be used as plasticisers and brominated cyclic compounds (PBDEs, HBCD) as flame retardants in various products, e.g. electric devices.

### Methods of removing contaminated materials: processes and technologies

The first step in the production of clean secondary raw materials from waste is to keep the waste fractions separate at the point of waste generation. As a rule, careless handling at source can only be reversed by work-, cost- and energy-intensive sorting processes. Separation of different waste fractions is generally carried out more consistently in companies than in households. However, the separation of waste fractions is limited by the space available. The following fundamentally different processes are available for the further use of separately collected products or materials, which are only briefly described here using a few examples:

Sorting of scrap and metallurgical processing: alloys often contain a large number of metals. The recycling of scrap requires separation of the various types of material and their feeding into the "exactly right" batch in the foundry. If this is not possible with material mixtures from waste, pyrometallurgical or hydrometallurgical processes can be used to isolate the metals and separate pollutants or impurities. However, depending on their chemical relationship to the main element, numerous alloy metals cannot be separated in conventional pyrometallurgical or hydrometallurgical processes. For example, when processing Fe scrap, platinum-group metals, copper, silver and gold are "lost" [33]. On the other hand, this may lead to "downcycling" of steel, by increasing the concentration of undesirable alloying metals, e.g. copper.

Material recycling: mechanical separation can be used to eliminate impurities with other grain sizes (sieving) or aerodynamic properties (air separator). This is the state of the art for mineral waste and plastics, in the latter case combined with physical separation processes (overbelt magnets, eddy current separators, near IR detection, X-ray detection, optoelectronic detection…). In the case of plastics, any remaining external impurities are removed by washing. However, intentionally added additives as well as decomposition products formed in the plastic remain in the material.

Raw material recycling: in the case of raw material recycling, used plastics are

a) used as a reducing agent to substitute coke in blast furnace processes,

b) decomposed into petrochemical raw materials by gasification,
c) depolymerised to monomeric building blocks ('chemical recycling'), or
d) dissolved in specific mixtures to remove additives.

In the processes mentioned under a) and b), which are only rarely used, pollutants are not separated beforehand; they are found in the output in various residual material fractions. For c) and d), the fate of impurities or pollutants depends on the process selected. Examples include the CreaSolv process, which can be used to separate brominated flame retardants from polystyrene, or the decomposition of PET by acid-catalysed hydrolysis into terephthalic acid and ethylene glycol. The reaction products are no longer waste but are, however, subject to REACH. Chemical recycling will generally result in better quality or separation of pollutants or impurities than material processing. Raw material recycling of plastics plays only a minor role today, but this may change in the future due to considerably higher recycling quotas required by law.

Energy recovery and materials to be used as fuels: destruction of organic matter in state-of-the-art incineration plants is usually combined with energy recovery (according to the R1 criterion of WFD, level 4 of the waste hierarchy) and recovery of metals from the bottom ash by mechanical and physical separation methods, mainly Fe and Al as well as various non-ferrous metals. In the thermal treatment of waste plastics, for example, organic substances including the additives mentioned above are mineralised, resulting salts are removed with the slag or via exhaust gas purification depending on their physical properties (e.g. approximately 90% of Cd [34]). In cement kilns, organic substances in materials used as fuels are completely destroyed when fed to the primary firing system. Inorganic compounds introduced are either firmly bound into the clinker matrix (most heavy metals) or separated with the kiln dust in the exhaust gas cleaning system. This dust is then either mixed with the raw material in the raw mill and completely returned to the system or transported to the cement mill, where it is mixed with other additives and ground with the clinker to cement, or can be disposed of separately.

The limits of recycling processes can be highlighted by two examples:

- Waste paper contains printing inks and residues of mineral oils used as solvents for printing (see "Sources of contaminants in secondary raw materials"). While the printing inks are removed in the deinking process, this applies only partially to the mineral oils. They are therefore also found in cardboard boxes. If these are used for the packaging of foodstuffs, there is a risk of migration of the oils into the respective foodstuffs [35].
- When dismantling buildings, numerous materials can be obtained separately from each other; however, it is not possible to remove used pigments from broken concrete, wallpaper, wall debris, etc. If the Commission were to categorise $TiO_2$ as SVHC because of its carcinogenicity, the further use of residual masses from building construction would be extremely questionable as pigments cannot be separated. It should be kept in mind that $TiO_2$ is a carcinogen only by inhalation and therefore applications where exposure by inhalation is negligible should not be excluded.

#### Is exposure risk an adequate criterion for the assessment of a secondary material?

As shown in Chapter 3, a classification of hazards according to the CLP regulation is not sufficient for the assessment of different types of waste and secondary products. It has to switch to a risk assessment which also considers exposure scenarios. Some existing cases are presented in Table 3. This will be examined in more detail using the example of Cd stabilisers. Since Cd compounds (e.g. Cd stearate etc.) have long been used as stabilisers in PVC, PVC window frames resulting from the dismantling of buildings contain these stabilisers. New plastic products may only be placed on the market with a Cd content of up to 0.01% by weight, with the exception of recycled PVC frames with a limit of 0.1% by weight. A technique for the selective separation of Cd stabilisers from PVC is not yet available. When PVC window frames are recycled, they are shredded and ground. The recycled PVC is either mixed with virgin PVC to meet the 0.1% threshold value for Cd during the extrusion of primary goods or is used exclusively for internal parts (core). These products must be visibly, legibly and permanently labelled with "Contains PVC-processed material" or with a special pictogram. This applies, for example, to the recycling of PVC with Cd values of up to 0.1% by weight and thus ten times above the usual limit value: As long as the stabiliser is firmly bound into the PVC, there is no risk of exposure during the use phase. Only if the material is used as a secondary raw material in other PVC products or waste from these products is not treated properly does it pose a risk of human exposure and environmental contamination [36].

The examples in Table 3 illustrate that—if decontamination is not possible—separate collection and further processing results in products to which, due to their use or the respective matrix, humans and the environment are not exposed. In the case of the "material recovery"

**Table 3 Examples of contaminated materials recovered for further use**

| Material | Contaminant | Maximum concentration | Separate collection | Product |
|---|---|---|---|---|
| PVC window frames | Cd stabilisers | 0.1%/0.01% | Voluntary | PVC window frames |
| Plastics from bottle crates | Pigments containing heavy metals | Regulations for Pb, Cd, … pigments | Voluntary, incentivised by deposits | Bottle crates |
| Used paper towels | Pathogens (cannot be excluded) | Should not be mixed with other used paper and cardboard | Voluntary (introduced by Essity, trade name Tork) | Toilet paper |
| Mixed plastic products | Unknown, potentially hazardous additives | Does not meet quality requirements for most products | Residues from sorting facilities | Substitute for concrete or wooden parts used outside |

(level 3 of the waste hierarchy) of rigid PVC profiles, the (irreversible) dissipation of cadmium in a previously uncontaminated material stream (new PVC) thus accepted is monitored by the European PVC Window Profile and related Building Products Association (EPPA) in recycled PVC (voluntary product monitoring) [37].

If substitutes for critical substances used so far enter the market, the further use of a contaminated material must be questioned. This means balancing the opportunities for resource efficiency against the risk of contamination. An interesting example is PVC cable sheaths containing DEHP and other phthalates. According to the REACH regulation, since 21 February 2015 these plasticisers may no longer be placed on the market in the EU. The Commission granted an exemption with a limit of 20% DEHP in the recyclate. Due to the high concentration of phthalates in soft PVC compounds, it was not possible to produce a material that met this threshold value. The plant in question was therefore shut down in 2018 [38].

For specific applications of secondary resources containing pollutants, exposure risks can thus be estimated and form the basis for product approval. This also applies (see Table 3) to what are referred to as wood or concrete substitute products made from plastic mixtures, which may contain pollutants that have been transferred or migrated. In the case of these products, possible pollutant contents are irrelevant because of their application, e.g. as garden benches, but have to be taken into consideration in the waste phase.

## Identical requirements for primary and secondary raw materials in any case?

In general, the restrictions for primary and secondary raw materials set out in Annexes XIV and XVII of the REACH Regulation apply equally. What should be done if the use of secondary materials that cannot be (completely) decontaminated is to be promoted for reasons of resource protection? In the business-as-usual scenario, only 17% of all plastic products from household waste can be recycled for the purpose of manufacturing new products ("closed loop") that comply with the relevant product regulations. Even in the case of far better separation at source and extensive improvements in sorting processes, about 45% of all recycled material would not fulfil the regulatory requirements for new products [39]. This shows the scale of the problem. In such cases therefore, an exposure assessment is required for the intended uses of the recyclate. It is clear that such exemptions must be subject to conditions. The applications still permitted may be categorised as downcycling. To date, only very few examples exist where authorisation or restriction under REACH has been issued solely for secondary raw materials. Extending this possibility for more recycled products to be placed on the market should be taken into consideration. As discussed above, matters of concern do not arise only from the hazard potential of a substance but also from the product containing this substance and its applications. At any rate, an overall evaluation of each individual case is necessary. We propose that the following criteria and questions are considered in cases where contaminants from secondary resources in products will exceed concentration limits:

- Is it a particularly important non-renewable material? Indication: e.g. EU list of strategically important resources.
- Can significant amounts of energy be saved by recycling? Indication: compare with the energy demand of the production of the primary material.
- Are the risks involved in re-using the product containing the pollutant negligible? Indication: whether the pollutant is firmly bound in a matrix.
- Can the material in question be used to manufacture products for applications where the exposure of humans and the environment can be excluded during the use phase? Indication: e.g. application as construction material.

- Is there a risk of carryover of the contaminant into other mass flows? Indications: no adequate matrix, highly dissipative application.
- Do corresponding limit values apply to these mass flows in relation to the contaminant? Will they comply with the limit values? Indication: plausibility check.

If these questions cannot be answered satisfactorily, the production of secondary raw material through recycling is not possible. Other disposal options should be considered, such as thermal treatment (incineration with energy recovery), chemical decomposition or—in case of inorganic material—disposal in a suitable landfill.

If, in the case of imported articles, it is not known whether they contain problematic substances and if so, which ones, this cannot be ruled out for the secondary raw material produced from them either—unless extensive analysis takes place. Therefore, only strict implementation at the EU's external borders of import regulations for products and substances of concern contained therein can lead to an improvement of the situation.

It is therefore inevitable that certain used products will not be allowed to be recycled mechanically but will have to be incinerated (with energy utilisation, if possible) or otherwise disposed of safely. Recycling is not an absolute goal in itself but a tool of resource management, alongside other instruments such as longevity, waste prevention, etc. An improvement in the recyclability of products can also be achieved through higher requirements in product legislation: For example, the Ecodesign Directive and other product-related legal standards, such as the RoHS or the Toy Safety Directive, could be supplemented by substance-related requirements and requirements for recyclability. Disassembling products after use would facilitate re-use and recycling. The newest amendments of the Ecodesign Directive implementing requirements on reparability and recyclability of certain products [40] are first steps in the right direction. This could also be complemented by voluntary procedures/platforms for the certification of recycling-oriented design.

## Conclusions

The 7th EAP addresses two distinct goals for chemical safety and resource conservation [1], which are summarised by the buzzwords "non-toxic environment" and "circular economy". If both goals are taken literally, they come into conflict with each other. Furthermore, they cannot be achieved individually and certainly not in combination. When bringing these two terms to the attention of the general public, they should be communicated carefully so as not to arouse expectations that will be disappointed.

We must approach both goals with a clear mission statement: The production of substances and materials and their use in products that then become waste must be viewed in terms of a "product life cycle" that covers mass streams. Only in this way can sustainable resource management be successful. Chemicals policy should strive for substances that are as inherently safe as possible. This is a goal of the Concept of Sustainable Chemistry [41–43].

As we have demonstrated with several examples, a unique classification "from substance to waste" based on chemicals legislation is not meaningful but instead counterproductive: substances are processed with other substances to materials, combined to make products and finally mixed as waste with other used products. This can also be coupled with material changes due to biochemical or chemical reactions. This means that the properties of a few starting materials are usually irrelevant for waste with the exception of waste from specific types of production. Only in this case is it still possible to classify and label it as hazardous in accordance with the CLP regulation ("substance" or "mixture" within the meaning of chemicals legislation). For all other types of waste, a risk assessment based on the presence of the substance in the respective product matrix, its physical state and additionally on potential reactions of the waste mixture is therefore required. On the other hand, the procedure in line with chemicals legislation that focusses on the hazards of individual substances has proven valuable and remains the correct option for substances. According to the REACH regulation, decisions regarding whether production and use of a substance is to be restricted or prohibited are also based on an extensive exposure evaluation and subsequent risk assessment.

If re-use and recycling processes are to be increased on a major scale, the flow of information from material and product level to waste management needs urgently to be improved and extended: For the recycling of waste fractions or used goods, information on the presence of substances of concern is needed to ensure not only recovery at the highest possible level of the waste hierarchy but at the same time the removal of pollutants and their destruction or transfer to final sinks. However, the database only for SVHC substances in products foreseen in the new WFD is by no means sufficient. All relevant information is required to build up a knowledge base for possible re-use (e.g. repair instructions, spare parts) and material recovery (materials suitable for recycling, potentially interfering materials). This is the only chance to introduce highly differentiated "used product" or "used material" types. This means that information transfer on the content of substances of concern and substances which interfere with recycling processes must also cover articles and become obligatory and should reach the waste manager and recycler. More transparency in the product chain is a prejudice for an increase of high-level recycling and to come closer to a circular economy. Responsibility for this transfer of information must become part of product responsibility and involve all stakeholders in the product chain—manufacturers, retailers, consumers. Producers should therefore set up collection systems for specific areas of use in cooperation with users and the waste management industry: The functions to be fulfilled for the application in question essentially determine the type and quantity of additives, which can be demonstrated with examples already in place: ERDE—Crop Plastics Recycling Germany [44] or Rewindo for PVC window frames [45]. The focus must therefore be on waste fractions that are relatively well defined. However, such systems for "sorted" waste will only work if the parties in the chain play their part correctly. This will be even more successful if "design for recycling" is taken into account in product design and enforced by ecodesign regulations. The Ecodesign Directive and other product-related directives (e.g. RoHS, Toy Safety Directive) could therefore be supplemented by substance-related requirements to facilitate the dismantling of products after use. The mere increase of "recycling quotas" will not result in additional material recovery if information is not enhanced and the separation of waste fractions is not enforced.

The recycling of materials from waste is subject to restrictions due to pollutants and/or interfering materials contained in the secondary material. The presence of interfering substances in the secondary material usually leads to "downcycling": products made of secondary material can then only be used for less demanding applications; their further "recyclability" is limited or no longer possible. Under certain conditions, this can take place in the same way for secondary materials containing harmful substances:

1. We save important non-renewable resources or significant amounts of energy by recycling.
2. The material in question can be used to manufacture new products for applications where exposure of humans and the environment can be excluded during the use phase.
3. There is no relevant risk of carryover of the contaminant into other mass flows.
4. Threshold values for the contaminant in these mass flows are in place.
5. It is possible to safely dispose of the recycled material in question after further use.

In a further step, the types of pollutants or effects for which such a concept is to be applied should be discussed. Depending on the number of users and the type of use, documentation of the fate of the products (and monitoring if necessary) is required during the "product life". A safe path for disposal after use could be indicated by a label "may not be further recycled after end of use". If appropriate, collection and safe disposal can be incentivised by economic instruments. If there is a relevant risk with regard to uncontrolled dissipation or release of the pollutant, the immediate route to disposal remains the only and last alternative.

The regulatory areas mentioned above must apply equally to all substances, materials and articles imported into the EU. Enforcement measures will be necessary. From this point of view too, internationally approved "types of used material", like those for scrap metals and waste paper, would be a major step forward. The recommended recycling route and a specific spectrum of minor constituents could characterise types of used material. This is an interesting field for industrial associations and standardisation bodies.

EU-wide harmonised criteria for EoW status are particularly useful for waste types that are traded internationally on a large scale and for which appropriate quality criteria should be defined. These include waste plastics and waste paper. If their composition varies too much or long-distance transport is not environmentally compatible and too expensive due to low added value (e.g. biowaste), uniform criteria are not needed.

The legal problems and experiences in the field presented here show that an isolated optimisation of waste regulations, chemicals legislation and product law is counterproductive if major resource savings and increased safety against harmful substances are to be achieved at the same time. Considering the interfaces and intersections of the regulations mentioned, we conclude:

- We need clear requirements for the recyclability of products in product legislation. The present delimitation of "ecodesign" to the energy consumption requirement in the use phase must be complemented by "design for repair" or "design for recycling".
- Research and development of processes to separate pollutants from product waste for subsequent recycling should be encouraged.
- Substitution of substances in products which interfere technically with recycling processes should be encouraged, too.
- In the case of substances that have previously been used but are now banned due to their harmful properties, it must be checked whether corresponding materials are acceptable for lower-quality products

(downcycling) and, if necessary, whether exceptions can be granted under REACH. Safe disposal of such products that cannot be re-used after their "second use" should be mandatory. This should be encouraged by corresponding labelling.
- The information system for SVHC substances in products initiated by the new WFD has a too narrow scope and is therefore not sufficient. This must be supplemented because the recycling of materials depends not only on the presence of SVHC but also of other hazardous substances and compounds that cause technical problems.

The development of guiding principles to clarify these interfaces, which can then be implemented with a clear time schedule and action plans, is an appropriate way forward.

## Additional file

**Additional file 1. Caption S1.** Goals according to the 7th Environment Action Programme of the European Commission. **Caption S2.** Alternative Classifications of Waste Considering Risk. **Table S1.** Deviations in classification between the Waste Shipment Regulation (WSR) and the European Waste Catalogue (EWC) (examples). **Caption S3.** Product Information on Substances of Concern – Special case of construction products. **Caption S4.** Examples for changes of legal provisions during the use phase of products. Example 1: Tris(2-chloroethyl) phosphate (TCEP). Example 2: Polycyclic-aromatic hydrocarbons (PAH). **Table S2.** Restrictions for PAH by REACH. **Table S3.** Classification/labelling as a product or as waste or component of typical waste, information requirements in the case of material recovery.

### Abbreviations

AVV: Abfallverzeichnisverordnungs (German waste catalogue ordinance); CLP: Classification, Labelling and Packaging (Regulation); CMR: Carcinogenic, mutagenic or reprotoxic (substances); CPR: Construction Products Regulation; DEHP: Di-2-ethylhexylphthalate; EAP: Environment Action Programme; ECHA: European Chemicals Agency; EJC: European Court of Justice; EoW: End of Waste (procedure, regulation); EU: European Union; EWC: European Waste Catalogue; FOEN: (Swiss) Federal Office for the Environment; GHS: Globally harmonized system (of Classification and Labelling of Chemicals); HBCD: Hexabromocyclododecane; I4R: Information for Recyclers Platform; IDIS: International Dismantling Information System; IMDS: International Material Data System; OECD: Organisation for Economic Co-operation and Development; PAH: Polycyclic aromatic hydrocarbons; PBB: Polybrominated biphenyls; PBDE: Polybrominated diphenylethers; PBT: Persistent, bioaccumulative and toxic (substance); POP: Persistent organic pollutant; PVC: Polyvinyl chloride; REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals; RoHS: (Directive on) Restrictions of Hazardous Substances (in Electrical and Electronic Equipment); SDS: Safety data sheet; SVHC: Substances of very high concern; TCEP: Tris(2-chloroethyl) phosphate; TRGS: Technische Regeln für Gefahrstoffe (Technical rules for hazardous substances); UN: United Nations; vPvB: Very persistent and very bioaccumulative (substance); WFD: Waste Framework Directive; WSR: Waste Shipment Regulation.

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### References

1. European Commission (2014) General Union Environment Action Programme to 2020—Living well, within the limits of our planet, ISBN 978-92-79-34724-5, Luxemburg. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32013D1386&. Accessed 25 Apr 2019
2. Regulation (EC) No 850/2004 of the European Parliament and of the Council of 29 April 2004 on persistent organic pollutants and amending Directive 79/117/EEC. https://eur-lex.europa.eu/legal-content/GA/TXT/?uri=celex:32004R0850. Accessed 26 Apr 2019
3. Directive (EU) (2018) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. OJ L 150, p. 109–140
4. REGULATION (EC) (2006) No 1907/2006 of the European parliament and of the council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. OJ L 396, p 1
5. EU Commission (2017) Study for the strategy for a non-toxic environment of the 7th Environment Action Programme. http://ec.europa.eu/environment/chemicals/non-toxic/pdf/NTE%20main%20report%20final.pdf. Accessed 26 Apr 2019

6. European Commission (2011) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions: Roadmap to a Resource Efficient Europe; COM 571 Final
7. Ellen MacArthur Foundation (2013) Towards the Circular Economy. Opportunities for the Consumer Goods Sector. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/TCE_Report-2013.pdf. Accessed 15 Dec 2016
8. Ellen MacArthur Foundation, McKinsey Center for Business and Environment (2015) Growth within a Circular Economy Vision for a Competitive Europe. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf. Accessed 18 Aug 2015
9. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the implementation of the circular economy package: options to address the interface between chemical, product and waste legislation as of 16.01.2018. COM (2018) 32 final
10. Regulation (EC) No. 1272/2008 of the European Parliament and of the Council of 16 December 2008 on the classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC and amending Regulation (EC) No 1907/2006
11. UNECE: GHS implementation. https://www.unece.org/trans/danger/publi/ghs/implementation_e.html. Accessed 26 Apr 2019
12. Commission Decision (2014) 2014/955/EU of 18 December 2014 amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council. OJ L 370, p 44
13. Verordnung über das Europäische Abfallverzeichnis, Artikel 1 V. v. 10.12.2001 BGBl. I S. 3379; zuletzt geändert durch Artikel 2 V. v. 17.07.2017 BGBl. I S. 2644
14. Regulation (EC) (2006) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste. OJ L 190 p. 1. https://eur-lex.europa.eu/search.html?DTN=1013&DTA=2006&qid=1454069470717&DB_TYPE_OF_ACT=regulation&DTS_DOM=EU_LAW&type=advanced&typeOfActStatus=REGULATION&lang=en&SUBDOM_INIT=CONSLEG&DTS_SUBDOM=CONSLEG. Accessed 25 Apr 2019
15. Stockholm Convention on Persistent Organic Pollutants (2001) Revised in 2017. http://chm.pops.int/Portals/0/download.aspx?d=UNEP-POPS-COP-CONVTEXT-2017.English.pdf. Accessed 26 Apr 2019
16. Einstufung und Kennzeichnung bei Tätigkeiten mit Gefahrstoffen. (TRGS 201), GMBl 2018 S. 234-235 vom 06.04.2018. https://www.baua.de/DE/Angebote/Rechtstexte-und-Technische-Regeln/Regelwerk/TRGS/TRGS-201.html. Accessed 26 Apr 2019
17. Kummer B (2018) Chemikalien- und Abfallrecht – Harmonisierungsbemühungen der EU. GAK – Gummi, Fasern, Kunststoffe – Fachmagazin für die Polymerindustrie 12:634–640
18. Verordnung des UVEK über Listen zum Verkehr mit Abfällen vom 18. Oktober 2005 (Stand am 1. Januar 2018), AS 2005, S. 5149. https://www.admin.ch/opc/de/classified-compilation/20021081/index.html. Accessed 26 Apr 2019
19. ECHA. Authorisation list. https://echa.europa.eu/authorisation-list. Accessed 12 July 2019
20. ECHA. Six new substances added to the Candidate List. ECHA/PR/19/01. https://echa.europa.eu/de/-/six-new-substances-added-to-the-candidate-list. Accessed 25 Apr 2019
21. European Court of Justice (ECJ). Judgment of the Court (Third Chamber) of 10 September 2015. Case C-106/14. https://eur-lex.europa.eu/legal-content/en/TXT/PDF/?uri=uriserv%3AOJ.C_.2015.363.01.0012.01.ENG. Accessed 12 July 2019
22. Information for Recyclers Platform (I4R). https://i4r-platform.eu/about/. Accessed 25 Apr 2019
23. The International Dismantling Information System. https://www.idis2.com. Accessed 25 Apr 2019
24. The International Material Data System. https://public.mdsystem.com/en/web/imds-public-pages. Accessed 25 Apr 2019
25. Zeschmar-Lahl B, Friege H, Borgmann A (2019) Gefährliche Stoffe in der „Circular Economy": III. PV-Zellen aus CdTe. Müll und Abfall 51(2):90–97
26. Hazenberg J (2012) citing Gerben-Jan Gerbrandy, MEP, in: Proposition: 'It is time for a Schengen Zone for waste'. Dutch Waste Management Association September 2012. https://www.wastematters.eu/uploads/media/DWMA_It_is_time_for_a_Schengen_Zone_for_waste_sept_2012.pdf. Accessed 25 Mar 2019
27. European Steel Scrap Specification. http://jbfab.com/custom/euspec.pdf. Accessed 25 Apr 2019
28. Council Regulation (EU) (2011) No 333/2011 of 31 March 2011 establishing criteria determining when certain types of scrap metal cease to be waste under Directive 2008/98/EC of the European Parliament and of the Council, OJ L 94/2-11
29. EN 643—European List of Standard Grades of Paper and Board for Recycling (Ed. CEPI aisbl), Brussels, 2013. http://www.cepi.org/system/files/public/documents/publications/recycling/2013/CEPI_EN%20643_brochure_FINAL_0.pdf. Accessed 2 Apr 2019
30. Villanueva A, Eder P (2011) End-of-waste criteria for waste paper: Technical proposals; JRC 64346, ISBN 978-92-79-19923-3. Luxemburg. http://jrc.es/pub/EURdoc/JRC64346.pdf. Accessed 26 Apr 2019
31. Villanueva A, Eder P (2014) End-of-waste criteria for waste plastic for conversion: Technical proposals; JRC91637, ISBN 978-92-79-40944-8. Luxemburg. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC91637/2014-jrc91637%20.pdf. Accessed 26 Apr 2019
32. British Environment Agency: Non-packaging plastics quality protocol. https://www.gov.uk/government/publications/non-packaging-plastics-quality-protocol/non-packaging-plastics-quality-protocol. Accessed 3 Mar 2019
33. Reuter MA, Hudson C, van Schaik A, Heiskanen K, Meskers C, Hagelüken C (2013) Metal recycling: opportunities, limits, infrastructure. A report of the working group on the global metal flows to the international resource panel. Ed.: UNEP. ISBN: 978-92-807-3267-2. https://www.wrforum.org/wp-content/uploads/2015/03/Metal-Recycling-Opportunities-Limits-Infrastructure-2013Metal_recycling.pdf. Accessed 26 Apr 2019
34. Morf LS, Gloor R, Haag O, Haupt M, Skutan S, Di Lorenzo F, Böni D (2013) Precious metals and rare earth elements in municipal solid waste—sources and fate in a Swiss incineration plant. Waste Manage 33(3):634–644. https://doi.org/10.1016/j.wasman.2012.09.010
35. Pivnenko K, Olsson ME, Götze R, Eriksson E, Astrup PF (2016) Quantification of chemical contaminants in the paper and board fractions of municipal solid waste. Waste Manage 51(6):43–54. https://doi.org/10.1016/j.wasman.2016.03.008
36. Friege H, Zeschmar-Lahl B, Borgmann A (2018) Managing Cd containing waste—caught by the past, the circular economy needs new answers. Recycling 3(18):1–24. https://doi.org/10.3390/recycling3020018
37. European PVC Window Profile and related Building Products Association (EPPA) (2018) Kunststoff-Fensterprofilsysteme mit Rezyklatanteil. https://eppa-profiles.eu/wp-content/uploads/2018/11/D173_2018_EPPA_Positionspapier-Recyclinganteil.pdf. Accessed 26 Oct 2018
38. VINYLOOP: Closure of operation in Italy/Phthalates issue under REACH brings down European PVC recycling project. https://www.plasteurope.com/news/VINYLOOP_t240095/. Accessed 25 Apr 2019
39. Kampmann Eriksen M, Damgaard A, Boldrin A, Astrup TF (2019) Quality Assessment and Circularity Potential of Recovery Systems for Household Plastic Waste. J Ind Ecol 23(1):156–168. https://doi.org/10.1111/jiec.12822
40. COMMISSION REGULATION (EU) …/… of XXX laying down ecodesign requirements for household dishwashers pursuant to Directive 2009/125/EC of the European Parliament and of the Council amending Commission Regulation (EC) No 1275/2008 and repealing Commission Regulation (EU) No 1016/2010. http://ec.europa.eu/transparency/regcomitology/index.cfm?do=Search.getPDF&ds_id=59941&version=2&AttLang=en&db_number=1&docType=DRAFT_MEASURE. Accessed 11 July 2019
41. Kümmerer K, Clark J (2016) Green and sustainable chemistry. In: Heinrichs H, Wiek A, Martens P, Michelsen G (eds) Textbook on sustainability science. Springer, Berlin, pp 43–60
42. Blum C, Bunke D, Hungsberg M, Roelofs E, Joas A, Joas R, Blepp M, Stolzenberg HC (2017) The concept of sustainable chemistry: key drivers for the transition towards sustainable development. Sustain Chem Pharm 5:94–104. https://doi.org/10.1016/j.scp.2017.01.001
43. Friege H (2017) Sustainable chemistry—a concept with important links to waste management. Sustain Chem Pharm 6:57–60. https://doi.org/10.1016/j.scp.2017.08.001

44. Erntekunststoffe Recycling Deutschland—ERDE: What is ERDE? https://www.erde-recycling.de/en/about-erde/what-is-erde.html. Accessed 26 Apr 2019
45. REWINDO Fenster-Recycling-Service. https://www.rewindo.de/. Accessed 26 Apr 2019

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