

E-plastics in a circular economy: A comprehensive regulatory review

Original

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(Article begins on next page)

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

2

3 **Abstract**

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

24

25 **keywords**

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

27

28 **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

29

30 **1 INTRODUCTION**

31 Electrical and electronic waste (e-waste) is a rapidly growing stream; it globally topped
32 53.6 Mt by 2018, and is predicted to reach 74.7 Mt in 2030 (Forti et al., 2020). Although
33 e-waste represents only 2 %-wt. of the total solid waste stream, it can reach up to 70 %-
34 wt. of all the hazardous waste disposed of in landfills (Allassali et al., 2020a; PACE,
35 2019).The plastic casings of electrical and electronic equipment (EEE) contain various
36 types and concentrations of additives, as pigments, flame retardants, impact modifiers,
37 and plasticizers. Many of which are classified hazardous(Andersson et al., 2019).

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

- 49 • Chemicals should comply with the requirements of the Registration, Evaluation,
50 Authorization and Restriction of Chemicals (REACH) regulation 1907/2006/EC and its
51 reviews. Any substance involved in Annex XVII is allowed on the EU market only if its
52 production was approved or if a specific application is included in Annex XIV with
53 limitations (European Parliament, 2006).
- 54 • There are specific product legislations regulating the use of chemical substances
55 in products (e.g., food packaging, EEE, etc.).
- 56 • When materials are considered for reuse or recycling after disposal, hazardous
57 materials should be restricted (article 6.1.d of Waste Framework Directive (WFD)
58 2008/98/EC) (European Parliament, 2008a). EU regulations on hazardous waste are
59 based on the Globally Harmonized System, executed through the Classification,
60 Labelling and Packaging (CLP) regulation 2008/1272/EC (European Parliament, 2008b).

61

62 However, the current guidelines and legislations can't catch up with the circular economy
63 market, and plastics containing toxic compounds derived from e-waste can be input

64 material for other plastic products when recycling is applied. A worth-mentioning example
65 is the presence of chemical substances derived from e-plastic in black food packaging
66 and trays (Turner, 2018). The scientific research on e-plastic waste management
67 focused on the development of recycling processes (among the others, Dewulf et al.,
68 2019; Dogu et al., 2021; Wagner et al., 2019), on the assessment of the environmental
69 impacts (among the others, Jiang et al., 2020; Reimonn et al., 2019; Turner, 2018), and
70 on the design of guidelines for circularity and recyclability for plastics and EEE (among
71 the others, Berwald et al., 2021; Ragaert et al., 2020). Despite the growing concern about
72 e-plastics management, the critical analysis of the EU regulatory framework is still limited
73 and mainly discussing legacy or regulated additives, in addition to the control of
74 hazardous waste, without considering the urgent need for recycling the actual e-waste
75 stream (Sharkey et al., 2020; Wagner and Schlummer, 2020). To our knowledge, a
76 systematic overview of the complementary aspect of the application of unregulated
77 additives is currently missing. Also, the future trend of the limitation of e-plastic additives
78 needs to be assessed. Therefore, this review compiled an inventory for the commercial
79 additives found in e-plastics, while analyzing the current European regulatory and
80 legislative frameworks. The aim of this review is threefold. The first aim is to understand
81 the future trends, gaps, and limitations of the EU regulations on e-plastics from the
82 viewpoint of the circular economy concept. Secondly, the aim is to summarize the
83 hazards of non-legacy high-concern flame retardant (FR) additives, which can be
84 restricted and/or limited in the future. Finally, further regulatory actions to avoid the
85 “regrettable substitution” of additives (i.e., the substitution of hazardous compounds with
86 other additives equally harmful, or potentially worse) are suggested.

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

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

92 **2 METHODOLOGY**

93 A thorough literature review was performed (Figure 1) through four main steps. In step
94 1, the scientific publications and EU regulations were scrutinized to retrieve information
95 on the additives that are typically used in e-plastic's manufacturing. Afterwards, a
96 database of the additives (intentionally added substances, IAS) was built (Step 2) and
97 their existing regulatory thresholds were cross-checked with the European Chemical
98 Agency (ECHA) database (www.echa.europa.eu) (Step 3). Finally, a full inventory of the
99 additives was set-up, containing complete information on the additives' main
100 applications, functions, and threshold limits across the existing regulations. The
101 mentioned steps are described below.

102 **2.1 LITERATURE AND REGULATORY REVIEW**

103 The literature review considered European legislations, scientific articles, and technical
104 reports. On the other hand, the regulatory review included regulations and directives
105 covering waste management, the regulation of substances and products – with focus on
106 plastic articles. The regulatory review was based on the official website of the EU
107 regulations (<https://eur-lex.europa.eu/homepage.html>). The framework and
108 communication documents from the European Commission (EC) on “circular economy”,
109 “chemicals” and “plastics” were derived from the official website of the EC
110 (https://ec.europa.eu/environment/index_en). The review of scientific articles, books and
111 technical reports was focused on additives and hazardous substances in e-plastics, and
112 on the environmental and health hazards of selected additives (e.g., brominated flame
113 retardants (BFRs) and Organophosphate flame retardants (OPFRs)). The keywords
114 “hazardous additives”, “e-waste”, “plastic additives”, “emerging flame retardants” and

115 “plastic recycling” in different combinations were applied on the bibliometric databases
116 Scopus, Science Direct and Google Scholar. In this review, flame retardants (FR) were
117 assessed in terms of their toxicity effects and regulatory view. Some of the previously
118 used FR in the manufacture of e-plastics were identified as POPs. The most common is
119 the BFRs. Whilst these substances were legitimately added to plastics at the point of
120 manufacture, they are now prohibited under the Stockholm Convention. These
121 substances were already identified and regulated. In this review, a thorough analysis was
122 conducted to summarize the additives used in e-plastics and to identify their
123 characteristics/toxicity when recycling is applied. Plastics containing POPs are not to be
124 recycled and they should be treated in a way to destroy these components. Hence, POPs
125 were of a less relevance to this study, when focusing on e-plastics circularity. FRs and
126 additives that were characterized as POPs were mentioned together with their threshold
127 limits.

128 The selected references (64.5 % published after 2016) consisted of: 55 journal articles,
129 37 technical reports, 10 books and chapters and 19 official documents of the EU. Figure
130 2a shows the number of selected references per year of publication and per the selected
131 keywords “plastic additives” (60), “e-plastics” (10), “plastic recycling” (9), the official
132 documents of the EU legislation and policy (19), and the studies supporting the regulatory
133 framework of e-waste and e-plastics (23). The number of regulatory support studies and
134 the EU legislation and policy documents indicates a tangible increase in the last decade,
135 mostly after 2016. This trend was possibly influenced by the publication of the first
136 Circular Economy action plan of the EC in December 2015.

137 The keyword “plastic additives” is very general; it encompasses different types of
138 chemical substances. Hence, a further distinction was applied to the references. Figure
139 2b shows the distinction of the references per the keywords “general FRs” (flame
140 retardants) (8), “BFRs” (brominated FRs) (8), “OPFRs” (organophosphate FRs) (9),

141 “Novel FRs” (10), “Additives (pigments, stabilizers, plasticizers)” (13) and “POPs,
142 hazardous substances” (12), and per year of publication. The continuously increasing
143 literature on POPs and hazardous substances in e-plastics since 2008 can reflect the
144 high scientific interest in response to the emerging restrictions of PBBs (polybrominated
145 biphenyls), PBDEs (polybrominated diphenyl ethers) and heavy metals from EEE by the
146 RoHS directive. An increase in literature of studies on alternatives of banned BFRs or
147 novel BFRs (NBFRs) after 2010 was triggered by the labeling of hexabromobenzene,
148 and tetra, penta, hexa, hepta BDEs (brominated diphenyl ethers) as POPs by Stockholm
149 Convention in 2009 (UNEP, 2009).

150 **2.2 COMPILATION OF THE E-PLASTICS ADDITIVES INVENTORY**

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

166 rolling action plan (CoRAP), the regulatory management option analysis (RMOA), the
 167 Persistence Bioaccumulation and Toxicity (PBT) assessment, and the endocrine
 168 disruptor (ED) assessment.

169

170 Table 1. Online lists accessed on ECHA official website during the regulatory
 171 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

172

173 The lists of CoRAP, RMOA, PBT and ED assessments do not belong to the regulatory
 174 actions yet, but it is important to evaluate the potential future updates to the relevant
 175 regulations. The extraction and classification of the hazard statement codes of
 176 compounds labeled hazardous from Table 3.1 of Annex VI of the CLP regulation list was
 177 important to assess the degree of environmental and health hazard effects. To facilitate
 178 the process, the hazard statement codes were extracted from the Classification and
 179 Labelling (C&L) inventory on the ECHA official website, which included the most recent
 180 consolidated version. The hazard statement codes of the non-harmonized, yet classified

181 compounds, were retrieved from the C&L Inventory. These were classified according to
182 the notifications received through the REACH registration process. However, C&L
183 inventory self-classification does not pose any regulatory action. According to the
184 outcomes of the step 1 (literature survey), 145 additives were included in the database
185 defined in step 2. The detailed inventory is provided in the supplementary material. The
186 additives of the inventory are classified into BFRs, OPFRs, inorganic FRs, phthalate
187 plasticizers, pigments as subgroups of modifiers (FRs, plasticizers, fillers), pigments, and
188 protective additives (stabilizers and anti-degradation) (Figure 3). Their amounts may vary
189 largely (from 0.001 % to 60 %-wt. of the plastic article), depending on their type.

190 3 RESULTS AND DISCUSSION

191 3.1 EU REGULATORY FRAMEWORKS

192 3.1.1 ACTIONS ON PRODUCTS AND E-WASTE MANAGEMENT TOWARDS CIRCULAR ECONOMY

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

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

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

230 (Annex IV). The aim was to ensure that the listed POP FRs (PBDEs, HBB, HBCD,
231 SCCPs) with concentration values exceeding the limits of Annex IV would not re-enter
232 the manufacturing process through recycling, and would instead be treated in
233 accordance with the disposal operations of Annex V. Hence, items containing the listed
234 POP additives in concentrations below the defined limit of Annex IV can be recycled. For
235 the sum of the banned PBDEs, the threshold is 1000 mg kg⁻¹ which is under review for
236 further decrease to 500 mg kg⁻¹. Their concentration limits in the secondary raw materials
237 (SRMs) should comply with the concentration limits of Annex I, since their presence can
238 fall under the article 4b. Among the POP labeled substances, the concentration limits on
239 EEE products for the RoHS restricted PBDEs are exempted and harmonized by RoHS
240 2. The concentration limits in the SRMs as per Annex I should be below 10 ppm (or below
241 500 ppm when the total PBDEs content is considered). These threshold limits are
242 foreseen to be revised again in July 2021.

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

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

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

259 Another action on toxic-free content is the regulation 66/2010/EC on Eco-label. This is
260 a pledge aimed to initiate the substitution of hazardous materials in products (European
261 Parliament, 2009). Among the requirements for the Eco-label award, the products should
262 not contain the hazardous substances included in Annex VI of the CLP regulation and
263 should not be included in the candidate list of SVHC for authorization under the REACH
264 regulation. The Eco-label initiative may facilitate the separation needs for recycling and
265 facilitate the transparency on chemical content of plastic products, which is one of the
266 main obstacles for recyclers (De Tandt et al., 2021; European Commission, 2018a). The
267 new EU strategy for sustainable chemicals and a toxic free environment, launched in
268 October 2020, aspires to initiate actions for transparency on the chemicals' content in
269 products while preparing further restrictions for toxic substances in consumers' articles.
270 The actions focus on subsidizing technologies for decontaminating the waste streams to
271 guarantee the safety of the SRMs and to increase their uptake in the market (European
272 Commission, 2020b). Among the actions for transparency is initiating activities on
273 tracking hazardous substances in waste and sharing the information on open-source
274 data bases. Until now, the majority of detailed data bases for e-plastic additives are
275 provided from academic and technical publications (e.g. Andersson et al., 2019; Groh et
276 al., 2019; Groß et al., 2008; Hansen et al., 2014; Lassen et al., 2014; Stenmarck et al.,
277 2017).

278

279 3.1.2 CHALLENGES AND POLICY GAPS ON THE APPLICATION OF CIRCULAR ECONOMY ON E-
280 PLASTICS

281 Several studies demonstrated that e-plastics recycling is challenged by the presence of
282 hazardous and high-concern substances (Crippa et al., 2019; Dahlbo et al., 2018; Delva
283 et al., 2018), since their fate and behavior during recycling is still unknown (Crippa et al.,
284 2019; Hahladakis and Iacovidou, 2019). Hence, the ecodesign principle should be
285 applied by controlling the application of hazardous substances. At present, the
286 application of the eco-design requirement of e-plastics is still limited. Therefore, it is
287 necessary for the recycling industries to separate the e-waste stream in accordance with
288 the WFD, POP and CELENEC requirements, in order to eliminate the recirculation of
289 hazardous substances. However, in practice, the identification of hazardous substances
290 in accordance with policy thresholds is very challenging. The most common techniques
291 used to separate plastics containing BFRs from a mixed plastic stream are X-ray
292 fluorescence (XRF) spectroscopy, near-infrared (NIR) spectroscopy and density
293 separation (Wagner et al., 2019; Wagner and Schlummer, 2020). The POP threshold of
294 10 ppm in the SRMs cannot be measured in practice, as industrial XRF cannot provide
295 a validated measurement for concentrations below 1,000 ppm (EURACTIV, 2020).
296 Considering this practical obstacle, which needs expensive investments in form of
297 analytical analyses (e.g., GC-MS), small-size recycling companies may not consider the
298 supply of SRMs as a profit business (EURACTIV, 2020; Haarman et al., 2020).
299 In 2018, the European Strategy for Plastics in a Circular Economy initiated the Circular
300 Plastics Alliance (CPA) ([https://ec.europa.eu/growth/industry/policy/circular-plastics-](https://ec.europa.eu/growth/industry/policy/circular-plastics-alliance_en)
301 [alliance_en](https://ec.europa.eu/growth/industry/policy/circular-plastics-alliance_en)), a voluntary ambitious action aimed to introduce more than 10 Mt of recycled
302 plastics by 2025. The current trend reveals that 1.3 Mt are annually collected in the EU,
303 with 1.0 Mt sent to the plastic recycling facilities, resulting in 555 kt of SRM (Haarman et
304 al., 2020). The relatively low amount of the generated SMR emphasizes the need for

305 boosting the recycling rate to reach the ambitious goals of the EC. At the same time, the
306 continuously increasing number of directives on products (Figures 4 and 5), waste
307 recycling, and SRMs along with many ongoing discussions created an unstable situation
308 for investments in the circular economy market for e-plastics. Hence, having too many
309 regulations talking for the same substances (EURACTIV, 2020), creates a great
310 confusion about the instructions, resulting in hindered recycling rates. Consequently, the
311 request for harmonization and stabilization became a priority (EURACTIV, 2020; EuRIC,
312 2019; Haarman et al., 2020). The EU tries to face this challenge with the “one substance
313 – one assessment” approach, to generate a uniform hazard assessment . Namely, the
314 concentration limit of legacy substances should be equal for virgin and recycled
315 materials, to improve the safety of the SRMs and increase their uptake in the market.
316 However, at the same time more plastic will be left out of the circular economy, due to
317 challenging and costly removal of legacy substances from the e-plastic stream (Katrakis
318 et al., 2017; Ügdüler et al., 2020).

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

327 The new Circular Economy Action Plan stated that in 2021 EU will review RoHS and
328 REACH regulations, promote policy objectives on circular electronics, and revise the
329 ecodesign regulation (European Commission, 2020c). But the continuous alterations of
330 the threshold limits in the adopted legislations cannot support the application of the

331 circular economy on EEE, especially for units with extended lifetime. Sorting the waste
332 stream respecting the 100-500 ppm of POPs is not cost-affordable (Andersson et al.,
333 2019; Bill et al., 2019; Delva et al., 2018). Additionally, the fraction of WEEE with PBDEs
334 has considerably decreased over the years (Haarman et al., 2020). Also, the Br content
335 in WEEE is decreasing and only a small fraction of older devices exceeds the RoHS limit,
336 while only 8 % of the BFRs in the market is restricted (Eera, 2018; Jandric et al., 2020).
337 As a response, stakeholders request the rise of the Bromine's threshold limit to 6,000
338 ppm for the aim of increasing the amount of recyclable e-plastics (Haarman et al., 2020).
339 Therefore, instead of establishing stricter threshold limits, the policy makers should
340 adjust the limits to the current waste streams and respect the industry's capabilities.

341 3.2 ACTIONS ON CHEMICAL MANAGEMENT AND CONTROL

342 3.2.1 ECHA AND REACH REGULATION

343 The REACH regulation 1907/2006/EC concerning the Registration, Evaluation,
344 Authorization and Restriction of Chemical, entered into force in 2007. Its main goal is to
345 ensure and control that all substances and products are manufactured and used safely
346 to protect the consumers and to promote a good communication among all actors of the
347 supply chain. Producers and importers of substances with volumes exceeding 1.0 t y^{-1}
348 are obliged to present a detailed technical dossier to ECHA (European Parliament,
349 2006). Additionally, according to the regulation 850/2004/EC (European Parliament,
350 2004), REACH is the appropriate instrument to implement the necessary control
351 measures on production, placing on the market, and use of the POP substances. The
352 importers and producers need to provide information about the classification and labeling
353 of the substances through the technical dossier or can self-classify and notify the
354 substance to the Classification and Labeling inventory (C&L) according to the CLP
355 criteria. Additionally, they can notify ECHA if the substance can have a harmonized

356 classification and labeling not included in the CLP regulation. However, ECHA cannot
357 evaluate these notifications and the C&L notified classification does not have any legal
358 effect. ECHA is the appropriate instrument to coordinate REACH actions and activities
359 towards the safety of consumers and the environment. This includes the registration of
360 substances, evaluation of the registered substances in cooperation with the authorities
361 of the EU member states, identification and controlling of substances of very high
362 concern (SVHC). Moreover, ECHA set limitations for substances through their inclusion
363 in the list of Annex XVII when their risk has been determined, and authorize SVHC
364 through their inclusion in the list of Annex XIV. When a substance is included in the
365 ECHA, its use is prohibited unless an exception is granted which is a high-cost
366 procedure.

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

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

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

381 Nowadays, 211 registered substances were identified as SVHC and are included in the
382 candidate list for authorization (refer to the supplementary material). Some have already
383 been restricted by REACH (ECHA, 2021). Considering e-plastics, the SVHC list includes:
384 15 phthalates plasticizers; 2 Chlorinated Flame Retardants (CFRs) (i.e., Tris(2-
385 chloroethyl) phosphate - TCEP and Short-chain chlorinated paraffins - SCCPs); 1 PFR
386 (trixylyl phosphate - TXP); 2 BFRs (i.e., decabromodiphenyl ether – decaBDE and
387 hexabromocyclododecane - HBCDD); and lead and cadmium with their compounds
388 (Andersson et al., 2019). Since the replacement of SVHC is done using substances of
389 analogous function, most compounds present structural similarities and health and
390 environmental risks (Swedish Chemicals Agency, 2018). Among the most studied non
391 legacy substances of “regrettable substitution” are BEH-TEBP, EH-TBB, PBT and TBP-
392 AE, replaced by the POPs pentaBDE, DBDPE, TBBPA, BTBPE. These substances have
393 been found to be more persistent and bioaccumulated than the replaced additives (de
394 Wit et al., 2010; Eljarrat and Barceló, 2011; Vorkamp et al., 2019).

395

396 3.2.2 CHALLENGES OF THE SVHC IDENTIFICATION PROCESS

397 Regulatory management option analysis (RMOA) has generally been introduced to
398 facilitate the identification of SVHC once a substance is selected to be a candidate by a
399 manual screening (Swedish Chemicals Agency, 2018). It can propose the most
400 appropriate regulatory action. Although the conclusion does not have a legal power, it
401 can propose to initiate a risk assessment (ECHA, 2013). The substances that should
402 undergo evaluation by a member state (as per the selection criteria) follow the
403 Community Rolling Plan (CoRAP). Among the selection are PBT and ED indications and
404 CMR potentials. Both, CoRAP and RMO analysis can take place simultaneously, along
405 with the PBT and ED assessments. However, the SVHC identification can be a long

406 process, due to the absence of data. Around 64 % of substances found under the
407 substance evaluation lack the necessary information (Loonen et al., 2019). Considering
408 the case of the most widespread BFR (TBBPA), it is under the PBT and ED assessments
409 since 2012 with no final conclusion, while the CoRAP have asked for data since 2017
410 (ECHA, 2017b).

411 Another obstruction slowing down the SVHC identification is that REACH obliges data
412 registration based on the produced or imported volumes. Namely, the safety data sheet
413 – including the PBT/vPvB assessment and health hazard, physicochemical hazard, and
414 environmental hazard assessments – should be only provided for volumes of rather than
415 10 tonnes. Accordingly, substances produced or imported in volumes less than 10 tonnes
416 cannot be selected for the SVHC identification, since the information of PBT/vPvB
417 assessment is missing. In response to that, ECHA recently started actions to increase
418 the registration requirements of technical dossier for low tonnage substances in
419 compliance with REACH by 2027 (ECHA, 2019a). Moreover, the data for the registration
420 requirements seems to be insufficient to provide information about the substance's
421 carcinogenic and mutagenic properties; these studies are expensive and require years
422 (Woutersen et al., 2019).

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

432 the recyclers need to submit a safety data sheet to ECHA. Hence, the authorization of
433 wastes containing SVHC is associated with high costs (De Tandt et al., 2021).
434 Due to the high cost of the required assessments (e.g., PBT assessment, short and
435 chronic ecotoxicity screening tests), completing the technical dossier is very challenging.
436 Accordingly, 75% of the dossiers are based on read-across data instead of experimental
437 results (Loonen et al., 2019). Considering the organic FRs, they pose limitations to
438 screening tests for persistence and bioaccumulation, and to bioassays for the short and
439 chronic ecotoxicity assessments in aquatic species due to their relatively high molecular
440 weight and low water solubility (Segev et al., 2009). Hence the experimental data for
441 these additives are scarce (Gramatica et al., 2016; Scheringer et al., 2012; Stieger et al.,
442 2014). Moreover, an alternative low-cost method accepted by REACH to submit data for
443 the required assessments is the use of quantitative structure activity relationship (QSAR)
444 models. There is a great number of free (Q)SAR tools. However, it is challenging to use
445 them. A careful evaluation is necessary to achieve a correct prediction (Petoumenou et
446 al., 2015; Zachary and Greenway, 2009). In conclusion, SVHC identification is a very
447 challenging and time-consuming process and only high tonnage compounds with a
448 compliance dossier can be screened if they meet the SVHC criteria.

449 3.3 INVENTORY OF THE E-PLASTICS ADDITIVES

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

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

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

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

494

495 Table 2. Summary of the inventoried compounds of concern in e-plastics presented in
 496 section 3.3 divided into BFRs, OPFRs, inorganic FRs, pigments and stabilizers, and
 497 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
Triaryl phosphate	TXP	25155-23-1
Tris(1-Chloro-2-propyl) phosphate	T CPP	13674-84-5
1,4,5,6,7,7-hexachloro-8,9,10-trinorborn-5-ene-2,3-dicarboxylic anhydride	HCBH-DCAh	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
Diisoheptyl 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

498

499 3.3.1 REGULATORY OVERVIEW OF BFRs

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

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

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

536 BTBPE and EH-TBB (which are alternatives for banned decaBDE and pentaBDE), and
537 the benzene derivatives, PBT, PBEB, HBBz and TBX have been having a great scientific

538 interest for more than a decade now. A high number of studies have proven them to be
539 persistent, bioaccumulative and have the ability for long range transport (e.g., Arctic pole)
540 (Covaci et al., 2011; de Wit et al., 2010; Li et al., 2019; Vorkamp et al., 2019). On top of
541 that, UNEP has addressed BTBPE and HBBz as emerging BFRs (UNEP, 2019). Despite
542 all the concerns, they are not under any regulation, activity or even CLP Regulation.

543 3.3.2 REGULATORY OVERVIEW OF OPFRs

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

553 TCEP and TXP are both included in the Authorization list as SVHC, since they are toxic
554 for reproduction with entry in Annex XIV of 13 and 47, respectively. In total, 11 OPFRs
555 are under CoRAP regulatory activities and RMO analysis, 4 are under PBT assessment,
556 and 2 are under ED assessment., Like BFRs, PBT concern is the most common reason
557 for assessment and few exhibit CMR and ED potentials. Nevertheless, only one PBT
558 assessment came with a conclusion of PBT identification, 2 RMO analysis and only one
559 CoRAP concluded for no need for further action. The rest analysis and assessments are
560 requesting more data, emphasizing again that the regulatory actions for organic FR are
561 significantly slow. Examples are the assessments for TCPP, HCBH-DCAh, and TPHP,
562 which are under development since 2013, 2015 and 2017, respectively. The difficulties

563 are related to the physicochemical characteristics and the chemical structure of these
564 compounds as they pose number of limitations for bioassays (Segev et al., 2009). A
565 number of assessed aliphatic OPFRs, TEP, TIBP, TBEP, TEHP (He et al., 2020;
566 Vorkamp et al., 2019; Wei et al., 2015) are not under any regulatory assessment. Yet,
567 Aliphatic OPFRs can act as plasticizers as well with different ranges of concentration
568 (%w/w) (Wei et al., 2015).

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

575 3.3.3 REGULATORY OVERVIEW OF INORGANIC FRs

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

584 3.3.4 REGULATORY OVERVIEW OF PIGMENTS AND STABILIZERS

585 Whereas most materials are post-colored, plastics are normally integrally colored
586 (Haacke et al., 1999). Commercial pigments include organic and inorganic pigments,
587 soluble colorants, and special colorants. Inorganic pigments are based on metal and

588 heavy metal oxides and salts (mostly of titanium, zinc, cobalt, lead, and cadmium).
589 Inorganic pigments can provide further protection as UV or heat stabilizers, fillers, and
590 as FRs synergists (Ambrogi et al., 2017).

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

600 Among the 20 inventoried pigments – which could obtain additional properties as UV
601 stabilizers, absorbers, catalysts, fillers, and/or synergistic flame retardants – 13 were
602 under a regulatory action or activity (Figure 6). Cobalt dichloride and cobalt (II) diacetate,
603 providing green/blue color, were identified as SVHC and included in the candidate list for
604 Authorization since 2008 and 2010, respectively. The RMO analysis in 2017 concluded
605 that the proper action is their restriction. The catalyst chromium trioxide was identified as
606 SVHC in 2010 because of its carcinogenic and mutagenic properties, and was included
607 in the Authorization list with entry 16.. Lead compounds, used to obtain green, yellow, or
608 red colors, are restricted under RoHS, with a limit of 0.1 %-wt. The pigments lead
609 chromate, lead chromate molybdate sulphate red, and lead sulfur chromate yellow were
610 identified as SVHC since 2010 and included in Authorization list with entries 10, 12 and
611 11 – based on the carcinogenic and production toxic properties.

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

614 (ECHA, 2019b), consistently with IARC. This classification was applied in 2020 on
615 powder solid mixtures containing at least 1 %-wt of TiO₂ (European Commission, 2019b).
616 Zinc oxide and antimony trioxide are also white pigments and UV stabilizers. They are
617 under the CoRAP evaluation for other hazard-based and carcinogenic concerns. The
618 IARC listed antimony trioxide as 2B carcinogenic (Alassali, 2020; Alassali et al., 2019),
619 which is also foreseen as human carcinogen in the US National Toxicology Program
620 (National Toxicology Program, 2018).

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

624 Barium carbonate and peroxide, and cobalt oxide are under CLP regulation, yet with no
625 further regulatory restriction. Carbon black is a black pigment that could act as UV
626 stabilizer. Currently, it has no CLP classification, but the CoRAP evaluation started in
627 2021 due to carcinogenic and reprotoxic risk potentials. This being said, the intentional
628 addition of carbon black to plastic articles is a source of contamination with polycyclic
629 aromatic hydrocarbons (PAHs) (Alassali et al., 2020b, 2020c). The Commission
630 Regulation 1272/2013/EU (European Commission, 2013) bans articles containing
631 rubber or plastic exceeding 0.0001 %-wt of 8 selected PAHs, while toys and childcare
632 items are restricted to 0.00005 %-wt (Alassali et al., 2020c, 2020b) . It can be concluded
633 that inorganic pigments/stabilizers are well regulated since decades as the 65 % of the
634 total number are under regulatory actions (mainly under CLP) compared to the
635 "problematic" FRs.

636 3.3.5 REGULATORY OVERVIEW OF PHTHALATES PLASTICIZERS

637 Plasticizers are the largest group of additives, aimed to enhance plastics fluidity and
638 processability. Specifically, plasticizers provide the following properties to plastic

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

645 From the 27 phthalates included in the inventory, 20 were found under a regulatory action
646 or activity (Figure 6), . Hence, this group is the most controlled onemainly due to their
647 toxicity for reproduction and endocrine disruption risks. DIBP, DBP, BBP and DEHP are
648 classified under the CLP and included in the restriction list (Annex XVII) with entry 51.
649 Also, the RoHS 3 limits their presence to 0.1 %-wt. These substances were identified as
650 SVHC due to reproduction hazard, and were included in the Authorization list with entries
651 07, 06, 05 and 04. They are proven to be endocrine disruptors. Therefore, DIBP and DBP
652 are under the PBT assessment, which is postponed since 2012. DNOP, DINP and DIDP
653 are not under the CLP classification, but they are included in the restriction list with entry
654 52 and are limited to 0.1 %-wt in toys and childcare items. Six low molecular weight
655 phthalates (i.e., DMEP, DIPP, DPP, DHxP, DnHP and DiHP) are classified toxic for
656 reproduction by the CLP and included in the Authorization list. DCHP and DIHP are
657 nominated SVHC and included to the candidate list for Authorization as endocrine
658 disruptor (DCHP) and toxic for reproduction (DIHP). RMOA considered DEHT and
659 DINCH due to their CMR and ED risks. Nonetheless, it concluded that there is no need
660 for further regulatory action. The CoRAP analysis for DPHP is still ongoing and there is
661 no need for further action for DEHA and DEP. . Furthermore, DEHA are under ED
662 assessment since 2018.

663 4 CONCLUSIONS

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

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

685 Design-for-recycling on e-plastics is a design principle addressing their recyclability and
686 therefore including end-of-life considerations at an early life cycle stage. For an efficient
687 application of a design-for-recycling, the application of hazardous chemicals should be

688 controlled from the production stage. Hence, guaranteeing safe products on the market
689 and better recycling rates on end-of-life products. This being said, the ecodesign and
690 eco-label will provide a waste stream that is recyclable and well defined. However, the
691 unambiguous identification of the additives labeled hazardous and/or of high-concern,
692 consistently across all the in-force directives and regulations, is crucial to boost e-plastic
693 recycling, at the same time limiting any risk of diffusion of compounds of concern into the
694 environment. A univocal approach for each additive is needed to provide the whole e-
695 plastics supply chain with a common reference database.

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

705

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713

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