E-plastics in a Circular Economy: a comprehensive regulatory review.

Abstract

Despite the economic and environmental significance of recovering plastics from e-waste, the presence of contaminants (in the form of chemical substances) strongly limits the recycling of this waste stream. Some chemical substances are controlled by international guidelines and policies, which are continuously updated to control new substances or apply different threshold limits in newly marketed electronic equipment. Nonetheless, recent studies have shown that e-plastics still contain several problematic compounds, which are not yet restricted.. Additionally, the continuously increasing number of regulations on products and waste recycling, and the unambiguous regulations on additives, created a challenging situation for e-plastics recycling. This paper is a literature review of commercial additives in e-plastics, which presents an inventory of 145 hazardous and high-concern additives, with cross-reference to their types, polymer of application and the relevant regulations and policies. The study also offers a comprehensive overview of the existing measures, legislations and activities related to e-plastics recycling, with the aim of understanding future trends, gaps, and limitations of the European regulatory framework. Additionally, the review highlighted additives which can be new candidates for restriction, by analyzing their hazardous effects.. The outcomes confirm that phthalate, plasticizers, and pigments are well regulated, yet, most additives are still candidates for future restrictions or are not yet considered. In conclusion, this review could facilitate proactive actions of the European stakeholders throughout the whole e-plastic circular value chain.

keywords

additive; e-waste; e-plastics; hazardous; high concern; EU Legislation

List of abbreviations

BFRS	Brominated Fire retardants
CE	Circular Economy
CoRAP	Community rolling action plan
ECHA	European Chemical Agency
EEE	Electrical and Electronic Equipment
FRs	Flame retardants
OPFRs	Organo-phosphorus flame retardants
PBBs	Polybrominated biphenyls
PBDEs	Polybrominated Diphenyl Ethers
PBT	Persistent, Bioaccumulative and Toxic
RMOA	Regulatory Management, Option Analysis
SVHC	Substance of Very High Concern
WEEE	Waste from Electrical and Electronic Equipment
WFD	Waste Framework Directive

1 INTRODUCTION

Electrical and electronic waste (e-waste) is a rapidly growing stream; it globally topped 53.6 Mt by 2018, and is predicted to reach 74.7 Mt in 2030 (Forti et al., 2020). Although e-waste represents only 2 %-wt. of the total solid waste stream, it can reach up to 70 %-wt. of all the hazardous waste disposed of in landfills (Alassali et al., 2020a; PACE, 2019).The plastic casings of electrical and electronic equipment (EEE) contain various types and concentrations of additives, as pigments, flame retardants, impact modifiers, and plasticizers. Many of which are classified hazardous(Andersson et al., 2019).

Additives of specific concern are phthalate plasticizers, bisphenol A (BPA), alkylphenols, brominated flame retardants and POPs. The presence of contaminants (in the form of chemical substances) strongly limits the recycling of e-plastics. Consequently, international guidelines and policies are continuously updated to control the types and amounts of e-plastic additives in newly marketed EEE (Alassali et al., 2020a; Wäger et al., 2012). For instance, the European Union (EU) Restriction of Hazardous Substances (RoHS) Directive 2002/95/CE prohibited and/or limited the use of certain substances in EEE from July 2006 (European Parliament, 2003). Additionally, the US Environmental Protection Agency evaluated high priority chemicals used in e-plastics (EPA, 2020). The European regulations related to plastics and plastic waste are summarized below (Alassali, 2020):

- Chemicals should comply with the requirements of the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation 1907/2006/EC and its reviews. Any substance involved in Annex XVII is allowed on the EU market only if its production was approved or if a specific application is included in Annex XIV with limitations (European Parliament, 2006).
- There are specific product legislations regulating the use of chemical substances in products (e.g., food packaging, EEE, etc.).
- When materials are considered for reuse or recycling after disposal, hazardous materials should be restricted (article 6.1.d of Waste Framework Directive (WFD) 2008/98/EC) (European Parliament, 2008a). EU regulations on hazardous waste are based on the Globally Harmonized System, executed through the Classification, Labelling and Packaging (CLP) regulation 2008/1272/EC (European Parliament, 2008b).

However, the current guidelines and legislations can't catch up with the circular economy market, and plastics containing toxic compounds derived from e-waste can be input material for other plastic products when recycling is applied. A worth-mentioning example is the presence of chemical substances derived from e-plastic in black food packaging and trays (Turner, 2018). The scientific research on e-plastic waste management focused on the development of recycling processes (among the others, Dewulf et al., 2019; Dogu et al., 2021; Wagner et al., 2019), on the assessment of the environmental impacts (among the others, Jiang et al., 2020; Reimonn et al., 2019; Turner, 2018), and on the design of guidelines for circularity and recyclability for plastics and EEE (among the others, Berwald et al., 2021; Ragaert et al., 2020). Despite the growing concern about e-plastics management, the critical analysis of the EU regulatory framework is still limited and mainly discussing legacy or regulated additives, in addition to the control of hazardous waste, without considering the urgent need for recycling the actual e-waste stream (Sharkey et al., 2020; Wagner and Schlummer, 2020). To our knowledge, a systematic overview of the complementary aspect of the application of unregulated additives is currently missing. Also, the future trend of the limitation of e-plastic additives needs to be assessed. Therefore, this review compiled an inventory for the commercial additives found in e-plastics, while analyzing the current European regulatory and legislative frameworks. The aim of this review is threefold. The first aim is to understand the future trends, gaps, and limitations of the EU regulations on e-plastics from the viewpoint of the circular economy concept. Secondly, the aim is to summarize the hazards of non-legacy high-concern flame retardant (FR) additives, which can be restricted and/or limited in the future. Finally, further regulatory actions to avoid the "regrettable substitution" of additives (i.e., the substitution of hazardous compounds with other additives equally harmful, or potentially worse) are suggested.

To conduct this literature review, the ECHA website was analyzed to investigate the existing and updated regulations for the selected additives, including CLP Regulation, REACH Regulation and other related legislations as the WFD, RoHS directive, RoHS 2

Directive and RoHS 3 Directive. The screening assessment is further investigated to have a reliable understanding for producers and recyclers.

2 Methodology

A thorough literature review was performed (Figure 1) through four main steps. In step 1, the scientific publications and EU regulations were scrutinized to retrieve information on the additives that are typically used in e-plastic's manufacturing. Afterwards, a database of the additives (intentionally added substances, IAS) was built (Step 2) and their existing regulatory thresholds were cross-checked with the European Chemical Agency (ECHA) database (www.echa.europa.eu) (Step 3). Finally, a full inventory of the additives was set-up, containing complete information on the additives' main applications, functions, and threshold limits across the existing regulations. The mentioned steps are described below.

2.1 Literature and regulatory review

The literature review considered European legislations, scientific articles, and technical reports. On the other hand, the regulatory review included regulations and directives covering waste management, the regulation of substances and products – with focus on plastic articles. The regulatory review was based on the official website of the EU regulations (https://eur-lex.europa.eu/homepage.html). The framework and communication documents from the European Commission (EC) on "circular economy", "chemicals" and "plastics" were derived from the official website of the EC (https://ec.europa.eu/environment/index_en). The review of scientific articles, books and technical reports was focused on additives and hazardous substances in e-plastics, and on the environmental and health hazards of selected additives (e.g., brominated flame retardants (BFRs) and Organophosphate flame retardants (OPFRs)). The keywords "hazardous additives", "e-waste", "plastic additives", "emerging flame retardants" and "plastic recycling" in different combinations were applied on the bibliometric databases Scopus, Science Direct and Google Scholar. In this review, flame retardants (FR) were assessed in terms of their toxicity effects and regulatory view. Some of the previously used FR in the manufacture of e-plastics were identified as POPs. The most common is the BFRs. Whilst these substances were legitimately added to plastics at the point of manufacture, they are now prohibited under the Stockholm Convention. These substances were already identified and regulated. In this review, a thorough analysis was conducted to summarize the additives used in e-plastics and to identify their characteristics/toxicity when recycling is applied. Plastics containing POPs are not to be recycled and they should be treated in a way to destroy these components. Hence, POPs were of a less relevance to this study, when focusing on e-plastics circularity. FRs and additives that were characterized as POPs were mentioned together with their threshold limits.

The selected references (64.5 % published after 2016) consisted of: 55 journal articles, 37 technical reports, 10 books and chapters and 19 official documents of the EU. Figure 2a shows the number of selected references per year of publication and per the selected keywords "plastic additives" (60), "e-plastics" (10), "plastic recycling" (9), the official documents of the EU legislation and policy (19), and the studies supporting the regulatory framework of e-waste and e-plastics (23). The number of regulatory support studies and the EU legislation and policy documents indicates a tangible increase in the last decade, mostly after 2016. This trend was possibly influenced by the publication of the first Circular Economy action plan of the EC in December 2015.

The keyword "plastic additives" is very general; it encompasses different types of chemical substances. Hence, a further distinction was applied to the references. Figure 2b shows the distinction of the references per the keywords "general FRs" (flame retardants) (8), "BFRs" (brominated FRs) (8), "OPFRs" (organophosphate FRs) (9), "Novel FRs" (10), "Additives (pigments, stabilizers, plasticizers)" (13) and "POPs, hazardous substances" (12), and per year of publication. The continuously increasing literature on POPs and hazardous substances in e-plastics since 2008 can reflect the high scientific interest in response to the emerging restrictions of PBBs (polybrominated biphenyls), PBDEs (polybrominated diphenyl ethers) and heavy metals from EEE by the RoHS directive. An increase in literature of studies on alternatives of banned BFRs or novel BFRs (NBFRs) after 2010 was triggered by the labeling of hexabromobenzene, and tetra, penta, hexa, hepta BDEs (brominated diphenyl ethers) as POPs by Stockholm Convention in 2009 (UNEP, 2009).

2.2 COMPILATION OF THE E-PLASTICS ADDITIVES INVENTORY

The selected additives were first verified to have a specific function in EEE, and then classified as per their application and polymer type (Figure 3). The CAS number for each compound was registered (see the supplementary materials), providing a valuable tool of manual search in the database. Additionally, the CAS number ensures that the provided commercial names correspond to the studied compound. The ECHA website was analyzed to investigate and register the existing and updated regulations for the selected additives (Table 1), including CLP Regulation 1272/2008/EC (European Parliament, 2008b), REACH Regulation 1907/2006/EC (European Parliament, 2006) and other related legislations as the WFD 2008/98/EC (European Parliament, 2008a), RoHS directive 2002/95/CE (European Parliament, 2003), RoHS 2 Directive 2011/65/EU (European Parliament, 2011) and RoHS 3 Directive 2015/863/EU (European Commission, 2015). The ECHA Restriction, Authorization and Candidate list of Substances of Very High Concern (SVHC) includes limit concentrations for substances listed by EC and/or CAS No., that are in correlation with the REACH Annexes. A further survey on the ongoing regulatory activities was conducted by considering the Community rolling action plan (CoRAP), the regulatory management option analysis (RMOA), the Persistence Bioaccumulation and Toxicity (PBT) assessment, and the endocrine disruptor (ED) assessment.

Table 1. Online lists accessed on ECHA official website during the regulatory assessment

Name of the list	reference	date of access
Restriction	https://echa.europa.eu/substances-restricted-under-reach,	12/15/2020
Authorization	https://echa.europa.eu/authorisation-list	12/15/2020
Candidates SVHC for Authorization	https://echa.europa.eu/candidate-list-table	12/15/2020
CoRAP	https://echa.europa.eu/information-on-chemicals/evaluation/community-rolling-action-plan/corap-table	12/16/2020
RMOA	https://echa.europa.eu/rmoa	12/17/2020
PBT assessment	https://echa.europa.eu/pbt	12/17/2020
ED assessment	https://echa.europa.eu/ed-assessment	12/17/2020

The lists of CoRAP, RMOA, PBT and ED assessments do not belong to the regulatory actions yet, but it is important to evaluate the potential future updates to the relevant regulations. The extraction and classification of the hazard statement codes of compounds labeled hazardous from Table 3.1 of Annex VI of the CLP regulation list was important to assess the degree of environmental and health hazard effects. To facilitate the process, the hazard statement codes were extracted from the Classification and Labelling (C&L) inventory on the ECHA official website, which included the most recent consolidated version. The hazard statement codes of the non-harmonized, yet classified compounds, were retrieved from the C&L Inventory. These were classified according to the notifications received through the REACH registration process. However, C&L inventory self-classification does not pose any regulatory action. According to the outcomes of the step 1 (literature survey), 145 additives were included in the database defined in step 2. The detailed inventory is provided in the supplementary material. The additives of the inventory are classified into BFRs, OPFRs, inorganic FRs, phthalate plasticizers, pigments as subgroups of modifiers (FRs, plasticizers, fillers), pigments, and protective additives (stabilizers and anti-degradation) (Figure 3). Their amounts may vary largely (from 0.001 % to 60 %-wt. of the plastic article), depending on their type.

3 RESULTS AND DISCUSSION

3.1 EU REGULATORY FRAMEWORKS

3.1.1 ACTIONS ON PRODUCTS AND E-WASTE MANAGEMENT TOWARDS CIRCULAR ECONOMY

Figure 4 (derived from Tables 1 and 2 in Janssen et al., 2016) summarizes the regulations and directives associated with e-plastics. These are divided into two categories, legislations related to products and chemicals, and to waste management. Generally, the EU regulations on e-plastics started off with listing, classification and labeling hazardous substances that need to undergo special treatment before disposal. These regulations evolved to be targeting specific groups of hazardous chemicals, where the different substances are assessed for their hazardous properties, based on which substances are authorized, restricted or regulated. These regulations expanded to control chemical substances in products for the aim of emphasizing recycling. The evolution of the EU regulations resulted in shifting the load of responsibility for end-of-life product processing from waste treatment industries to the producers, by the inclusion of eco-design. Figure 5 represents the timeline of their introduction (from 2003 to 2021).

The EU has set various ambitious targets on the collection and recycling rate per e-waste category through the WFD and the Waste from Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU (European Parliament, 2012). With the new Circular Economy Action Plan (European Commission, 2020a), the EU initiated a process of intensified efforts with respect to the life cycle of a product. The product's design is a key factor – in view of reuse, repair, and recycling needs – for the transition to circular economy. Most concerns on plastic additives are related to the possible presence of BFRs and potentially toxic elements (PTEs). Their presence in e-waste makes recycling challenging. To obtain "toxic-free" waste streams while achieving higher recycling efficiencies, the Annex VIII of the WEEE Directive states that e-plastics containing BFRs should be separately treated. However, the directive does not distinguish legacy from non-legacy BFRs, obligating to separate plastics containing any type of BFRs. Besides BFRs, there are no further actions required on other RoHS-restricted substances in e-waste treatment. Meanwhile, RoHS 2 Directive sets concentration limits for 4 heavy metals (Cd, Pb, Hg, Cr VI) and 2 BFR groups (PBBs and PBDEs). The first RoHS directive had already prohibited the application of these substances from 2006, but without providing threshold limits. The limits for the restricted BFRs were set at 1,000 ppm by RoHS 2. In agreement with RoHS 2, CELENEC (EN 50625 standard) indicates that e-plastics containing Bromine in concentrations exceeding 2,000 ppm should be separated from the waste stream. The bromine threshold limit was introduced considering that the identification of the type of BFR is expensive and is not a usual practice for the recycling industries.

The POP regulation 2019/1021/EU (recast) (European Parliament, 2019) defined the prohibited labeled FRs and their concentration limits in the applications exempted under the article 4b (Annex I), and the concentration limits in waste management prevision

(Annex IV). The aim was to ensure that the listed POP FRs (PBDEs, HBB, HBCD, SCCPs) with concentration values exceeding the limits of Annex IV would not re-enter the manufacturing process through recycling, and would instead be treated in accordance with the disposal operations of Annex V. Hence, items containing the listed POP additives in concentrations below the defined limit of Annex IV can be recycled. For the sum of the banned PBDEs, the threshold is 1000 mg kg^{-1} which is under review for further decrease to 500 mg kg^{-1}. Their concentration limits in the secondary raw materials (SRMs) should comply with the concentration limits of Annex I, since their presence can fall under the article 4b. Among the POP labeled substances, the concentration limits on EEE products for the RoHS restricted PBDEs are exempted and harmonized by RoHS 2. The concentration limits in the SRMs as per Annex I should be below 10 ppm (or below 500 ppm when the total PBDEs content is considered). These threshold limits are foreseen to be revised again in July 2021.

Furthermore, Annex III of the WFD defined hazardous waste following the properties defined in Annex VI of the Directive 67/548/EEC (European Parliament, 2008a). In 2014, the regulation 1357/2014 (European Commission, 2014) replaced the Annex III of the WDF and harmonized the CLP regulation and the 67/548/EEC directive, which were already in-force. The regulation 1357/2014 includes 15 classes (HP) for the classification of hazardous waste with specific hazard statement codes (H), and of different concentration limits (%). Each compound may have several H codes according to the Annex VI of the CLP Regulation, but the lowest limit prevails. However, e-plastics can contain compounds which have not been classified under CLP yet.

With respect to the recycling demands and toxic-free content, the European Commission's regulation on Ecodesign requirements for electronic displays (European Commission, 2019a) aims to prevent the accumulation of high-concern compounds in the waste stream. With this regulation, EU may pave the way for restricting halogenated

FRs and control FRs in EEE. Namely, Annex II prohibits the use of halogenated FRs in the frame of electronic displays. Generally, the EEE components including FRs should be labeled with the abbreviation of the polymer type and the FR code number.

Another action on toxic-free content is the regulation 66/2010/EC on Eco-label. This is a pledge aimed to initiate the substitution of hazardous materials in products (European Parliament, 2009). Among the requirements for the Eco-label award, the products should not contain the hazardous substances included in Annex VI of the CLP regulation and should not be included in the candidate list of SVHC for authorization under the REACH regulation. The Eco-label initiative may facilitate the separation needs for recycling and facilitate the transparency on chemical content of plastic products, which is one of the main obstacles for recyclers (De Tandt et al., 2021; European Commission, 2018a).The new EU strategy for sustainable chemicals and a toxic free environment, launched in October 2020, aspires to initiate actions for transparency on the chemicals' content in products while preparing further restrictions for toxic substances in consumers' articles. The actions focus on subsidizing technologies for decontaminating the waste streams to guarantee the safety of the SRMs and to increase their uptake in the market (European Commission, 2020b). Among the actions for transparency is initiating activities on tracking hazardous substances in waste and sharing the information on open-source data bases. Until now, the majority of detailed data bases for e-plastic additives are provided from academic and technical publications (e.g. Andersson et al., 2019; Groh et al., 2019; Groß et al., 2008; Hansen et al., 2014; Lassen et al., 2014; Stenmarck et al., 2017).

3.1.2 CHALLENGES AND POLICY GAPS ON THE APPLICATION OF CIRCULAR ECONOMY ON E-PLASTICS

Several studies demonstrated that e-plastics recycling is challenged by the presence of hazardous and high-concern substances (Crippa et al., 2019; Dahlbo et al., 2018; Delva et al., 2018), since their fate and behavior during recycling is still unknown (Crippa et al., 2019; Hahladakis and Iacovidou, 2019). Hence, the ecodesign principle should be applied by controlling the application of hazardous substances. At present, the application of the eco-design requirement of e-plastics is still limited. Therefore, it is necessary for the recycling industries to separate the e-waste stream in accordance with the WFD, POP and CELENEC requirements, in order to eliminate the recirculation of hazardous substances. However, in practice, the identification of hazardous substances in accordance with policy thresholds is very challenging. The most common techniques used to separate plastics containing BFRs from a mixed plastic stream are X-ray fluorescence (XRF) spectroscopy, near-infrared (NIR) spectroscopy and density separation (Wagner et al., 2019; Wagner and Schlummer, 2020). The POP threshold of 10 ppm in the SRMs cannot be measured in practice, as industrial XRF cannot provide a validated measurement for concentrations below 1,000 ppm (EURACTIV, 2020). Considering this practical obstacle, which needs expensive investments in form of analytical analyses (e.g., GC-MS), small-size recycling companies may not consider the supply of SRMs as a profit business (EURACTIV, 2020; Haarman et al., 2020).

In 2018, the European Strategy for Plastics in a Circular Economy initiated the Circular Plastics Alliance (CPA) (https://ec.europa.eu/growth/industry/policy/circular-plastics-alliance_en), a voluntary ambitious action aimed to introduce more than 10 Mt of recycled plastics by 2025. The current trend reveals that 1.3 Mt are annually collected in the EU, with 1.0 Mt sent to the plastic recycling facilities, resulting in 555 kt of SRM (Haarman et al., 2020). The relatively low amount of the generated SMR emphasizes the need for boosting the recycling rate to reach the ambitious goals of the EC. At the same time, the continuously increasing number of directives on products (Figures 4 and 5), waste recycling, and SRMs along with many ongoing discussions created an unstable situation for investments in the circular economy market for e-plastics. Hence, having too many regulations talking for the same substances (EURACTIV, 2020), creates a great confusion about the instructions, resulting in hindered recycling rates. Consequently, the request for harmonization and stabilization became a priority (EURACTIV, 2020; EuRIC, 2019; Haarman et al., 2020). The EU tries to face this challenge with the “one substance – one assessment” approach, to generate a uniform hazard assessment . Namely, the concentration limit of legacy substances should be equal for virgin and recycled materials, to improve the safety of the SRMs and increase their uptake in the market. However, at the same time more plastic will be left out of the circular economy, due to challenging and costly removal of legacy substances from the e-plastic stream (Katrakis et al., 2017; Ügdüler et al., 2020).

The sustainable chemicals strategy considers, as exception, the SRMs with higher concentration of hazardous substances in applications not posing environmental and health concerns, but without any action yet (European Commission, 2020b). An example on such applications is the construction material, like asphalt and concrete, where e-plastics can be incorporated as aggregates (Butturi et al., 2020; Luhar and Luhar, 2019). This may have a positive impact on boosting the recycling rate of e-plastics. Nevertheless, the establishment of different threshold limits for high concern substances in articles with recycled plastics requires EU-approved risk assessments.

The new Circular Economy Action Plan stated that in 2021 EU will review RoHS and REACH regulations, promote policy objectives on circular electronics, and revise the ecodesign regulation (European Commission, 2020c). But the continuous alterations of the threshold limits in the adopted legislations cannot support the application of the circular economy on EEE, especially for units with extended lifetime. Sorting the waste stream respecting the 100-500 ppm of POPs is not cost-affordable (Andersson et al., 2019; Bill et al., 2019; Delva et al., 2018). Additionally, the fraction of WEEE with PBDEs has considerably decreased over the years (Haarman et al., 2020). Also, the Br content in WEEE is decreasing and only a small fraction of older devices exceeds the RoHS limit, while only 8 % of the BFRs in the market is restricted (Eera, 2018; Jandric et al., 2020). As a response, stakeholders request the rise of the Bromine's threshold limit to 6,000 ppm for the aim of increasing the amount of recyclable e-plastics (Haarman et al., 2020). Therefore, instead of establishing stricter threshold limits, the policy makers should adjust the limits to the current waste streams and respect the industry's capabilities.

3.2 ACTIONS ON CHEMICAL MANAGEMENT AND CONTROL

3.2.1 ECHA AND REACH REGULATION

The REACH regulation 1907/2006/EC concerning the Registration, Evaluation, Authorization and Restriction of Chemical, entered into force in 2007. Its main goal is to ensure and control that all substances and products are manufactured and used safely to protect the consumers and to promote a good communication among all actors of the supply chain. Producers and importers of substances with volumes exceeding 1.0 t y^{-1} are obliged to present a detailed technical dossier to ECHA (European Parliament, 2006). Additionally, according to the regulation 850/2004/EC (European Parliament, 2004), REACH is the appropriate instrument to implement the necessary control measures on production, placing on the market, and use of the POP substances. The importers and producers need to provide information about the classification and labeling of the substances through the technical dossier or can self-classify and notify the substance to the Classification and Labeling inventory (C&L) according to the CLP criteria. Additionally, they can notify ECHA if the substance can have a harmonized classification and labeling not included in the CLP regulation. However, ECHA cannot evaluate these notifications and the C&L notified classification does not have any legal effect. ECHA is the appropriate instrument to coordinate REACH actions and activities towards the safety of consumers and the environment. This includes the registration of substances, evaluation of the registered substances in cooperation with the authorities of the EU member states, identification and controlling of substances of very high concern (SVHC). Moreover, ECHA set limitations for substances through their inclusion in the list of Annex XVII when their risk has been determined, and authorize SVHC through their inclusion in the list of Annex XIV. When a substance is included in the ECHA, its use is prohibited unless an exception is granted which is a high-cost procedure.

According to the three criteria of the Article 57 of REACH, a substance can be identified as:

1. SVHC if it has one or more these properties: carcinogenic, mutagenic and toxic for reproduction, consistently with Annex VII of the CLP regulation.
2. persistent, bioaccumulative and toxic (PBT) or very persistent and very bioaccumulative (vPvB) in accordance with the screening criteria of article 1 and 2 of the Annex XIII (ECHA, 2017a).
3. causing equivalent concern, mostly with endocrine disruption action.

Once the substance is identified as a SVHC, it is included in the candidate list for authorization and the importers or producers need to notify ECHA if their articles include SVHC in concentrations above 0.1 %-wt. The notification would then be published in the new database of substances of concern in products (SCIP) database (https://echa.europa.eu/it/scip-format), for the waste operators requesting transparency on the substances included in post-consumer or post-industrial products.

Nowadays, 211 registered substances were identified as SVHC and are included in the candidate list for authorization (refer to the supplementary material). Some have already been restricted by REACH (ECHA, 2021). Considering e-plastics, the SVHC list includes: 15 phthalates plasticizers; 2 Chlorinated Flame Retardants (CFRs) (i.e., Tris(2-chloroethyl) phosphate - TCEP and Short-chain chlorinated paraffins - SCCPs); 1 PFR (trixylyl phosphate - TXP); 2 BFRs (i.e., decabromodiphenyl ether – decaBDE and hexabromocyclododecane - HBCDD); and lead and cadmium with their compounds (Andersson et al., 2019). Since the replacement of SVHC is done using substances of analogous function, most compounds present structural similarities and health and environmental risks (Swedish Chemicals Agency, 2018). Among the most studied non legacy substances of "regrettable substitution" are BEH-TEBP, EH-TBB, PBT and TBP-AE, replaced by the POPs pentaBDE, DBDPE, TBBPA, BTBPE. These substances have been found to be more persistent and bioaccumulated than the replaced additives (de Wit et al., 2010; Eljarrat and Barceló, 2011; Vorkamp et al., 2019).

3.2.2 CHALLENGES OF THE SVHC IDENTIFICATION PROCESS

Regulatory management option analysis (RMOA) has generally been introduced to facilitate the identification of SVHC once a substance is selected to be a candidate by a manual screening (Swedish Chemicals Agency, 2018). It can propose the most appropriate regulatory action. Although the conclusion does not have a legal power, it can propose to initiate a risk assessment (ECHA, 2013). The substances that should undergo evaluation by a member state (as per the selection criteria) follow the Community Rolling Plan (CoRAP). Among the selection are PBT and ED indications and CMR potentials. Both, CoRAP and RMO analysis can take place simultaneously, along with the PBT and ED assessments. However, the SVHC identification can be a long process, due to the absence of data. Around 64 % of substances found under the substance evaluation lack the necessary information (Loonen et al., 2019). Considering the case of the most widespread BFR (TBBPA), it is under the PBT and ED assessments since 2012 with no final conclusion, while the CoRAP have asked for data since 2017 (ECHA, 2017b).

Another obstruction slowing down the SVHC identification is that REACH obliges data registration based on the produced or imported volumes. Namely, the safety data sheet – including the PBT/vPvB assessment and health hazard, physicochemical hazard, and environmental hazard assessments – should be only provided for volumes of rather than 10 tonnes. Accordingly, substances produced or imported in volumes less than 10 tonnes cannot be selected for the SVHC identification, since the information of PBT/vPvB assessment is missing. In response to that, ECHA recently started actions to increase the registration requirements of technical dossier for low tonnage substances in compliance with REACH by 2027 (ECHA, 2019a). Moreover, the data for the registration requirements seems to be insufficient to provide information about the substance's carcinogenic and mutagenic properties; these studies are expensive and require years (Woutersen et al., 2019).

Another data gap limiting the SVHC identification is that about 50% of the technical dossiers are not compliant with the REACH requirements or are still incomplete or outdated (Loonen et al., 2019). Hence, only 20% of the registered substances can undergo a minimum screening for risk assessment (Bakker et al., 2017; European Commission, 2018b). ECHA committed to evaluate all the registered dossiers if they are compliant, but there is the further limitation that ECHA will require additional data. The whole procedure will require years to be completed, and the waste operators and recyclers will have difficulties to manage e-plastics with incompliant or incomplete dossiers. Additionally, the producers are not obliged to provide a safety data sheet, while the recyclers need to submit a safety data sheet to ECHA. Hence, the authorization of wastes containing SVHC is associated with high costs (De Tandt et al., 2021).

Due to the high cost of the required assessments (e.g., PBT assessment, short and chronic ecotoxicity screening tests), completing the technical dossier is very challenging. Accordingly, 75% of the dossiers are based on read-across data instead of experimental results (Loonen et al., 2019). Considering the organic FRs, they pose limitations to screening tests for persistence and bioaccumulation, and to bioassays for the short and chronic ecotoxicity assessments in aquatic species due to their relatively high molecular weight and low water solubility (Segev et al., 2009). Hence the experimental data for these additives are scarce (Gramatica et al., 2016; Scheringer et al., 2012; Stieger et al., 2014). Moreover, an alternative low-cost method accepted by REACH to submit data for the required assessments is the use of quantitative structure activity relationship (QSAR) models. There is a great number of free (Q)SAR tools. However, it is challenging to use them. A careful evaluation is necessary to achieve a correct prediction (Petoumenou et al., 2015; Zachary and Greenway, 2009). In conclusion, SVHC identification is a very challenging and time-consuming process and only high tonnage compounds with a compliance dossier can be screened if they meet the SVHC criteria.

3.3 Inventory of the e-plastics additives

In step 4, the 145 additives included in the data base (section 3.1, and supplementary material) were categorized in an inventory by type and polymers of application, with cross-reference to the related legislation (section 3.2) and REACH and ECHA procedures (section 3.3). In general, the additives included in the inventory (Figure 6) – excluding POP substances – can be classified by type and according to their involvement in the regulatory actions and activities (CLP regulation, REACH list of SVHC, CoRAP, RMOA, PBT and ED assessment), or only in the candidate list of SVHC for Authorization.

The regulatory actions and activities cover nearly half of the inventoried additives (almost all phthalate plasticizers (92.6%), more than half pigments (65%), about half of the OPFRs (44%), and a small fraction of the BFRs (19.6%) and the IFRs (18%)). Conversely, only one sixth of the considered additives (less than half of the phthalate plasticizers, one third of the pigments, and just 2 OPFRs and few IFRs) are candidates for the list of SVHC for Authorization. Overall, around 80% of the BFRs, half of the inventoried OPFRs and pigments despite all the concerns arisen from scientific community, and most of the categorized IFRs are not regulated by any regulatory action or procedure. Almost all the phthalate plasticizers are included in Authorization list for toxic for reproduction concerns, in addition to their identification as SVHC for endocrine disrupting action. On the contrary, the most common reason for pigments' Authorization is due to the carcinogenic concerns combined with toxic for reproduction or mutagenic action. BFRs and OPFRs are among the additive types with the most PBT/vPvB assessments. Moreover, few IFRs and OPFRs, and only 1 BFR are under CLP regulation, regardless the notified hazards for the submitters. The detailed inventory is provided in the supplementary material.

Despite all the ECHA coordinated assessments for BFRs and OPFRs due to PTB or CMR ground of concerns, only very few came up with a conclusion of SVHC identification or no need for further regulatory action. Thus, the roadmap for SVHC identification for organic FRs seems to be very challenging. Most of the assessments are under development or were postponed for 4 to 5 years in average. The pending status for around 67% and 78% of BFRs and OPFRs, respectively, induce high uncertainty for recycles and the plastic sector as a whole, discouraging the efforts to increase the recycled content in new products. In addition to this, it is almost impossible to follow changes and all the discussion on every single substance. The incomplete and not ECHA compliant technical dossiers is a significant barrier for the necessary assessment for

SVHC identification, since most of the assessments are being requesting additional data for 4-5 years in average (some cases for a decade). Therefore, regulations cannot encompass and control the application of these substances yet. However, the implementation of PBT assessments (e.g bioaccumulation ecotoxicity tests) for organic FRs face many challenges due to their physicochemical characteristics. This can be the reason for the high number of organic FRs that are under regulatory assessment without a conclusion. Policy makers should encourage the development of new approaches for SVHC screening or promote more in silico modeling approaches which can predict a persistence and bioaccumulative behavior without the need of experimental results. But these models should be user-friendly. In this context, the generation of the necessary data is paramount for more complete risk assessments.

Table 2. Summary of the inventoried compounds of concern in e-plastics presented in section 3.3 divided into BFRs, OPFRs, inorganic FRs, pigments and stabilizers, and phthalate plasticizers.

Chemical Name	Abbreviation	CAS
Section 3.3.1 BFRs		
Tris(2,3-dibromopropyl) phosphate	TDBPP	126-72-7
2,2-Bisbromomethyl-1,3-propanediol	DBNPG	3296-90-0
Bis(2-ethylhexyl)tetrabromo phthalate	BEH-TEBP	26040-51-7
2,4,6-Tribromophenol	TBP	118-79-6
Decabromodiphenyl ethane	DBDPE	84852-53-9
Tetrabromobisphenol A	TBBPA	79-94-7
Tetrabromobisphenol A Bis(2,3-dibromopropyl) ether	TBBPA-DBPE	21850-44-2
1,2-Bis(2,4,6-tribromophenoxy) ethane	BTBPE	37853-59-1

2-Ethylhexyl-2,3,4,5-tetrabromobenzoate	EH-TBB	183658-27-7
Pentabromotoluene	PBT	87-83-2
2,3,4,5,6-pentabromoethylbenzene	PBEB	85-22-3
Hexabromobenzene	HBBz	87-82-1
1,2,4,5-Tetrabromo-3,6-dimethylbenzene	TBX	23488-38-2
Section 3.3.2 OPFRs		
Tris(2-chloroethyl) phosphate	TCEP	115-96-8
Trixylyl phosphate	TXP	25155-23-1
Tris(1-Chloro-2-propyl) phosphate	TCPP	13674-84-5
1,4,5,6,7,7-hexachloro-8,9,10-trinorborn-5-ene-2,3-dicarboxylic anhydride	HCBH-DCAnh	115-27-5
Triphenyl phosphate	TPHP	115-86-6
Triethyl phosphate	TEP	78-40-0
Triisobutyl phosphate	TIBP	126-71-6
tris(2-Butoxyethyl) phosphate	TBEP	78-51-3
tris(2-Ethylhexyl) phosphate	TEHP	78-42-2
medium chain chlorinated paraffins	MCCPs	85535-85-9
Section 3.3.3 Inorganic FRs		
Boric acid		10043-35-3
Molybdenum trioxide		1313-27-5
Magnesium hydroxide		1309-42-8
Aluminum hydroxide		21645-51-2
Section 3.3.4 Pigments and Stabilizers		
Titanium dioxide		13463-67-7

Cobalt dichloride		7646-79-9
Cobalt (II) diacetate		71-48-7
Chromium trioxide		1333-82-0
Lead chromate molybdate sulphate red		12656-85-8
Lead chromate		7758-97-6
Lead chromate molybdate sulphate red		12656-85-8
Lead sulfur chromate yellow		1344-37-2
Zinc oxide		1314-13-2
Antimony trioxide		1309-64-4
Cobalt oxide		1307-96-6
Carbon black		
Barium peroxide		1304-29-6
Barium carbonate		513-77-9
Section 3.3.5 Phthalate Plasticizers		
Di-isobutyl phthalate	DIBP	84-69-5
Di-butyl phthalate	DBP	84-74-2
Benzylbutyl phthalate	BBP	85-68-7
Bis(2-ethylhexyl) phthalate	DEHP	117-81-7
Dioctyl phthalate	DNOP	117-84-0
Diisononyl phthalate	DINP	68515-48-0
Diisodecyl phthalate	DIDP	68515-49-1
Bis(2-methoxyethyl) phthalate	DMEP	117-82-8
Di-isopentyl phthalate	DIPP	605-50-5

Di-n-penyl phthalate	DPP	131-18-0
1,2-Benzenedicarboxylic acid, dihexyl ester, branched and linear	DHxP	68515-50-4
Di-n-hexyl phthalate	DnHP	84-75-3
1,2-Benzenedicarboxylic acid, di-C6-8-branched alkyl esters, C7-rich	DiHP	71888-89-6
Di-cyclohexylphthalate	DCHP	84-61-7
Diisohexyl phthalate	DIHP	71850-09-4
Di (2-ethyl-hexyl) terephthalate	DEHT	6422-86-2
1,2-Cyclohexanedicarboxylic acid, 1,2-diisononyl ester	DINCH	166412-78-8
Bis(2-ethylhexyl) Adipate	DEHA	103-23-1

3.3.1 REGULATORY OVERVIEW OF BFRs

Flame Retardants (FRs) are common additives in polymers (Hahladakis et al., 2018), inhibiting ignition and retarding combustion. Typically, NBFRs are added in concentrations ranging between 0.7 and 3%-wt., while BFRs are added with higher concentrations (3-25%-wt.) (Hahladakis et al., 2018). Halogenated Flame Retardants (HFRs) are efficient and cost effective. However, CFRs and BFRs are particularly concerning since a number of them is POPs (Hendriks and Westerink, 2015; Kobetičová and Černý, 2018). The exposure to BFRs has been linked to neurotoxicity potential, thereby the need for safer alternatives (Hendriks and Westerink, 2015).

In total, 46 BFRs were assessed in the study and only 9 were found to be under regulatory action or activity (Figure 6). The phthalate BFR (TDBPP) is the only compound in the inventory included in the restriction list (Annex XVII). However, its use is restricted to textiles only. The CoRAP and RMO analysis lists include 9 BFRs; 6 of them are under

PBT assessment and 2 of them are under ED assessment. The PBT risk is the most common reason, which has initiated assessment for BFRs. However, RMO analysis concluded that only 2 compounds (DBNPG, BEH-TEBP) are SVHC. The PBT assessment and CoRAP determined that the pentaBDE alternative (BEH-TEBP) is vP/vB. The analysis of further compounds for CMR and PBT risk potentials is under development or postponed, requiring additional investigation. For instance, PBT assessment for TBP and CoRAP analysis for DBDPE (DecaBDE alternative)due to PBT concerns are under development since 2012, requesting more data from the submitters. For decades , both compounds have been studied for PBT concerns from various researchers (Covaci et al., 2011; Vorkamp et al., 2019; Watanabe, 2003, among others). This is underlying the slow process that a regulatory action requires, due to difficulties on the necessary data generation from bioassays. Another pertinent example is the assessment for DBDPE, which is one of the most widespread additives in e-plastics. TBBPA is a bisphenol which has intensively attracted the interest of scientist (Guerra et al., 2010) and Danish EPA has undertaken various assessments for TBBPA since 2012 (CoRAP evaluation, RMOA analysis, PBT and ED assessments), yet no decisions were met. Since 2018, TBBPA is under assessment, coordinated by the Oeko Institute on behalf of the EC, along with diantimony trioxide and Medium chain chlorinated paraffins (MCCPs), for restriction by RoHS 2 (Oeko, 2019a, 2018). A possible restriction has raised concerns due to the negative effect on waste plastic recycling rates, pointing out that TBBPA is a reactive additive with minimal exposure risks to the environment and humans (EERA, 2020; EuRIC, 2020). Generally, bisphenols are a group of BFRwhich was strictly evaluated, as TBBPA derivates, TBBPS and TBBPA-DBPE obtain PBT and CMR risks. Yet, no decisions were met since 2014.

BTBPE and EH-TBB (which are alternatives for banned decaBDE and pentaBDE), and the benzene derivates, PBT, PBEB, HBBz and TBX have been having a great scientific interest for more than a decade now. A high number or studies have proven them to be persistent, bioaccumulative and have the ability for long range transport (e.g., Artic pole) (Covaci et al., 2011; de Wit et al., 2010; Li et al., 2019; Vorkamp et al., 2019). On top of that, UNEP has addressed BTBPE and HBBz as emerging BFRs (UNEP, 2019). Despite all the concerns, they are not under any regulation, activity or even CLP Regulation.

3.3.2 REGULATORY OVERVIEW OF OPFRs

OPFRs have been introduced as safer non-halogenated alternatives for regulated BFRs. Nonetheless, numerus studies have demonstrated their similar and sometimes higher PBT and neurotoxic potentials (AbouDonia, 2016; Gao et al., 2019; Samani and van der Meer, 2020; Vorkamp et al., 2019). The regulatory overview demonstrated that of the 41 OPFRs in the inventory, 18 were under a regulatory action or activity (Figure 6). Hence, the 44 % of OPFRs under regulatory action or activity outnumber the 19.6 % of BFRs, demonstrating that OPFRs are a “regrettable substitution”. Moreover, their presence in e-plastics can decrease the recyclability and deteriorate the material’s mechanical properties more significantly than the BFRs (Imai et al., 2003).

TCEP and TXP are both included in the Authorization list as SVHC, since they are toxic for reproduction with entry in Annex XIV of 13 and 47, respectively . In total, 11 OPFRs are under CoRAP regulatory activities and RMO analysis, 4 are under PBT assessment, and 2 are under ED assessment., Like BFRs, PBT concern is the most common reason for assessment and few exhibit CMR and ED potentials. Nevertheless, only one PBT assessment came with a conclusion of PBT identification, 2 RMO analysis and only one CoRAP concluded for no need for further action. The rest analysis and assessments are requesting more data, emphasizing again that the regulatory actions for organic FR are significantly slow. Examples are the assessments for TCPP, HCBH-DCAnh, and TPHP, which are under development since 2013, 2015 and 2017, respectively. The difficulties are related to the physicochemical characteristics and the chemical structure of these compounds as they pose number of limitations for bioassays (Segev et al., 2009). A number of assessed aliphatic OPFRs, TEP, TIBP, TBEP, TEHP (He et al., 2020; Vorkamp et al., 2019; Wei et al., 2015) are not under any regulatory assessment. Yet,. Aliphatic OPFRs can act as plasticizers as well with different ranges of concentration (%w/w) (Wei et al., 2015).

MCCPs belong to the group of non-OPFRs and are alternatives to the POP SCCPs. The RMO analysis for CMR, ED and PBT/vPvB concerns concluded the SVHC nomination and restriction as a more effective regulatory instrument. Additionally, the PBT assessment identified MCCPs as a PBT/vPvB substance. In parallel, the Swedish and German Agency proposed the restriction of MCCPs form EEE under the RoHS regulation (Oeko, 2019b; Swedish Chemicals Agency, 2016).

3.3.3 **REGULATORY OVERVIEW OF INORGANIC FRs**

Inorganic FRs represent a relatively small fraction of FRs. The inventory includes 12 inorganic FRs. Only boric acid and molybdenum trioxide are classified under the CLP. Boric acid is classified as toxic for reproduction, and it is included in the candidate list of SVHC for Authorization since 2010.. The CMR concern initiated a RMOA for molybdenum trioxide, which concluded in 2020 that there is no need for a risk management action. Among the rest of the IFRs, the use of magnesium hydroxide and aluminum hydroxide - which is known as DecaBDE alternative – can be authorized in recycled plastic for food contact material, under Regulation 10/2011/EU.

3.3.4 REGULATORY OVERVIEW OF PIGMENTS AND STABILIZERS

Whereas most materials are post-colored, plastics are normally integrally colored (Haacke et al., 1999). Commercial pigments include organic and inorganic pigments, soluble colorants, and special colorants. Inorganic pigments are based on metal and heavy metal oxides and salts (mostly of titanium, zinc, cobalt, lead, and cadmium). Inorganic pigments can provide further protection as UV or heat stabilizers, fillers, and as FRs synergists (Ambrogi et al., 2017).

Stabilizers are used to slow down the plastics' decomposition during (re)processing and service life (by high temperature, UV light, oxygen). Inorganic stabilizers are based on epoxies, or on calcium, zinc, tin and other metals oxides (Andrady and Rajapakse, 2016; Murphy, 2001). Additionally, stabilizers are added during the mechanical recycling, aiming to reach the initial material quality of plastics (Ragaert et al., 2017). There are different types of stabilizers: heat stabilizers, including metallic salts of barium, cadmium or lead; UV stabilizers and inorganic pigments mostly of white color (titanium dioxide and zinc sulfide) or other color as iron oxide and chromium trioxide (Ambrogi et al., 2017; Andrady, 2015); and antioxidants, mostly based on organic compounds (Murphy, 2001).

Among the 20 inventoried pigments – which could obtain additional properties as UV stabilizers, absorbers, catalysts, fillers, and/or synergistic flame retardants – 13 were under a regulatory action or activity (Figure 6). Cobalt dichloride and cobalt (II) diacetate, providing green/blue color, were identified as SVHC and included in the candidate list for Authorization since 2008 and 2010, respectively. The RMO analysis in 2017 concluded that the proper action is their restriction. The catalyst chromium trioxide was identified as SVHC in 2010 because of its carcinogenic and mutagenic properties, and was included in the Authorization list with entry 16.. Lead compounds, used to obtain green, yellow, or red colors, are restricted under RoHS, with a limit of 0.1 %-wt. The pigments lead chromate, lead chromate molybdate sulphate red, and lead sulfur chromate yellow were identified as SVHC since 2010 and included in Authorization list with entries 10, 12 and 11 – based on the carcinogenic and production toxic properties.

Titanium dioxide is extensively used in plastics as white pigment, UV and light stabilizer, or as filler (Table 2). ECHA proposed its classification as carcinogen cat. 2 by inhalation

(ECHA, 2019b), consistently with IARC. This classification was applied in 2020 on powder solid mixtures containing at least 1 %-wt of TiO_2 (European Commission, 2019b). Zinc oxide and antimony trioxide are also white pigments and UV stabilizers. They are under the CoRAP evaluation for other hazard-based and carcinogenic concerns. The IARC listed antimony trioxide as 2B carcinogenic (Alassali, 2020; Alassali et al., 2019), which is also foreseen as human carcinogen in the US National Toxicology Program (National Toxicology Program, 2018).

There is no risk of exposure to antimony trioxide from plastic products because it is solid bound to the plastics' matrices. Broader contamination may however occur through plastics recycling or incineration (Alassali, 2020; Filella et al., 2020).

Barium carbonate and peroxide, and cobalt oxide are under CLP regulation, yet with no further regulatory restriction. Carbon black is a black pigment that could act as UV stabilizer. Currently, it has no CLP classification, but the CoRAP evaluation started in 2021 due to carcinogenic and reprotoxic risk potentials. This being said, the intentional addition of carbon black to plastic articles is a source of contamination with polycyclic aromatic hydrocarbons (PAHs) (Alassali et al., 2020b, 2020c). The Commission Regulation 1272/2013/EU (European Commission, 2013) banns articles containing rubber or plastic exceeding 0.0001 %-wt of 8 selected PAHs, while toys and childcare items are restricted to 0.00005 %-wt (Alassali et al., 2020c, 2020b) . It can be concluded that inorganic pigments/stabilizers are well regulated since decades as the 65 % of the total number are under regulatory actions (mainly under CLP) compared to the "problematic" FRs.

3.3.5 REGULATORY OVERVIEW OF PHTHALATES PLASTICIZERS

Plasticizers are the largest group of additives, aimed to enhance plastics fluidity and processability. Specifically, plasticizers provide the following properties to plastic products (Subramanian, 2013): viscosity, favorable fusion properties, excellent resistance to stain, extraction and abrasion. Phthalates are the most ubiquitous group of plasticizers. Their main application (10-70 %-wt) is in PVC due to the poor quality of its resins. For over two decades, phthalates attracted scientific interest as endocrine disruptors and toxic compounds for their tendency to migrate from plastic packaging to consumers (Xu et al., 2020).

From the 27 phthalates included in the inventory, 20 were found under a regulatory action or activity (Figure 6), . Hence, this group is the most controlled onemainly due to their toxicity for reproduction and endocrine disruption risks. DIBP, DBP, BBP and DEHP are classified under the CLP and included in the restriction list (Annex XVII) with entry 51. Also, the RoHS 3 limits their presence to 0.1 %-wt. These substances were identified as SVHC due to reproduction hazard, and were included in the Authorization list with entries 07, 06, 05 and 04. They are proven to be endocrine disruptors. Therefore, DIBP and DBP are under the PBT assessment, which is postponed since 2012. DNOP, DINP and DIDP are not under the CLP classification, but they are included in the restriction list with entry 52 and are limited to 0.1 %-wt in toys and childcare items. Six low molecular weight phthalates (i.e., DMEP, DIPP, DPP, DHxP, DnHP and DiHP) are classified toxic for reproduction by the CLP and included in the Authorization list. DCHP and DIHP are nominated SVHC and included to the candidate list for Authorization as endocrine disruptor (DCHP) and toxic for reproduction (DIHP). RMOA considered DEHT and DINCH due to their CMR and ED risks. Nonetheless, it concluded that there is no need for further regulatory action. The CoRAP analysis for DPHP is still ongoing and there is no need for further action for DEHA and DEP. . Furthermore, DEHA are under ED assessment since 2018.

4 CONCLUSIONS

Considering that plastics represent a relevant fraction of the e-waste, e-plastics recycling deserves maximum attention to fulfil the EU targets defined by the new Circular Economy Action Plan. E-plastics recycling is currently limited by the presence of toxic additives, particularly halogenated organic flame retardants. The EU chemical and product frameworks prioritize the environment and human health protection, resulting in stringent recycling guidelines, which in return is strongly limiting the recycling of e-plastics. Additional limitations to the e-plastics recycling are the continuous alterations of the threshold limits for substances in products and wastes, and the unharmonized frameworks. In parallel, the slow and postponed regulatory chemical assessments (mostly for organic FRs) create unfavorable condition for the growth of the e-plastic recycling sector and of the market for SMR.

This review presented an inventory of 145 commercial additives found in e-plastics, providing a comprehensive overview on the existing legislations and activities. Some additives (phthalate plasticizers, and pigments) are already restricted by EU regulations and actions, while others are currently under evaluation as potential candidates for future restrictions. Phthalate plasticizers and pigments/stabilizers were well regulated for decades, showing a wider inclusion in the REACH lists. Nonetheless, many additives are still unregulated, despite the hazardous properties. The reason behind this is the challenging screening assessment for these compounds. The majority of organic FRs, especially the well-studied high concern Benzene derivatives BFRs and aliphatic organophosphate OPFRs, are still lacking of a rigorous assessment.

Design-for-recycling on e-plastics is a design principle addressing their recyclability and therefore including end-of-life considerations at an early life cycle stage. For an efficient application of a design-for-recycling, the application of hazardous chemicals should be controlled from the production stage. Hence, guaranteeing safe products on the market and better recycling rates on end-of-life products. This being said, the ecodesign and eco-label will provide a waste stream that is recyclable and well defined. However, the unambiguous identification of the additives labeled hazardous and/or of high-concern, consistently across all the in-force directives and regulations, is crucial to boost e-plastic recycling, at the same time limiting any risk of diffusion of compounds of concern into the environment. A univocal approach for each additive is needed to provide the whole e-plastics supply chain with a common reference database.

Future regulations should establish realistic and updated threshold limits for high-concern substances in plastics, considering the risk to be exposed and their life cycle as well. A distinction between risk assessments of virgin and recycled article should be made, considering the application of each article and the function of each additive in plastics. Special focus should be given to facilitate the PBT assessments for organic FRs, which are of high concerns, but are not yet properly regulated. This inventory also analyses the relations between substances restriction or regulation and their harmful properties. This could provide a tool for the e-plastic recyclers to understand the future impacts and limitations on e-plastic recycling.

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