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The European Regulatory Strategy for flame retardants – The right direction but still a risk of getting lost

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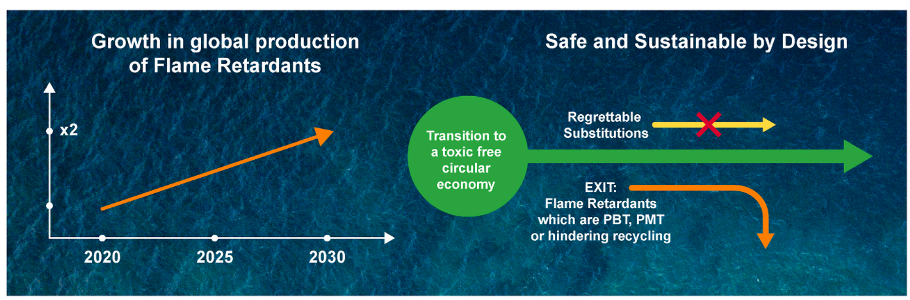
HIGHLIGHTS

- Discussion on new European strategy on regulation of flame retardants.
- Proposal to group flame retardants in the risk assessment.
- Additional criteria in relation with circular economy.

GRAPHICAL ABSTRACT



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ABSTRACT

Flame retardants (FRs) are a major group of chemicals used to protect against fast developing fires and comply with fire regulations. Many of them have a negative impact on the environment and human health. Some have been phased out, but the vast majority remain on the market including a substantial number of harmful ones. The European Chemicals Agency (ECHA) presented a strategy to phase out harmful flame retardants, based on a group approach. While this approach will help to finally overcome the loop of banning individual chemicals, which are then replaced by similar ones, which need to be banned again, the proposed strategy also contains several flaws, which may inadvertently weaken the strategy. A stronger grouping system is discussed and proposed, in which additional criteria for the evaluation of FRs as groups are included, e.g., more attention for toxic effects, mobility, recyclability and waste production. This discussion paper is intended to contribute to a sustainable approach as proposed in the European Chemicals Sustainability Strategy. It should also help create a truly circular economy.

1. Introduction

In modern society, chemicals play an important role in the wide array of products that we use and from which we derive a large part of our well-being. Some chemicals, however, may have a negative impact as well. The concept of 'safe and sustainable by design' (Patinha Caldeira et al., 2022) presents an approach to help prevent these negative impacts by considering safety and all life cycle aspects early in the design process

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of chemicals and materials. For several chemical groups, evolving knowledge has led to concern about alternatives, with a risk of regrettable substitution. Accounting for their full life cycle is therefore essential. In the global transition to a safe and circular economy[1], the European Union (EU) can play a leading role by regulating harmful flame retardants (FRs) and encouraging the use of safer alternatives and more sustainable materials, chemicals, and products. EU innovation policy, as a complement to chemicals policy, should aim at the development and adoption of such innovations. The European Commission (EC) already underlined the need for innovation to stimulate toxic-free and safe life cycles of chemicals in 2020 through the Chemicals Strategy for Sustainability (EC, 2020). In April 2022, the European Commission published a REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) Restrictions Roadmap which aims to be a tool for prioritising certain substances '*for (group) restrictions under REACH*'. The European Chemicals Agency ECHA was tasked to '*prepare an overall strategy on flame retardants by 2022, which will* support *the Commission when it decides to request (a) restriction dossier(s). The substances in scope are in principle all flame retardants, and there will be particular focus on brominated flame retardants and their prioritisation for restriction*' (EC, 2022a). Since the publication of the Roadmap, recycling and circularity aspects have been further emphasized in product legislation through the proposal for a regulation on Ecodesign requirements for sustainable products (ESPR), in which the European Commission commits to reinforcing circularity aspects, including a focus on '*chemicals hindering re-use and recycling*'. Circularity aspects are also being integrated in EU chemicals legislation through the proposal for the CLP (Classification, Labelling and Packaging) regulation; for example, the introduction of new hazard classes for (very) persistent and mobile substances, aims to reduce human and environmental exposure to hazardous substances in waste (EC, 2022b).

The aim of this paper is to critically discuss the new European Regulatory Strategy for FRs (ECHA, 2023b) (See 2.5.) in relation with regrettable substitution, circular economy and life cycle assessment of FRs. Another way of grouping FRs is proposed to assist in speeding up the evaluation of these chemicals. We carried out an extensive literature research using Google Scholar, with particular attention to grey literature on regulatory papers and reports on FRs.

Fire safety is related to many products and materials, such as furniture, insulation materials, childcare articles, and electronics. Chemical substances which are added for this purpose include FRs (Fig. 1).

However, whether these chemicals actually do improve fire safety is questionable as: the delays in fire onset achieved by FRs can be counted in seconds; there is suspected increased toxicity of smoke from burning FR-treated materials (McKenna et al., 2018); and other lifestyle factors and improved fire safety awareness may have a greater impact on safety than chemical treatment (Doyle et al., 2019). The International Standardization Organization (ISO) defines an FR as a '*substance added, or a treatment applied, to a material in order to suppress or delay the appearance of a flame and/or reduce the flame-spread rate*' (ISO, 2017). Similarly, the European human biomonitoring project HBM4EU defines an FR as '*any compound or mixture added to a consumer product or building material to reduce the flammability and thus improve product safety*' (HBM4EU, 2023). FRs can be characterised in chemical classes or groups related to their chemical composition. Table 1 gives an overview of the most used FRs, together with some exemplar applications, production volume estimates and classification as far as known. The total global FR production volume in 2019 was 2.39 million tons of which 25% was consumed in Europe (FR online, 2023).

Around 21% of the total annually produced FRs globally are brominated (BFRs) and chlorinated (CFRs) organic FRs together, combined referred to as organohalogen FRs. These compounds often require a synergist which in many cases will be antimony trioxide. Including this synergist brings this share to 30%. The characteristics of halogens to absorb radicals when a fire is about to ignite render organohalogen compounds as very effective FRs (although delay times in retarding a fire should not be overestimated; these are often less than 30 s, a benefit that must be considered against the increase of carbon monoxide and toxic smoke produced by some FRs) (Jayakody et al., 2000). However, most organohalogen compounds are highly persistent and often bioaccumulative and toxic (Strempel and Scheringer, 2012), which causes huge problems for current and future generations once they arrive in the environment. Although there are differences in structure, toxicity, and other characteristics of FRs, many of them would be characterised as harmful, which will be further outlined in the below, at least at a certain concentration level. To be effective, FRs need to be applied in relatively high concentrations in materials, often 10–20% or more, e.g., for polyolefins (Ampacet, 2023).

Since the beginning of this century, four BFRs have been listed as POPs (Persistent Organic Pollutants) for worldwide restrictions under the United Nations Environment Programme (UNEP) Stockholm Convention: tetra/penta (Penta-mix) and hexa/hepta (Octa-mix) related brominated diphenylethers (PBDEs), decabromodiphenylether (DecaBDE) and hexabromocyclododecane (HBCD or HBCDD) (UNEP, 2019). However, despite this listing, few countries or international bodies outside the EU have enacted bans on these chemicals (UNEP, 2019). Comparatively little has been done in other parts of the world, most notably in the major E-waste and textile waste producing countries. Furthermore, there remain at least another 63 commercial BFRs on the market (Zuiderveen et al., 2020) and there is no standstill. During recent years, polymers with bromine bound to the polymer skeleton have for example been introduced in the belief that they would not bioaccumulate (see below). Many FRs are used and produced in high volumes (FR online, 2023). In the EU, several regulations include provisions on certain substances used as FRs, i.e., REACH, the Waste Electrical and Electronic Equipment Directive (WEEE), the Food Contact Materials Regulation, and the Restriction of Hazardous Substances Directive (RoHS). While the EU and the US Environmental Protection Agency (USEPA), are working on further measures to ban more BFRs, discussions are ongoing on how to achieve that in the most efficient way. Apart from BFRs, there are other FRs that, due to their harmful characteristics, may also need to be phased out, such as chlorinated paraffins, halogenated organophosphorus FRs (OPFRs) and possibly some other less frequently used categories. Almost all categories comprise tens to hundreds of different compounds. Huang et al. (2022) reported that there are at least 56 OPFR monomers and 62 OPFR mixtures currently produced in 367 factories around the world, 201 of them being in China. Some examples are mentioned in Table 1.

2. Discussion

2.1. Regulating fire safety - rationale for adding harmful chemicals?

To help reduce the total volume of FRs currently produced and used, existing chemicals regulations should be revised. Current regulations addressing fire safety of products and buildings prescribe how a product must perform to be allowed for use, but not if that performance is to be achieved with or without flame retardants. Restricting harmful FRs will drive the design to achieve the performance needed without the use of FRs. This will facilitate the concept "safe and sustainable by design" as products will have to be designed to ensure safety for humans and the

[1] The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. N practice, it implies reducing waste to a minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible thanks to recycling. These can be productively used again and again, thereby creating further value (https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits).

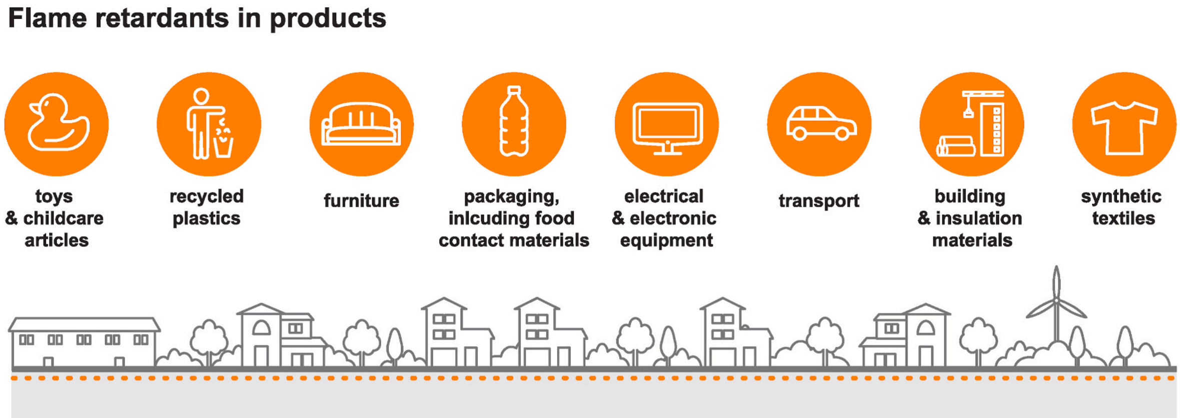

Fig. 1. Flame retardants in various products.

environment (Fig. 2).

Until now, FRs are often added to products in their design and development phase to achieve the fire safety performance required by regulations. FRs are for example easily added to insulation materials to make them pass flame tests, while using a different material would not require the application of an FR at all. There is no product regulation that dictates the use of an FR to protect against fire. Alternative and more safe design solutions should be evaluated against the limited delay times an FR can provide in retarding a fire, as well as the increase of carbon monoxide and toxic smoke produced by some FRs during a fire (McKenna et al., 2018).

A re-assessment of chemicals regulations would help create a stronger legal basis to at least reduce FR consumption and start to phase out the most harmful FRs. Fire safety regulations are organised at a national level, not centrally at the EU level. They are very hard to change, and with a reason, nobody would like to see increasing numbers of fire casualties. In France alone, every year accidental fires lead to 460 deaths and thousands of injuries. Upholstery fires are the main cause of this (Guillaume et al., 2008). The addition of FRs to products to meet fire safety regulations and indeed the regulations themselves should be re-evaluated to develop a more targeted fire legislation without adversely impacting fire safety. Charbonnet et al. (2020) reviewed evidence of how flammability standards drive the continued use of harmful FRs and identified cases where flame retardants are used to achieve standard compliance without providing a significant fire safety benefit. The widespread continuous use of toxic FR chemicals demonstrates that toxicological evidence and chemical-by-chemical regulation alone are not sufficient to prevent their inclusion in consumer products.

2.2. Innovation

FRs may be needed in polymer materials that are heated during use, such as in electric appliances and electronics such as computers, televisions, coffee machines, etc. In other materials and applications, regulation should support the development of new materials that do not require FRs. In many cases, alternative materials that meet fire safety regulations without requiring addition of FRs already exist. The use of glass, wood, steel, novel building materials and innovative woven materials should be stimulated. Especially in sensitive sectors such as childcare articles (Harrad et al., 2023a, 2023b) where the potential for exposure of a vulnerable sector of the population to chemicals may exceed any benefits from their use, harmful FRs should be banned entirely. They should also be banned in products where FRs hinder recycling and in products where safe and sustainable alternatives are already available on the market. Introducing a ban on harmful FRs will stimulate innovations to develop alternative solutions without FRs thereby inherently reducing production volumes of harmful FRs. This development is also needed to create a better basis for a circular economy (see below).

2.3. Alternatives

As highlighted above, for electronics and electrical equipment, FRs might be needed. However, those FRs should not necessarily be halogenated. As far back as 2012, the research project '*ENFIRO*' showed that many BFRs can be replaced by other FRs, such as non-halogenated OPFRs, metal-based and other inorganic FRs. The ENFIRO project clearly showed that the argument that BFRs cannot be replaced by other FRs because the polymeric materials in which they were impregnated would become brittle, is not valid (EC, 2012). While the polymer-FR combination is important and not all FRs are suitable for all polymers, there is scope to use non-halogenated FRs in applications that currently only use BFRs. Indeed, EU Regulation 2019/2021 restricted the use of all HFRs in the plastic casings and stands from display items, shifting towards non-halogenated FRs or reducing their use where lower voltages are used (EU, 2019); this practice could similarly be extended to a wider range of EEE products. Beyond electronic equipment, in 2014, a UN report on POPs identified alternative insulation materials to replace materials containing HBCDD (UNEP, 2014). In this respect it should be noted that the EU's General Court supported the EC's view '*that the use of FRs generally, and of HFRs specifically, causes issues in so far as concerns the recyclability of plastics containing such retardants*' (Curia, 2023). Other European projects on safe and sustainable design in textile such as CISUTAC and CITE (Textile, 2023) and IRISS in automotive (CLEPA, 2023) make similar suggestions.

2.4. Recycling and barriers to circularity

Achieving a circular economy for end-of-life textiles is a major challenge. Currently, after disposal, textiles often end up in landfills or incineration plants. The textile industry exhibits high growth rates, with annual global fibre production reaching 100 million tons (Piribauer et al.). Textiles typically make up mixtures of materials that prove difficult to mechanically separate for recycling. The high FR load of carpets, furniture, and curtains, makes those products very hard to recycle or reuse. FRs normally need to be applied in relatively high amounts, up to tens of percentages in weight (Ampacet, 2023). Recycling of such highly flame-retarded materials is difficult and, in some cases, authorities even refuse to take the materials back. Recycled materials may end up as materials with another application than the original products. FRs that cannot be removed from the original material prior to recycling, might become a direct threat for human health when used in such a different application. Well-known examples are plastic toys and childcare articles. This is in addition to the intentional use of

Table 1
Most frequently used flame retardants – production volumes and examples of classification.

FR type	Application examples	Global production volume (2019) (tons)	Classification (examples)
Chlorinated organic FRs	Chlorinated paraffins in thermoplastics and elastomers	95 600	SCCPs: POPs, banned; MCCPs: SVHC
Brominated organic FRs	TBBP-A in pcbs, HBCDD in textiles and polystyrene, decaBDE in plastics and textile	406 300	HBCDD, decaBDE, penta & octa-BDEs: POPs, banned; TBBP-A: on CoRap list and SVHC; TBPH: SVHC
Phosphorus-based (organic) OP esters (OPEs), organophosphonates, OP salts, phosphine oxides, OP heterocycles & others	Triaryl phosphates in thermoplastics, DOPO in polyester fibers and pcbs	430 200	RDP on CoRap list, being checked for endocrine disruption
Metal-based FRs	Al hydroxide in PVC and polyethylene, Al oxide in pcbs, Mg hydroxide in polypropylene, cables and wires, zinc borate in thermosplastics, smoke suppressants	908 200 (Al hydroxide) 215 100 (Sb oxides)	Zinc borate: pre-registered under REACH
Other organic and inorganic compounds, nanocomposites and intumescent FRs	Melamine in polyurethane flexible foams, railway, and aircraft seats, nanoclay and melamine cyanurate in glass fiber reinforced polyamide	334 600	Melamine: SVHC (ECHA)

SCCPs: short-chain chlorinated paraffins, POPs: persistent organic pollutants; MCCPs: medium-chain chlorinate paraffins, SVHC: substances of high concern; TPPB-A: tetrabromobisphenol-A; pcbs: printed circuit boards; HBCDD: hexabromocyclododecane; decaBDE: decabromodiphenylether; BDE: brominated diphenylether; CoRap: Community Rolling Action Plan; TBPH: Bis(2-ethyl hexyl) tetrabromo-phthalate; OP: organophosphorus; OPE: organophosphorus ester; DOPO: 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide; RDP: resorcinol diphosphate; PVC: polyvinyl chloride; Mg: magnesium; Al: aluminum; Sb: antimony.

FRs in such products. Harrad et al. (2023a) found in 120 out of 275 childcare articles at least one HFR – either a brominated FR or a chlorinated OPFR – exceeding a current or proposed EU content limit of 1000 mg/kg. Moreover, Mikkelsen (2023) identified that children remain exposed to dust containing high levels of harmful FRs in childcare institutions.

In 2022, the UN adopted a resolution to end plastic pollution (UN, 2022). However, Wang and Praetorius (2022) point to the risk of forgetting inclusion of chemical additives in plastics in this regulation. They plead for reducing the complexity of chemical additives in plastics, ensuring transparency about the use of such additives in plastics, and aligning the right incentives for a systematic transition. In a circular economy, recycling will be much more important than in the current linear economy. Therefore, using no, or safe alternative FRs is very important to enable recycling of bulk goods. E-waste is the fastest growing part of the waste stream. If not disposed properly, its harm to the environment and humans cannot be neglected. Recyclers are calling for FR producers to provide solutions (RWM, 2023).

Current iterations of wastewater treatment (domestic, industrial, and landfill) regulations largely overlook emerging contaminants in their purviews, mainly focusing on parameters such as organics, metals, and bacteria in their treatments. These treatments are shown to be insufficient to remove organic contaminants such as Cl-OPFRs (Saaristo et al., 2023). Suspended solids are similarly removed during water treatment processes, though are sinks for lipophilic chemicals such as BFRs (Harrad et al., 2020). The reuse of these waste solids as agricultural fertilizers is part of the EU's circularity strategy; however, with the lack of suitable screening technologies, this will likely result in further environmental contamination from FRs (among other synthetic chemicals) (McGrath et al., 2020).

Performing in-depth risk assessments on each individual FR would require considerable resources over an extended timeframe, thus rendering grouping as the only practical path forward. Recently, ECHA has applied grouping of substances to identify chemicals which 'may eventually require regulatory action' (ECHA, 2023a). The concept of grouping is not new and has for example been used to identify classes of FRs for regulatory action in the US (Blum et al., 2019) and in 2003, KEMI, the Swedish chemicals agency published a report about considerations for a national ban of BFRs (KEMI, 2003).

Other examples of grouping similar harmful substances have been applied to fluorine containing substances. In the past, halogenated compounds like hydrochloro fluorocarbons (HCFCs) have been restricted as a group by the UN in the Montreal Protocol (UN, 2023). Another grouping approach that is currently being discussed is the proposal for a REACH restriction of per- and polyfluorinated alkyl substances (PFAS) in the EU. Five EU Member States submitted this proposal based on a reasoning that grouping is the most efficient way to tackle these hazardous chemicals. Whilst there have been regulatory measures before, tackling these substances as one category has now been deemed the appropriate way forward (RIVM, 2021). The proposal restriction covers all PFAS, except maybe a few essential ones for which no alternatives are currently available, e.g., for some health care applications, and was forwarded to the European Commission on February 7, 2023. Because there are many similarities in especially persistence, but also in mobility and bioaccumulation, PFAS could serve as an example for FRs.

When phasing out FRs, it is extremely important to avoid the so-called regrettable substitution, in which one chemical of concern is replaced by another substance later proven to be of concern. Such regrettable substitutions take place because FR production plants are normally based on halogen-based commodity flows. Safe halogen-free alternatives cannot be produced in such plants because that would need a completely different production concept. For example, for producing BFRs, there is a cheap commodity flow, e.g., bromine from the Dead Sea (Israel), there are chemical processes developed for specific BFRs based on a lot of research, and there is extensive knowledge on what fillers and catalyst might be needed, etc. This cannot be turned overnight into a factory that would produce e.g., silicon or metal based FRs (Georiette et al., 2000). To maintain their position in the market, these companies therefore always offer alternatives containing halogens. There are many examples of such substitutions in the past: polychlorinated biphenyls (PCBs) were replaced by polybrominated biphenyls (PBBs), PBBs by PBDEs, PBDEs by HBCDD, and decaBDE by decabromodiphenylethane (DBDPE) (Wemken et al., 2019). More recently, PBDEs were replaced by OPFRs and HBCDD by the brominated polymeric FR PolyFR. Concern about regrettable substitution must be taken seriously by regulators. In such cases, many years are lost to environmental research to demonstrate that the alternative was also harmful, and to regulatory processes to restrict or ban the substitute. A breakthrough is urgently needed, and this can only be obtained by grouping and phasing out all HFRs and other harmful FRs, similar to the current attempt to phase out all PFAS (RIVM, 2021). Given strong opposition from the FR industry (Babrauskas et al., 2012) to such a holistic approach, an alternative solution would be grouping of FRs, provided that regrettable substitution is completely avoided.

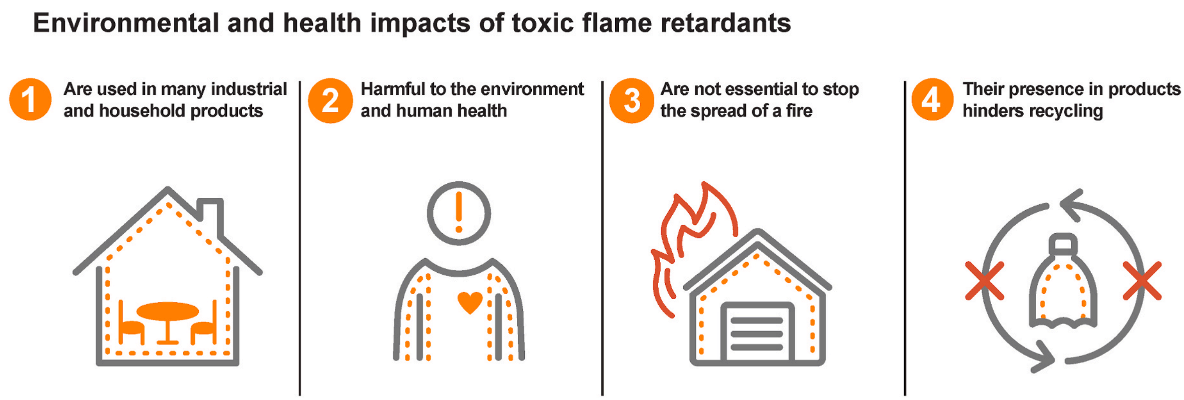

Fig. 2. Environmental and health impacts of toxic flame retardants.

2.5. *The European Regulatory Strategy for flame retardants*

In March 2023 ECHA launched their Regulatory Strategy for flame retardants (ECHA, 2023b). Due to evidence of a considerable number of substances with potentially undesirable properties, the regulatory strategy has a focus on BFRs, CFRs, and OPFRs, as indicated in the Restrictions Roadmap (EU, 2022a). FR chemistries other than halogen and organophosphorus based, will be covered in future assessments of regulatory needs (ARNs). The aims of the regulatory strategy are to i) identify substances used as FRs, ii) identify common hazards of groups of FRs, iii) identify needs for consistent regulatory risk management and faster action due to grouping of FRs, iv) offer solutions to avoid regrettable substitution, v) provide long-term predictability to market actors by more transparency of the regulatory risk management processes, and vi) integrate considerations with regard to sustainable product design and circular economy in order to promote sustainable solutions.

The strategy contains several very positive elements. For example, the strategy is very clear on the concern about aromatic BFRs, particularly due to their potential PBT/vPvB properties. A wide and generic restriction is proposed although more information is still required on the waste stage of these FRs, to prevent release of them to the environment at the end of life of the products they are used in. While this comes late, given the reports on extremely high values of BFRs in many rivers, sewage sludge and birds in Europe (Law et al., 2006; Leslie et al., 2021); a learning curve can be discerned in the European risk assessment. Based on these references and many other reports, penta/octa BDEs, decaBDE, and HBCDD have been banned. Although welcomed by environmental scientists, the impact of these bans was not wholly benign. A suite of other BFRs was applied instead of the three banned ones and much less was achieved in terms of environmental and human safety than was hoped for. Therefore, the attention to avoiding regrettable substitution and approaching the aromatic FRs as a group is encouraging. An additional positive element in the strategy is the introduction of an ecodesign requirement for FRs. Such a requirement is already known from the energy sector and would now be widened to the FR market. Finally, fire safety regulations will be re-evaluated to assess if some regulations may be redundant or if alternative materials can be used without or with less FRs. As an example, the report specifically highlights the relatively stringent UK/Irish furniture fire safety standards. Though both countries are in the (slow) process of reviewing these standards, EU-level or international prompts could expedite this process and encourage alignment with other EU standards (Irish Department of Business, Enterprise and Innovation, 2019).

The positive elements in the new FR strategy mentioned above are truly encouraging. However, further reading through the document also raises concern. The group approach mentioned in the beginning of the document seems to slowly fall into pieces, ending up in long lists of individual FRs. The strategy says for example: "Aliphatic BFRs and OPFRs are more difficult to 'group'. The hazards are more diverse and less information on their life cycle is available. Several OPFRs do not seem to pose environmental hazards". Further in the strategy, it is repeatedly emphasized that quite a lot of time is needed for all evaluations and the application of the ecodesign approach and sustainability principle. Given the very large pool of FRs, it is understandable that grouping is difficult and suffers from many exemptions that need to be made. This directly translates into delays and a risk of falling behind. In other words, regulations for new FRs develop slower than the addition of new FRs to the list, in fact, the actual problem in REACH. Table 1 in the strategy shows that the outcome of ECHA's assessment of regulatory needs of 59 FRs, is that actions and data generation for 40 of them are still pending (ECHA, 2023b). Therefore, we plea for a stricter approach, in which the grouping of aromatic FRs could serve as an example. We argue that the addition of a number of criteria in the group selection phase would help to make faster decisions on categories of FRs. In addition to the PBT criteria, these criteria could be, mobility (M), recyclability (R), and waste production (W) (Fig. 3). The recyclability test will evaluate if an FR can be recycled safely and economically from the products in which it was used. The W test is added because of possible waste production during production such as undesired side-products or intermediate substances that need to be used during production. All FRs should be subjected to a series of tests on these criteria. As soon as the compound fails one test, further tests are redundant because the substance is then labeled as unsuitable to be used as an FR. The strategy mentions these criteria: "*Hazardous FRs may need to be phased out, or there may need to be a demonstrably very low mobility of the FR or degradation products in the material, combined with dedicated end-of-life collection and waste management systems (including recycling and destruction* e.g., *via incineration), as well as controlled by industrial or professional users*".

The criteria are, however, not applied at this stage. Also, the aforementioned quote at the same time includes an exemption, which is in fact not required when applying a grouping system based on strict criteria. Admittedly, the R test in particular would currently be hard to swallow for industry. At the moment, there really isn't a way to screen materials en masse for FRs. The only system close to ready to remove BFRs from waste and HBCDD from EPS/XPS is 'Creasolv', although there are still issues with supply (low density, high volume, low yields). Awaiting better test systems, introduction of the R test should not hinder progress in decisions on HFRs that are of most concern and not hinder practices for inorganics.

In addition to the additional criteria, the T in the PBT concept would need much greater consideration. The current criteria for toxicity may lead to misclassifications (Arnot and Mackay, 2008). The criterion for T under the Stockholm Convention is defined as "not toxic for humans and the environment" (Andrade et al., 2019; Fiedler et al., 2020) and are mainly based on a long-term no observed effect concentration (NOEC) of <0.01 mg/L and human chronic toxicity or carcinogenicity. Currently, P

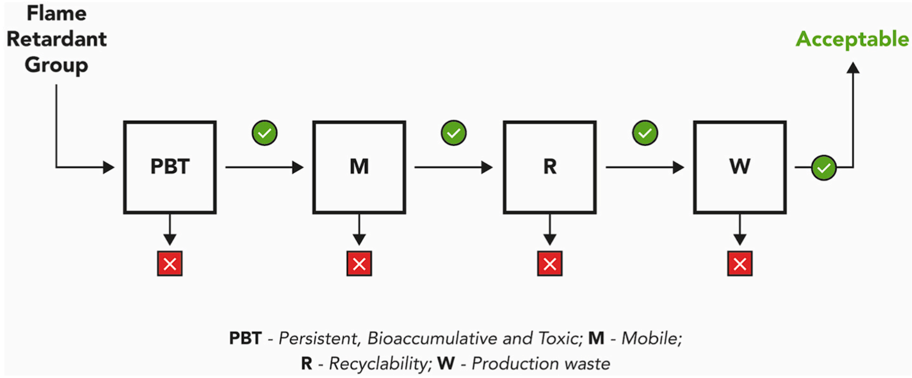

Fig. 3. Testing groups of flame retardants with additional criteria.

and B have the same weight in the PBT system, but T has a lower weight, and M (mobility/long range transport) an even lower weight (Lambert et al., 2011). There are many different endpoints in toxicology. Using the current criteria means that many other possible endpoints are not being considered. The entire concept of endocrine disruption (ED) is in fact disregarded, while some FRs such as TPP and TDCIPP show ED properties (Bajard et al., 2021). TBBP-A is also a known endocrine disrupting compound (Feiteiro et al., 2021; Yamasaki et al., 2021). Due to its polar character, it may contaminate surface water, and could easily become a threat to drinking water quality. TBBP-A-contaminated house dust could potentially threaten people's health. TBBP-A is already on the CoRAP list (Community Rolling Action Plan of the EU, prioritising chemicals for evaluation within the next three years) and an SVHC (Table 1). It is technically already restricted in waste materials *via* the Waste Directive. As it is listed as H400 and H410, waste containing TBBP-A above a limit of 2500 ppm is categorised as hazardous (HP 14 ecotoxic) and cannot be recycled. According to Bajard et al. (2021), the anti-androgenic potential is of concern and has also been predicted by in silico model(s) for 21 additional replacement FRs with no in vitro data available. This raises high concerns for mixture effects and urges investigation of endocrine disrupting activities of the "non-tested" replacement FRs. Specifically, their anti-androgenic potential should be addressed as a priority. Neurotoxicity is in fact also not considered as a criterion for toxicity. However, a lot of damage is done by neurotoxic or endocrine disrupting compounds. One study on neurobehavioural deficits caused by endocrine disruptors estimated the costs in the EU to exceed 150 billion euros per year (Bellanger et al., 2015). These authors reported moderate-to-high evidence of IQ loss due to PBDEs. Trasande et al. (2016) studied other effects of endocrine disruptors such as autism, obesity, and IQ loss and estimated costs at 163 billion euros per year, more than 1 % of the EU's GDP. Moreover, there are several reports that suggest neurotoxicity of OPFRs (e.g., Sun et al., 2016). In addition, in some cases environmental toxicity may be more important than human toxicity. In summary, we recommend widening the scope of effects considered when evaluating the toxicity of FRs (and related chemicals), such that impacts such as endocrine disruption and neurotoxicity are properly considered.

The strategy ends with a few questions: i) Is it easily possible (i.e., economically feasible) to analytically differentiate bromine bound in polymers from restricted organo-bromine compounds that may migrate during or after recycling? And if it is not feasible to differentiate easily, would this mean that it is not possible to target the restriction to exempt polymeric or reacted bromine? and ii) Is it likely to establish dedicated material-cycles with bromine being present, but not leading to the release of hazardous organo-bromine compounds? These points have been studied extensively by various research groups in the last decade. The industry standard for WEEE plastics in this regard is reportedly density separation for WEEE plastics, the theory being that higher density materials likely contain FRs. However, this method is unable to differentiate between a restricted BFR (such as a POP) and alternative FRs or even other additives such as plasticizers and colorants. Additionally, this method can reportedly only screen to ca. 1500 ppm (BSEF, 2020), well-above the current LPCLs for PBDEs and HBCDD. More sophisticated methods have been developed which involve more precise qualification and/or quantification as the current industry standard. However, the obvious caveats with these analytical methods are their scalability and cost-effectiveness in light of the vast quantities of articles entering both the market and the waste stream. Numerous studies have investigated the utility of more rapid and cost-effective methods such as X-Ray Fluorescence (XRF) and infrared for both Br- and Cl-based FRs (Gallen et al., 2014, Turner and Filella, 2017). By necessity for the less expensive methods, these are non-specific for the chemical characteristic of the HFR present though they have been shown to be effective in screening for POP-BFRs as well as for Br-containing compounds in plastics and textiles (Hennebert and Filella, 2018; Sharky et al., 2018). However, the invariable shift towards replacements for restricted FRs has diminished the efficacy of screening specifically for restricted compounds (PBDEs and HBCDD) (Sharkey et al., 2022). While further method development in this area is ongoing, the difficulty in targeted screening of specific FRs in materials such as WEEE plastics has already led to a proposed general screening threshold of 2000 mg/kg Br from the European Committee for Electrotechnical Standardization (CENELEC) as well as a restriction on all organohalogen flame retardants in the casings and stands of electronics (CLC, 2015; EU, 2019).

Release of BFRs during dismantling or disposal/recycling may need further action. Currently, dismantling of electrical and electronic instrumentation as well as disposal of textile waste mainly occurs in developing countries, which are points to address. Additionally, there will be continuous leaching of these restricted BFRs and emerging HFRs from virgin and recycled consumer products during their lifetimes so long as additive FRs are so ubiquitously used.

3. Conclusions

The European Strategy for flame retardants is a step forward in the protection of the European and global environment. By choosing a grouping approach, evaluation of FRs can be carried out faster while unnecessary toxicological testing will be avoided. Further improvements can, however, be made. The toxicity component in the PBT concept should be critically evaluated, to include endpoints as well as lethality and carcinogenicity, such as endocrine disruption and neurotoxic effects. Additional criteria should be added to the tests of groups of FRs: mobility, recyclability, and waste production. We propose that groups of FRs be tested for all criteria (PBT, M, R and W) and declared unsuitable as soon as they fail one of these tests. At the moment, EU authorities struggle in finding sufficient information on recyclability and waste production. However, as outlined herein, such information is available. Recent research shows that the ability of economically viable screening methods to discern hazardous BFRs from "safe" alternatives, is limited at the requisite scales and level of accuracy required. This limitation is well-established for recycling of electronics plastics and is likely to be a barrier to textile recycling also. Notwithstanding this, the generation of more life cycle assessment studies of FRs is warranted. Such assessments should fully consider the environmental emissions and impacts of FRs from their manufacture and incorporation into products, through their use phase, and further into what happens at their end-of-life; either disposal, or - crucial in the context of the circular economy - their recycling. With respect to the latter for example, it is essential that the presence of FRs does not impede recycling of the polymers in which they are used. Currently, this is not the case; in Ireland alone, an estimated 2800 t/yr of waste plastic articles are prevented from being recycled because of their BFR content (Drage et al., 2022); if legislative limits on the presence of chlorinated OPFRs in waste were introduced, the estimated mass of waste that would be prevented from being recycled would be even greater – specifically 7200 t/yr or 24% (Harrad et al., 2023b). The scientific community should be prepared to carry out more of those studies for FRs in the near future. Together with initiatives in the US (Chen et al., 2023), this European strategy with modifications as proposed, would constitute a major step towards liberating the world from toxic FRs.

CRediT authorship contribution statement

Jacob de Boer: Funding acquisition, Conceptualization, Investigation, Writing – original draft. **Stuart Harrad:** Writing – review & editing. **Martin Sharkey:** Writing – review & editing.

Declaration of competing interest

This paper has been written with financial contribution to J. de Boer from ROCKWOOL, Hedehusene, Denmark. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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