



**HAL**  
open science

## Value-added products from thermochemical treatments of contaminated e-waste plastics

Pallab Das, Jean-Christophe P Gabriel, Chor Yong Tay, Jong-Min Lee

► **To cite this version:**

Pallab Das, Jean-Christophe P Gabriel, Chor Yong Tay, Jong-Min Lee. Value-added products from thermochemical treatments of contaminated e-waste plastics. *Chemosphere*, 2021, 269, pp.129409. 10.1016/j.chemosphere.2020.129409 . cea-03097050

**HAL Id: cea-03097050**

**<https://cea.hal.science/cea-03097050>**

Submitted on 5 Jan 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Value-added products from thermochemical treatments of**  
2 **contaminated e-waste plastics – A review**

3 Pallab Das<sup>1,2</sup>, Jean-Christophe P. Gabriel<sup>1,3</sup>, Chor Yong Tay<sup>1,4,5</sup>, Jong-Min Lee<sup>1,2</sup>

4 <sup>1</sup>Energy research institute, Nanyang Technological University, SCARCE Laboratory 50 Nanyang  
5 Drive, Singapore 639798, Singapore

6 <sup>2</sup>School of Chemical and Biomedical Engineering, Nanyang Technological University, 62 Nanyang  
7 Drive, Singapore 637459, Singapore

8 <sup>3</sup>Université Paris-Saclay, CEA, CNRS, NIMBE, 91191, Gif-sur-Yvette, France.

9 <sup>4</sup>School of Materials Science and Engineering, Nanyang Technological University, N4.1, 50 Nanyang  
10 Avenue, Singapore 639798, Singapore

11 <sup>5</sup>School of Biological Sciences, Nanyang Technological University, 60 Nanyang Drive, Singapore  
12 637551, Singapore

## 13 **Abstract**

14 The rise of electronic waste (e-waste) generation around the globe has become a major concern  
15 in recent times and their recycling is mostly focussed on the recovery of valuable metals such  
16 as gold (Au), silver (Ag) and copper (Cu) etc. However, a significant weight fraction of e-waste  
17 consists of plastics (25 – 30%) that are either discarded or incinerated. There is a growing need  
18 for recycling of these e-waste plastics majority of them are made from high-quality polymers  
19 (composites) such as acrylonitrile butadiene styrene (ABS), high impact polystyrene (HIPS);  
20 polycarbonate (PC); polyamide (PA); polypropylene (PP); and epoxies. However, these  
21 plastics are contaminated with hazardous materials such as brominated flame retardants (BFRs)  
22 and heavy metals (such as lead and mercury). Under any thermal stress, the bromine element  
23 (Br) present in the e-waste plastics produces environmentally hazardous pollutants, such as  
24 hydrogen bromide or polybrominated diphenyl ethers/furans (PBDE/Fs). The discarded  
25 plastics can lead to the leaching of toxins into the environment. Therefore, removal of the toxics  
26 chemicals from the e-waste plastics is pre-requisite before considering any thermal process.  
27 This review article gives a detailed account of e-waste plastics recycling and recovery using  
28 thermochemical processes, such as extraction and pyrolysis. A basic framework of the existing  
29 processes has been established by reviewing the most interesting findings in recent times and  
30 the prospects that they open in the field recycling of e-waste plastics.

31 **Key words:** e-waste plastic, brominated flame retardants, pyrolysis, extraction and  
32 solvothermal treatment

33

34

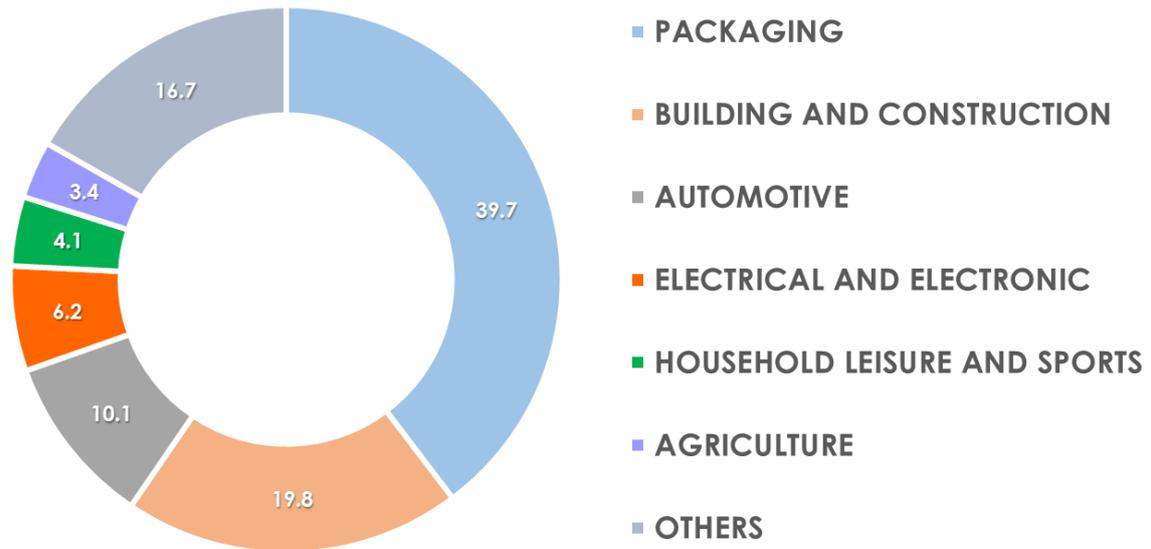
35

36	<b>Contents</b>		
37	1	Introduction	4
38	2	Plastic waste and its environmental impact	10
39	3	Plastic waste management and disposal techniques	14
40	3.1	Primary and secondary (mechanical) recycling	15
41	3.2	Tertiary (chemical and thermal) recycling	17
42	4	Removal of toxic molecules from e-waste plastics	19
43	4.1	Removal of Brominated flame retardants from e-waste plastics	20
44	4.2	Solvothermal processes to remove BFRs from e-plastic	20
45	5	Thermochemical treatment of plastic waste	23
46	5.1	Incineration/combustion process for plastic disposal:	23
47	5.2	Pyrolysis of plastic waste	26
48	5.3	Catalytic pyrolysis of plastics	29
49	5.3.1	Bromine fixation from BFR containing e-waste plastics degradation	30
50	5.4	Effect of pyrolysis reactor configuration	34
51	5.4.1	Batch/semi-batch reactor	34
52	5.4.2	Fluidized bed reactor	34
53	5.4.3	Two stage pyrolysis reactor	35
54	5.4.4	Auger (screw kiln) reactor	36
55	5.4.5	Microwave assisted pyrolysis	37
56	6	Conclusion and outlooks	39
57			

## 58 **1 Introduction**

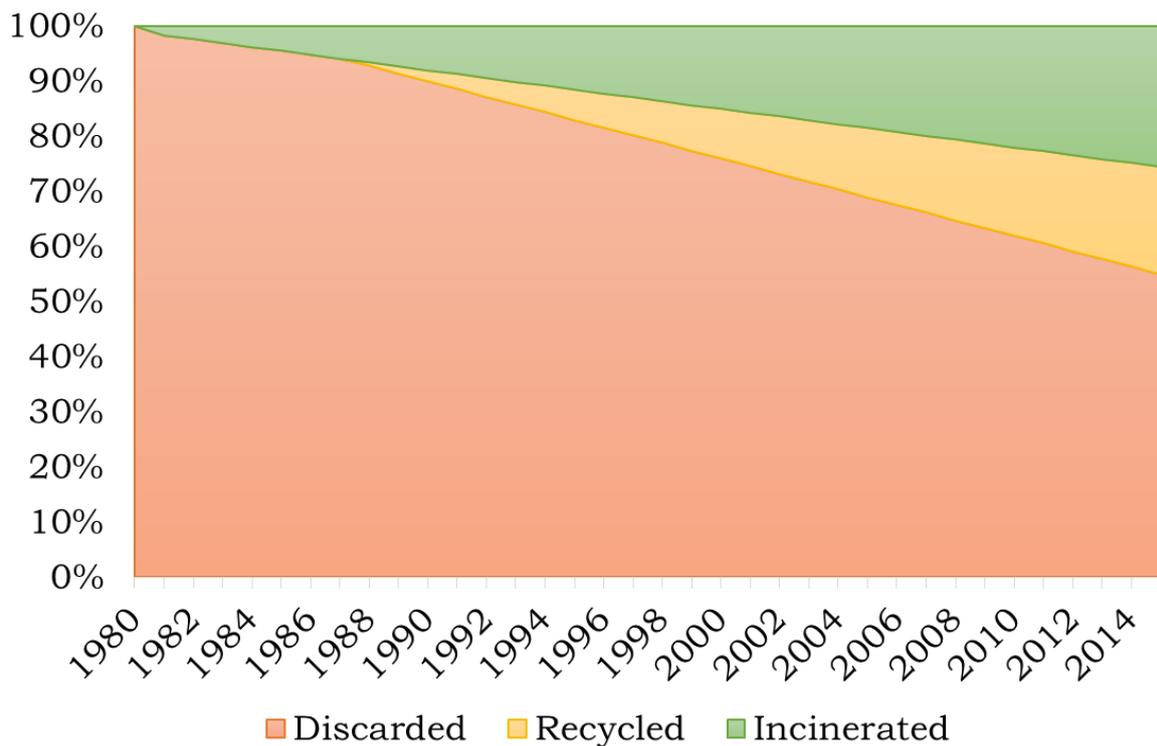
59 Plastics are considered as synthetic and semisynthetic materials that are produced from large  
60 organic molecules, mixed with different additives, like flame retardants, stabilizers,  
61 plasticizers, colours and pigments. Additives improve the physical and chemical properties of  
62 the plastic end products. Extensive use of plastics in the manufacturing industry could be  
63 attributed to their superior physical and chemical properties, such as high tensile strength,  
64 durability, lightweight, flexibility, heat and chemical resistance etc. A recent report estimated  
65 that till date the production of virgin plastics amounted to 8300 million metric tons (MMT) and  
66 out of which 6300 MMT becomes waste (Geyer et al., 2017).

67 Both plastic production and plastic generation have been increasing due to wide spread  
68 application of plastics and its low life span such packaging plastics. Sector wise demand of  
69 plastics in Europe is shown in Fig. 1. It was estimated in 2015, that around 55 percent of global  
70 plastic waste was discarded, 25 percent was incinerated and only 20 percent was recycled (Fig.  
71 2). Out of the total plastic waste produced between 1950 and 2015, only 9 percent was recycled  
72 (Geyer et al., 2017). Most of the discarded plastics are non-biodegradable and take hundreds  
73 of years to degrade naturally. The majority of plastics waste can be traced back to its original  
74 source such as packaging, building material and automobile waste. However, only 6-7% of  
75 plastic waste comes from the e-wastes. The presence of e-waste plastics in the waste stream  
76 makes it problematic since they may contain contaminated toxins, such as brominated flame  
77 retardants (BFRs) and heavy metals (Wang, 2018; Forum, 2019).



78

79 **Fig. 1: Distribution of plastics demand by segments in Europe 2017 (Europe, 2018;**  
 80 **Forum, 2019)**



81

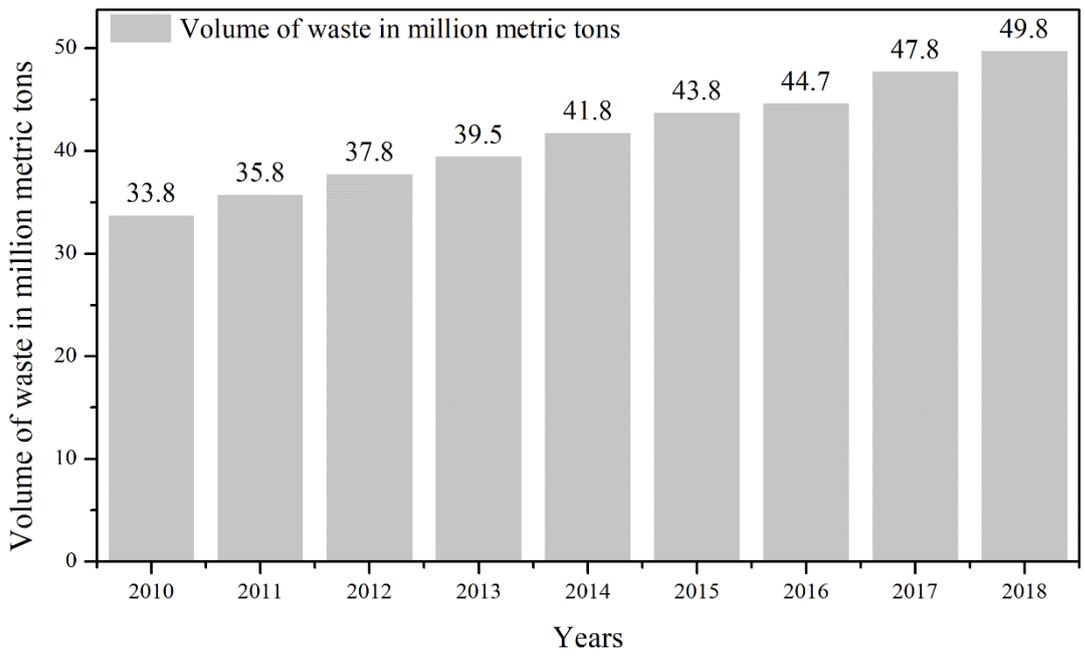
82 **Fig. 2: Global disposal of plastic waste from 1980 to 2015 (Geyer et al., 2017)**

83

84 Due to the rapid technological advancement in the field of household appliance, mobile  
85 communication and computers, the global generation of e-waste keeps on increasing and  
86 becomes a burden to the waste management systems. The quantity of e-waste generation varies  
87 with countries based on the economy and lifestyle of the country (Wang et al., 2016). The per  
88 capita generation of e-waste is highest in Norway which was estimated to be 28.5 kg/person  
89 (2016). The countries, like China, India, Philippines and African nations, hugely processed the  
90 electronic wastes generated in developed countries. Electronic waste contains a variety of  
91 substances including precious gold, silver, copper along with toxic substances, such as lead  
92 (Pb), polybrominated diphenyl ethers (PBDEs), polychlorinated and polybrominated dioxins  
93 and furans (Tsydenova and Bengtsson, 2011). The emission of these toxic substances during  
94 recycling may cause serious health hazards to the lives of workers and other livelihoods present  
95 in the surrounding (Grant et al., 2013).

96 The generation of electronic and electrical waste increases continuously in recent years due to  
97 the fast growth of the use of home appliances, consumer electronics gadgets, like cell phones,  
98 tablets, video game consoles, music player, digital camera, laptops, set-top boxes, etc. E-wastes  
99 definition usually comprises of discarded electronic, electrical pieces of equipment, light bulbs,  
100 and batteries. The waste generator can be the manufacturer (due to defect or obsolescence) or  
101 the consumer when the equipment reached its end of their service life (Robinson, 2009). Fig.  
102 3 shows the trends of generation of electronic and electrical waste in recent years. An increase  
103 of 47% of e-waste generation has been observed from the year 2010 to 2018 (Baldé et al.,  
104 2017). The United Nation's recent assessment reported that about 44.7 MMT of e-waste was  
105 generated globally in the year 2016 and only 20% (8.9 million metric tonnes) was recycled. The  
106 amount of e-waste generation was projected to reach 52.2 MMT by 2021 (Forum, 2019). Of these  
107 discarded e-waste, 80% go either in landfills or incineration. An extra amount of complexity in  
108 the treatment of these e-wastes arises from their toxic content and potential hazardous

109 emissions which makes it paramount to search for sustainable solutions for their recycling.  
110 Most of modern electrical and electronic pieces of equipment use engineering plastics in the  
111 manufacturing of their outer body. Inner components also use plastics/epoxy, such as insulating  
112 foams, printed circuit boards (PCBs), component's packaging, cables insulators, wirings,  
113 connector, switches etc. To ensure both safety and longevity of electronic devices, additives  
114 like BFRs, bromine bearing hydrocarbons, are added to the plastics to improve their fire  
115 resistance (Altarawneh et al., 2019). But if BFRs are efficient flame retardant they may also  
116 produce toxins during waste treatment. Apart from BFRs, e-waste plastics may contain trace  
117 amounts of metals and heavy metals, such as Pb, Cu, Ni, Al, Zn, Ba, Ag, Au, Sn, etc. These  
118 are very profusely present within plastics from PCBs, their soldered components or in plastics  
119 in their near vicinity (Nnorom and Osibanjo, 2009). Heavy metals are also sometime added as  
120 additive (for example as pigment) to the plastics (Cherif Lahimer et al., 2017). Heavy metals  
121 contamination also limits the recovery of the e-waste plastics for the recycle and reuse.



122

123 **Fig. 3: Trend of worldwide e-waste generation in recent years (Wang, 2018)**

124 The plastic used in Waste Electrical & Electronic Equipment (WEEE) are fabricated from  
 125 polymers that are produced from fossil fuels (petroleum/coke) and are rich in carbon and  
 126 hydrogen. Depolymerisation or control degradation can revert back plastics into useful feed  
 127 stock or in last resort into fuel for transport industry. The latter being the least favourable from  
 128 an entropy point of view, it allows to recover the contained energy but waste all the chemical  
 129 treatment that has been put into its manufacturing process. Common plastics used in WEEEs  
 130 with respective calorific values are listed in Table 1. The utilization of plastics as energy source  
 131 is significant as a vast quantity of plastics goes into the waste stream every day.

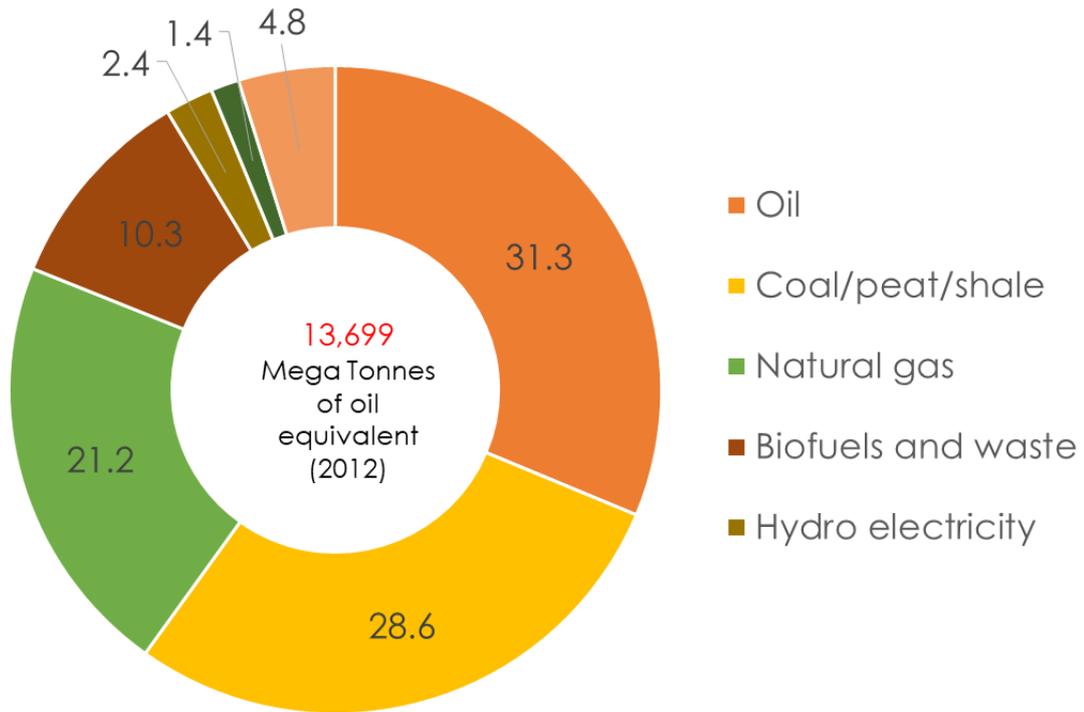
132 **Table 1: Heating values of plastics found in solid waste stream (Walters et al.; Othman et**  
 133 **al., 2009)**

Plastics	Calorific value (MJ/kg)
PE (LD/HD)	47.7
PP	45.3
PET	24.1
PS	41.4
PVC	14.1
PC	26.7
PMMA	24.1
PA	26.5
ABS	35.2
HIPS	37.8

134

135 Indeed, the global energy consumption increases constantly and it was estimated to be around  
 136 20,000 million tons of oil equivalent by the year 2050 (Coyne, 2018). In the year 2018, the rate  
 137 of growth of energy consumption to the previous year was 2.9% which was the highest rate of  
 138 growth compared to the previous seven years and double the average of last 10 years along  
 139 with 2% growth of carbon emission due to energy production (Global, 2019). Due to carbon  
 140 emission and the shortage of fossil fuel resources, the world is moving towards renewable and  
 141 sustainable energy sources, such as solar, wind, tidal, hydropower, geothermal, bio-energy, etc.

142 About 80% of the current global energy demand is currently provided by fossil fuel and 90%  
 143 of world transportation runs on petroleum oil (Jefferson, 2016). Around 14% (total) of global  
 144 energy demand is supplied by renewal sources (Fig. 4). The fraction of energy supplied by  
 145 renewal energy sources increases continuously over the years to minimize the energy  
 146 dependency on fossil fuel.



147

148 **Fig. 4: Primary global energy consumption by sources (Agency, 2014)**

149 In this critical review of thermochemical conversion of WEEE plastic wastes, their use as an  
 150 alternative source for useful mono- or oligomers or for fuel, such as gasoline and diesel, is  
 151 discussed in details. The effect of WEEE plastics' contamination in their production is  
 152 investigated on the basis of the most relevant previous studies. It should be noted that plastics  
 153 used in electric and electronics devices are not similar to those of commodity plastics or single-  
 154 use plastics present in the Municipal Solid Waste (MSW). The presence of toxins and

155 contaminants like BFRs and heavy metals in e-waste plastics makes their thermochemical  
156 conversion process more complex and challenging.

157 Previous review articles mostly focused on the impact of toxins present in e-wastes on the  
158 environment as well as on the recovery of metals from e-waste. Therefore, in addition to the  
159 impact of e-waste plastics on the environment, we will compare here the different recycling  
160 processes enabling their transformation into valuable products, discuss the significance of  
161 recycling e-waste plastics, the effect of the toxins present in the plastics and the complexity  
162 involved in the removal of toxins to recover original polymers. Hence, this review article  
163 addresses the gaps in the current status quo of the industrial recycling of e-waste plastics and  
164 the latest developments in this field. This critical study will furthermore help future researchers  
165 and engineers to choose how to process and recycle their mixed stream of plastic wastes  
166 containing e-waste plastics including their possible conversion into energy.

## 167 **2 Plastic waste and its environmental impact**

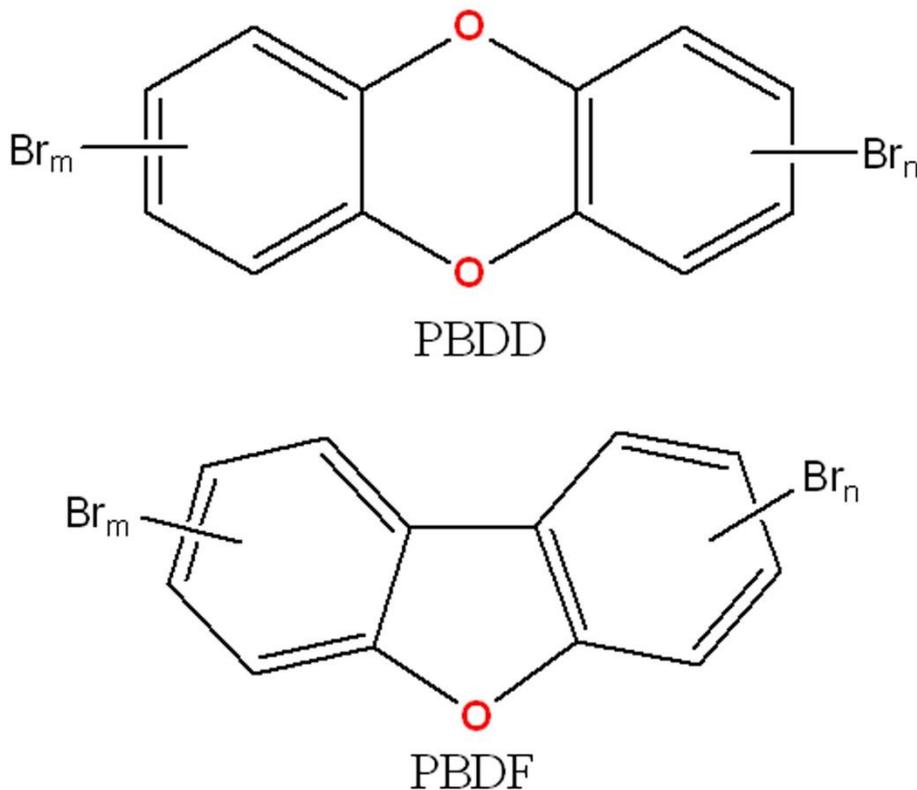
168 The global generation of plastic waste keeps on increasing as the production of new plastics  
169 keeps on increasing. In the year 2015, an estimated amount of 381 MMT of plastics (polymer  
170 resin and fibre) was produced globally (Geyer et al., 2017). Around 44% of global plastic  
171 production consumed in packaging application such as single-use containers, bottles, bags etc.  
172 (Geyer et al., 2017). The life span of plastics products varies, from weeks for packaging plastics  
173 to several years for electronics, electrical equipments and building appliances (Buekens, 2006;  
174 Lazarevic et al., 2010).

175 Most plastics are non-biodegradable and the growing plastic waste generation leads to huge  
176 garbage accumulation in landfills as well as various natural surroundings like rivers and oceans.  
177 In 2010 an estimated amount of 4.8 to 12.7 MMT of plastic waste debris entered in to the  
178 oceans from 192 coastal countries(Jambeck et al., 2015). This situation is worsening due to the

179 global increase of plastic waste generation, which raise the concern regarding the adverse  
180 consequences to marine life, ecosystem sustainability and potentially to human health  
181 (Lebreton et al., 2017). This threat is even more significant than initially estimated due to the  
182 mechanical degradation of plastics into microparticles (Hurley et al., 2018). Solid waste  
183 plastics are also responsible for many socio-environmental complications in many developed  
184 as well as developing countries, such as soil contamination, ground water pollution, floods,  
185 deadly diseases, animal death due to direct consumption or strangling and surface water  
186 pollution (Rigamonti et al., 2014).

187 WEEEs are generally treated separately from MSW as they contain many toxic substances,  
188 such as mercury (Hg), lead (Pb), selenium (Se), cadmium (Cd), hexavalent chromium (Cr(VI)),  
189 polybrominated diphenyl (PBD) and BFR. Sorted out e-wastes undergo separate treatments for  
190 dismantling, separation of metallic and non-metallic fractions. Non-metallic fractions, mainly  
191 containing plastics, undergo recovery and recycling processes. E-waste plastics have diverse  
192 composition but are mostly made up of ABS, HIPS, HDPE, PA, PP, PC, etc. Flame retardants  
193 are essential to electronic and electrical pieces of equipment due to meet requirements from  
194 fire safety codes. Most common form of flame retardants used in the plastics of electronic  
195 products are BFRs. Most abundantly used commercial flame retardants were polybrominated  
196 diphenyl ethers (PBDEs), tetrabromobisphenol A (TBBPA), hexabromocyclodecane (HBCD),  
197 Decabromodiphenyl ether (deca-BDE) etc., however, due to environmental safety, use of these  
198 BFRs was restricted and they have been replaced by less harmful ones based on nitrogen,  
199 phosphorous and other inorganics (Singh and Jain, 2009). Polybrominated diphenyl ethers  
200 (PBDEs) were some of the most commonly used BFRs over the last few decades. More  
201 specifically, BFRs such as HBCDs and TBBPA are still extensively used despite being  
202 considered as persistent organic pollutants (POP) and referred as novel BFRs (Covaci et al.,  
203 2011). During any thermal stress, the BFRs in the e-waste plastics can produce brominated

204 aromatic compounds which are precursors to the polybrominated dibenzo-p-dioxins (PBDD)  
205 and polybrominated dibenzo furans (PBDF) (Weber and Kuch, 2003; Zhang et al., 2016). Trace  
206 amount of PBDD and PBDF can cause severe health hazards. Toxicity profiles of different  
207 isomers of PBDD/Fs depend on the number of Bromine atoms and what positions they attached  
208 to. Basic PBDE and PBDF structures are given in Fig. 5.



209

210 **Fig. 5 : Molecular structure of PBDD and PBDF**

211 Metal hydroxides, such as Gibbsite (aluminium trihydroxide, ATH), magnesium di-hydroxide  
212 (MDH), and Boehmite (Aluminium-oxide-hydroxide, AOH), are among the most common  
213 inorganic ones (Qian et al., 2014). Flame retardants are also used based on their compatibility  
214 with polymer resins such as melamine cyanurate and melamine phosphate which are  
215 compatible with polyamides and polypropylene, respectively (Liu et al., 2006). Although most  
216 European countries restricted the use of halogenated flame retardants, a worldwide replacement

217 with non-halogenated FR is not yet achieved and BFRs are still the primary source of flame  
218 retardants in various regions of the world. Due to the huge volume accumulation of e-waste  
219 most European countries and USA export the e-waste to Asia or Africa for recycling, where e-  
220 waste recycling workers often put themselves into high health risk due to the lack of sustainable  
221 technology and safe practice know-how (Zhu et al., 2008; Muenhor et al., 2010; He et al., 2012;  
222 Malliari and Kalantzi, 2017; Li et al., 2018). Open burning of e-waste to recover metals is a  
223 common practice in African countries (Cao et al., 2020) resulted the emission of harmful  
224 dioxins, furans, polycyclic aromatic hydrocarbon (PAHs), polyhalogenated aromatic  
225 hydrocarbon (PHAHs) and hydrogen halides. E-waste can further be a source of soil and  
226 ground water contamination due to lixiviation and leaching as well as air pollution due to  
227 burning. Tang *et al.* (Tang et al., 2010) investigated the soil sample near Wenling, an e-waste  
228 recycling city of Taizhou province in China and reported concentrations ranging from 371.8 to  
229 1231.2  $\mu\text{g}/\text{kg}$  of polycyclic aromatic hydrocarbons (PAHs) and 52 – 5789.5  $\mu\text{g}/\text{kg}$  of  
230 polychlorinated biphenyls, which are significantly higher than the permissible limit set by the  
231 governmental bodies and legislatures. Tue et al. (Tue et al., 2017) reported high concentration  
232 of Cl-PAH and Br-PAH in the range 160 – 220 ng/g and 19 – 40 ng/g respectively in the soil  
233 samples from the soil samples collected from the open e-waste burning area of Agbogbloshie's  
234 e-waste recycling site in Ghana.. Reports of soil contamination with heavy metals at the e-  
235 waste recycling sites have been reported (Luo et al., 2011; Wu et al., 2015; Damrongsiri et  
236 al., 2016; Zhang et al., 2019).

237 Surface water contamination due to non-regularised and un-licensed e-waste recycling  
238 facilities is also a major concern. Leaching and lixiviation of toxic chemicals (PAHs, heavy  
239 metals) from e-waste landfilling and waste acidic waters from recycling sites led to significant  
240 surface and ground water contamination (Wu et al., 2015). Air borne pollutants are also  
241 generated by open burnings, incinerations and combustions. Heating or burning of e-waste that

242 contain halogenated compounds, such as BFRs, may lead to the emission of environmentally  
243 hazardous substances, like polybrominated, diphenyl ethers (PBDEs), polychlorinated dibenzo  
244 dioxins (PCDDs), polybrochlorobenzo dioxins and polychlorobenzofurans (PBCDD/Fs)  
245 (Vehlow et al., 2000; Vehlow et al., 2003; Wang et al., 2010). Such toxins from e-wastes can  
246 cause chronic and acute health conditions to human (Kiddee et al., 2013). Traces of toxic  
247 substances like brominated or chlorinated fire retardants and heavy metals were found in the  
248 human (recycle workers) blood, urine, and milk and hair samples (Grant et al., 2013). These  
249 pollutants and toxic chemicals can cause serious health risk to human as well as animals. The  
250 recycling processes of plastic wastes from different sources require sincere attention in removal  
251 of toxics and contaminants before converting the waste into useful resources.

### 252 **3 Plastic waste management and disposal techniques**

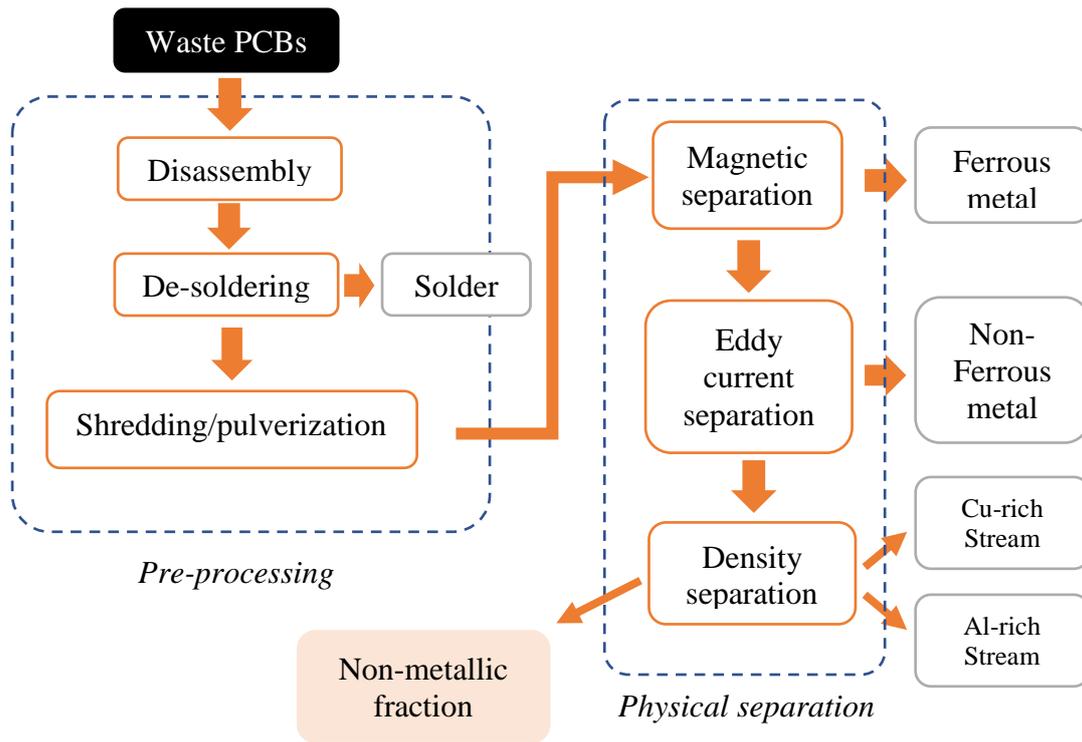
253 Physical properties of plastics vary with polymer types, class of additives and manufacturing  
254 techniques employed. Polyethylene (PE), polypropylene (PP), polyethylene terephthalate  
255 (PET) and polystyrene (PS) etc. are widely used for packaging and single use plastic products.  
256 On the other hand, polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), Nylon 6,  
257 Nylon 6,6, polyamide (PA), polybutylene terephthalate (PBT), polycarbonate (PC),  
258 polyetheretherketone (PEEK), polyetherketone (PEK), polysulphone (PSU),  
259 polytetrafluoroethylene (PTFE/Teflon), etc, are known as engineering plastics used as building  
260 materials and in automobile parts. The service life of most engineering plastics are higher than  
261 that of single use or packaging ones. ABS, HIPS, PC, PP, PA, etc., are also found in electronic  
262 or electrical plastic wastes. Due to the turnover rate of lifestyle electronic goods like mobile  
263 phones, computers, tablets, etc., there is a significant increase in e-waste plastic generation in  
264 recent years.

265 Around 10 – 12 % of MSW of the world consists of plastic waste (Diaz et al., 2020). The  
266 recycling of solid waste like plastics depends of efficient collection and segregation which is  
267 influenced by the economic status of the country(Joshi and Ahmed, 2016). The techniques of  
268 plastics recycling can be classified into primary secondary and tertiary recycling, which we  
269 will review in subsequent sections.

### 270 **3.1 Primary and secondary (mechanical) recycling**

271 Primary and secondary recycling deal with the mechanical means of recycling of plastic wastes,  
272 such as grinding, washing, separating, drying, re-granulating, extrusion and compounding (Al-  
273 Salem et al., 2009). Mechanical processes are utilized to produce recyclates from plastic waste.  
274 Primary recycling is the process of producing the same or similar products, whereas secondary  
275 recycling produces products with substandard quality, such as dustbins, furniture, plastic vases,  
276 etc. Primary recycling needs pure and homogenous plastic wastes (in-plant scrap), while  
277 secondary recycling uses post-consumer plastic. High production costs are the concern in the  
278 implementation of primary and secondary recycling. Mechanical processing is at the basis of  
279 any recycling process, especially for electronic wastes that comprise of a complex mixture of  
280 many materials (valuable and hazardous, or not) including metals (ferrous or non-ferrous) and  
281 non-metals like plastics, glass, ceramics with various sizes and shapes. Hence, it is important  
282 to utilize cost effective sustainable mechanical processes to separate the different components  
283 of e-wastes as best as possible. WEEEs undergo dismantling and sorting steps at the beginning  
284 of the recycling process. Complex components, such as PCBs, after being extracted from their  
285 original equipment usually undergo grinding and the separation of metallic (ferrous and non-  
286 ferrous) and non-metallic fractions. In Fig. 6, a process flowchart is shown that is rigorously  
287 followed in many waste PCB recycling industries. Separation processes include screening  
288 (Wilson et al., 1994), shape separation (Furuuchi and Gotoh, 1992; Furuuchi et al., 1993),  
289 magnetic separation (Veit et al., 2005), electric conductive base separation (Meier-Staude and

290 Koehnlechner, 2000), density base separation (Schubert, 1991), etc. Wäger *et al.* (Wäger et al.,  
291 2011) confirmed that mechanically recycled electronic and electrical waste plastics have five  
292 times lower environment impact than virgin plastics in the manufacturing of plastic products.  
293 However, past studies suggested that 25 – 30 wt% of the collected e-waste plastics have BFR  
294 as additive and it is difficult to recycle them mechanically (Brennan et al., 2002; Stenvall et al.,  
295 2013; Baldé et al., 2017). The e-waste plastics with BFR are not suitable for primary and  
296 secondary recycling. Pre-treatment processes like solvent extraction, chemical leaching and  
297 other chemical treatment (with acid/alkalis) can remove the toxic chemicals from e-waste  
298 plastics and convert them into mechanically reusable plastics. BFRs that are not chemically  
299 bound to the polymer chain can be removed from the plastic matrix by the solvent extraction  
300 processes. Efficient and sustainable solvent extraction process assisted by microwave, ultra-  
301 sonication or supercritical CO<sub>2</sub> extraction processes can be developed for BFR extraction from  
302 e-waste plastics. On the other hand, thermal degradation can remove chemically bonded Br in  
303 the plastics.



304

305 **Fig. 6: schematic representation of the physical separation process of MF and NMF of**  
 306 **PCB**

### 307 3.2 Tertiary (chemical and thermal) recycling

308 Tertiary or chemical recovery of plastic waste is a promising aspect in the recovery of valuable  
 309 chemicals and fuels (Achilias et al., 2007; Yildirim et al., 2014; Zhou et al., 2014). Its principle  
 310 lies behind the alteration of the polymer's chemical structure by depolymerisation. Major  
 311 advantages of chemical recycling over mechanical recycling is that it allows processing of  
 312 heterogeneous and contaminated plastics with limited pre-treatment opportunities. Chemical  
 313 recycling can convert plastics like polyethylene terephthalate (PET) and nylon into their  
 314 monomer units (feedstock recycling) (Veregue et al., 2018; Choi and Choi, 2019; Jehanno et  
 315 al., 2019; Vesnin et al., 2020), while the polyolefin type of plastics produce a mixture that can  
 316 be precursor to liquid fuel (Coates and Getzler). Processes, such as dissolution, hydrogenation,  
 317 gasification, pyrolysis, and catalytic cracking, come under chemical recycling of plastics.

318 Achilias et al. (Achilias et al., 2009) carried out chemical recycling of PC, PABS, and PS from  
319 WEEE by means of dissolution/re-precipitation and pyrolysis. More than 90% recovery of  
320 polymers was reported by the dissolution process where pyrolysis converted the model PC  
321 sample into 63% liquid product. Pyrolysis or thermolysis of plastics is a process of thermal  
322 decomposition of plastics under inert or oxygen-starved conditions. These processes are able  
323 to convert high molecular weight plastics into low molecular weight hydrocarbons and  
324 chemicals (Kaminsky et al., 1995; Adrados et al., 2012). The process of plastic waste into oil  
325 (fuel) through pyrolysis has been developed and practiced. Processes like Thermofuel™  
326 (Ozmotech Pty Ltd), Smuda process, Royco process (EZ-oil generator), Reentech process,  
327 Hitachi process, Chiyoda process (Chiyoda corp. Japan), Blowdec process, Conrad processes  
328 are some of the processes available for the commercial utilization (Scheirs and Kaminsky,  
329 2006). These processes are mostly handled polyolefin types of plastics available in MSW. By  
330 reducing the process cost and up-scaling the present capacity of the technologies may lead to a  
331 wide-scale industrial application of plastic pyrolysis. The heat recovery processes like  
332 combustion, incineration and gasification are also considered as tertiary recycling processes,  
333 however, these techniques are sometimes separately identified as quaternary recycling  
334 processes (Al-Salem et al., 2009).

335 Regarding PCBs' epoxy resin, they are usually used as fuel in pyrometallurgy plants that recover  
336 precious metals. Since they are made of cross-linked polymers with the aim of high chemical,  
337 time and temperature stabilities their up-cycling is a difficult problem. In the field of  
338 depolymerisation, it is worth noting that in 2019, Chen et al. (2019) reported an original process  
339 enabling the dissolution of anhydride epoxy thanks to a transesterification reaction occurring  
340 between the -OH group in ethylene glycol, used as solvent, and the ester bond within the epoxy  
341 network. To be efficient, the reaction uses the transesterification catalyst (1,5,7-  
342 Triazabicyclo[4.4.0]dec-5-ene). Also, a diffusion solvent (N-Methyl-2-Pyrrolidinone) allows

343 for the swelling of the resin, allowing for both the ethylene glycol and catalyst to penetrate  
344 within the cross-linked epoxy network. Reaction time varied from 6h to 40 min when using  
345 reaction temperatures of 100 °C and 180 °C, respectively.

#### 346 **4 Removal of toxic molecules from e-waste plastics**

347 E-waste plastics a notoriously known to be tainted with toxic compounds such as BFRs and  
348 heavy metals (Tange and Drohmann, 2005; Das et al., 2009; Li et al., 2009; Peng et al., 2010;  
349 Damrongsiri et al., 2016; Debnath et al., 2018). Over the years, the European Union regulated  
350 and restricted various substances in plastics particularly in the case of electronics and electrical  
351 goods (E.U., 2015). Table 2 lists restricted substances and their permissible limits in such  
352 goods. The science of removal of the toxic chemicals from e-wastes has been explored and a  
353 number of technologies were investigated that optimize energy and material consumptions.  
354 The removal of metal contamination at the molecular level is difficult by mechanical and  
355 physical means described in section 3.1 (Kurose et al., 2006; Li et al., 2007). Although  
356 hydrometallurgical processes like leaching assisted with cyanide, thiourea, thiosulfate or halide  
357 have been developed mainly for to recover precious metals from waste PCBs (Cui and Zhang,  
358 2008; Zhang et al., 2012), they can also be used for the removal of contaminated metal from  
359 e-waste plastics. Regarding PCBs, they are an essential part of any electronic equipment and  
360 represent between approximately 2-3% of total e-waste generated worldwide (Vats and Singh,  
361 2014). PCBs are also abundant in small electronic devices, such as mobile, tablets and other  
362 smart devices. A typical PCB is constructed with a Cu-clad laminate which consists of glass  
363 fibre reinforced with epoxy resin, plastics and metals (Hsu et al., 2019). It was approximated  
364 that a PCB contains roughly 40% metals, 30% organics and 30% refractory (ca. fibre glass)  
365 (Shuey and Taylor, 2005). PCBs are generally treated for the extraction of some of the valuable  
366 metals they contain, such as Cu, Al, Ag and Au (Oh et al., 2003). The pre-treatment process  
367 follows the common processes stated in section 3.1 (Fig. 6) to separate the metallic fraction

368 (MF) and the non-metallic fraction (NMF). The MF then undergoes intense chemical treatment  
 369 to recover valuable chemical components. The non-metallic part of the PCBs is most toxic as  
 370 it contains traces of solders made from Pb/Sn and BFRs. Although, recent PCBs are lead free  
 371 solder most old PCBs have 2-5% of Pb in their solder (Ghosh et al., 2015).

372 **Table 2: Restricted substances used in the electronic and electrical goods by EU (E.U.,**  
 373 **2015)**

Toxic substance	Permissible limit (wt%) <sup>†</sup>
Lead (Pb)	0.1
Mercury (Hg)	0.1
Cadmium (Cd)	0.01
Hexavalent Chromium (Cr <sup>6</sup> )	0.1
Polybrominated biphenyls (PBB)	0.1
Polybrominated diphenyl ethers (PBDE)	0.1
Bis(2-ethylexyl)phthalate (DEHP)	0.1
Butyl benzyl phthalate (BBP)	0.1
Dibutyl phthalate	0.1
Diisobutyl phthalate (DIBP)	0.1

374 <sup>†</sup>0.1 wt% = 1000 ppm and 0.01 wt% = 100 ppm

#### 375 4.1 Removal of BFR from e-waste plastics

376 The BFRs are relentless and bioaccumulative toxins in nature, and their decomposition  
 377 pathways during thermal treatment have been previously reported (Ma et al., 2016a). The  
 378 treatments to recover BFR free plastics or products are discussed in the subsequent sections.

#### 379 4.2 Solvothermal processes to remove BFRs from e-waste plastic

380 High extraction efficiencies can be achieved with conventional solvent extraction with organic  
 381 solvents (Suzuki et al., 2002; Zhang and Zhang, 2012b). Toluene, methanol, 1-propanol,  
 382 isopropanol, acetonitrile, and ethanol are some of the common organic solvents used (Altwaiq  
 383 et al., 2003; Evangelopoulos et al., 2019). Different extraction processes, such as pressurised

384 liquid extraction (PLE), ultrasonic assisted extraction (UAE), microwave assisted extraction  
385 (MAE) and simple Soxhlet extraction have been proposed and investigated for BFRs extraction  
386 (Vilaplana et al., 2008).

387 Chandrasekaran *et al.* (Chandrasekaran et al., 2018) recovered 89% of pure PC from the  
388 mixture of PC/PA (from waste cell phones) by solvent extraction using N-methyl-2-  
389 pyrrolidone (NMP). NMP was preferred to dichloromethane (DCM) for selective dissolution  
390 of PC and to avoid the use of the chlorinated solvents. The study also emphasize the important  
391 of the factors such as solid matrix, initial BFR content, solvent polarity, solid liquid ratio,  
392 temperature and pressure affecting the BFR removal efficiency and temperature being the most  
393 dominant factor in the extraction process. Vilaplana et al. (Vilaplana et al., 2008) reported the  
394 use of mixed solvent systems (isopropanol/hexane and isopropanol/methanol) and achieved a  
395 high recovery of BFRs. Complete recovery of TBBPA and HBCD was reported by the process  
396 of MEA, using isopropanol/n-hexane as solvents at 130°C for 60 min, however UAE gives  
397 recovery rates that are strongly temperature dependant and that increase with temperature  
398 (Vilaplana et al., 2008; Romarís-Hortas et al., 2009). Hence, optimal conditions for extraction  
399 processes vary for different types of feedstock. carried out extraction of deca-BDE from HIPS  
400 matrix using an ionic liquid (IL) prepared with by the mixture of 1-bromobutane, 2-(2-  
401 chloroethoxy) ethanol and 3-bromopropionitrile. The IL was able to achieve 92.7% of BDE  
402 recovery from the HIPS. ILs can be designed based on the material property and improve the  
403 extraction efficiency, however in plastic waste recycling processes, operational costs play a  
404 vital role which as yet precluded the industrial use of ILs so far. Zhang and Zhang (2012a)  
405 studied three alcohols (methanol, ethanol and isopropanol) as solvent for the extraction of  
406 TBBPA from e-waste plastics inside a pressurised vessel reactor, and reported that methanol  
407 was the most suitable one under optimum conditions of 90°C, 2h of extraction time and liquid  
408 to solid ration of 15:1, respectively. It should be noted that at high extraction temperature it

409 was observed that plastics underwent marginal swelling, but this did not seem to affect it  
410 properties.

411 Properties of the solvent plays a critical role in the solvothermal treatment in removal of BFRs  
412 from plastic. The solvents must have swelling capacity without dissolving the plastic and at the  
413 same time must have the affinity to dissolve the BFRs. Mixed solvents with polar and non-  
414 polar solvents tends to increase the efficiency of the extraction if we are dealing with different  
415 types of analytes having contrasting polarity and molecular weight (Vandenburg et al., 1998).  
416 Temperature play a crucial role in the extraction process. The optimum temperature for the  
417 extraction of additives from the plastics should not exceed the glass transition temperature  
418 (Lateef et al., 2008). High temperature may result excessive swelling and collapse of the  
419 polymer structure.

420 Supercritical carbon dioxide (Sc-CO<sub>2</sub>) extraction processes have also been proposed, as early  
421 as 2000 (Gamse et al., 2000), as possible advanced sustainable processes for BFR removal  
422 (Altwaiq et al., 2003; Wang et al., 2004) and the decontamination and recovery of pure plastics  
423 from the contaminated e-waste plastics (Gamse et al., 2000; Nakajima et al., 2002; Ma et al.,  
424 2016a; Ben Said et al., 2017; Egerer et al., 2019). The interest in using Sc-CO<sub>2</sub> reside in its  
425 intermediate properties between liquid and gas which enable for fast diffusion within polymer  
426 and reasonable solubilizing capacity. High extraction efficiency has however only be reported  
427 when using organic co-solvents which significantly reduce the environmental advantage as  
428 well as increase running costs. More research is therefore needed to enable a pure ScCO<sub>2</sub> based  
429 extraction process allowing for plastics decontamination and reuse.

430 In 2020, Zhang and Zhang (2020) reported a high efficiency Sc-CO<sub>2</sub> based process for  
431 dehalogenation of e-waste plastics into halogen-free products without the need of any catalysts  
432 or additives. When temperature in the range of 375-550°C dehalogenation of up to 99.51%

433 could be achieved producing halogen-free products (solid carbon materials as well as organic  
434 chemicals). This study performed at the laboratory scale will still need further investigations  
435 to prove its industrial potential and economic viability.

436 These results indicate that significant amount of work is required for the development and  
437 optimization of large scale extraction processes adapted to additive BFRs. In cases of reactive  
438 BFRs, which cannot be lixiviated out, a thermochemical treatment is usually required. Bromine  
439 or its derivatives must be separated during the pyrolysis process from the oil/gas products,  
440 ideally into solid residues, by using suitable catalysts. The following sections will discuss the  
441 thermochemical treatment of plastic waste and role of high temperature processes, such as  
442 incineration, combustion and pyrolysis in the recycling of e-waste plastics.

## 443 **5 Thermochemical treatment of plastic waste**

444 Thermochemical approaches of recycling e-waste plastics entail processes, such as  
445 incineration, combustion or pyrolysis. Incineration and combustion involve burning the waste  
446 (oxidation) and pyrolysis is here referred as a process of degradation by heating the material  
447 under an oxygen-starved environment (Das and Tiwari, 2018b).

### 448 **5.1 Incineration/combustion process for plastic disposal:**

449 Incineration and combustion of MSW are usually carried out to reduce the amount of waste to  
450 landfill as well as whenever possible to recover some of its chemical energy, to convert it into  
451 electricity (Liu and Liu, 2005). As most plastics are produced from petroleum resources, they  
452 intrinsically have high calorific value. Up to now, incineration/burning of post-consumer  
453 plastic waste is one of the traditional ways of retrieving energy from waste, and incineration  
454 plants are successfully operated in many developed countries. A major advantage of  
455 incineration of plastics is the solid volume reduction by 90 – 99% (Arvanitoyannis, 2013). With  
456 reduced volume, it is easy to dispose of the solid residue. The major plastic types found in the

457 waste stream are highly carbonaceous and have a very high heat of combustion (Table 3).  
 458 Within well controlled incineration chambers an efficient burning can produce heat energy that  
 459 can be utilized to produce steam and subsequently the electrical energy. Contrary to the latter,  
 460 pyrolysis processes convert highly carbonaceous materials (like plastics) into useful chemicals  
 461 and fuels, in the solid, liquid and gas forms. Both incineration and pyrolysis have advantages  
 462 and disadvantages. Incineration destroys the plastic to produce energy that can be utilized as  
 463 electrical power, which is not sustainable. Whereas, pyrolysis can transform the material into  
 464 other useful forms and therefore is more sustainable. However, both incineration and  
 465 combustion lead to toxic emissions through gas and the residues.

466 **Table 3: Heat of combustion some of the plastics found in waste stream**

Waste Plastic (s)	Heating value (MJ/kg)	Reference
PE	47.74	Lyon et al. (1998)
PP	45.8	
PS	43.65	
PVC	18	Costiuc et al. (2011)
PET	24.13	
ABS	39.84	
PC	31.30	
PMMA	26.81	
PCB	24.12	Areeprasert and Khaobang (2018)
ABS/PC	37.5	

467  
 468 Proper gas filtration systems and careful handling of residual solids or ashes can make  
 469 incineration processes an acceptable solution to dealing with a large spectrum of plastic wastes.  
 470 On the contrary, narrow process windows coupled with consumption of energy for heating and

471 sorting out suitable feed restrict pyrolysis process to more specific and precisely defined  
472 feedstock.

473 Hence, an in-situ generated supply of product fuel gas from the pyrolysis furnace could lead to  
474 a cost effective pyrolysis process for the disposal of plastic waste. Pyrolysis products, such as  
475 plastic derived oil, may fulfil a fraction of petroleum product demand due to the continuous  
476 depletion of fossil fuel reserves. Thus, producing value-added oil and chemicals from plastics  
477 waste by pyrolysis could be an efficient way to dispose of plastic wastes.

478 Heating the plastic under inert condition may lead to depolymerisation, breaking of long chain  
479 polymeric chain into small chain hydrocarbons, which can be a source of petroleum products  
480 and chemicals (Das and Tiwari, 2018b). Presence of plastics improves the MSW quality as it  
481 improves the overall heating value of the MSW. Although garbage burning is not encouraged  
482 due to emissions, it is one of the viable solutions for the huge accumulation of solid waste in  
483 the natural habitats, especially when land is scarce and therefore landfilling is not an option.  
484 The incineration/burning of e-waste plastics is or should not however be practiced as they  
485 contain brominated and chlorinated components, such as BFRs, which may lead to severe toxic  
486 emissions.

487 Vehlow *et al.* (Vehlow et al., 2000) mixed e-waste plastics with household MSW to find out  
488 the toxic emission in the different exit streams from an incineration plant. Increasing the e-  
489 waste plastic fraction in the feedstock increases organic compounds related to flame retardants,  
490 such as poly brominated diphenylethers (PBDPE), polybrominated biphenyls (PBB), tetra-  
491 bromo-bisphenol A (TBBA), as well as active elements like bromine (Br), chlorine (Cl) or  
492 phosphorous (P). The chlorine and bromine elements were found more in the flue gas stream  
493 than in the other exit streams, such as fly ash, grate ash, boiler ash, etc. The process' combustion  
494 temperature influences the production of PCDD/Fs and PBDD/Fs. It was found that incomplete

495 combustion may results in more PCDD/Fs and PBDD/Fs than what is measured when it is  
496 complete. The chances of emission of PCDD/Fs and PBDD/Fs are more when the combustion  
497 takes place at low temperature whereas at a very high temperature (>600 °C) the Cl and Br get  
498 reduced to HCl and HBr (Duan et al., 2011). Since incineration is a high temperature operation,  
499 Cl and Br containing plastic may produce hydrogen halides which may corrode the equipment  
500 and create serious problem in downstream plants.

## 501 **5.2 Pyrolysis of plastic waste**

502 As previously mentioned, pyrolysis is a process that turns organic material into gas, oil and  
503 char thanks to degradation processes induced by the application of heat under an oxygen  
504 starving environment. Pyrolysis end products can be valuable petroleum-like feedstock, which  
505 can be treated in oil refineries for the synthesis of various chemicals and fuels. Under pyrolysis,  
506 macromolecular structures of polymers present in plastic wastes are broken down into smaller  
507 molecules and produce a wide range of hydrocarbons. Product distribution and quality of the  
508 pyrolytic products depend primarily on temperature, heating rate, feedstock composition,  
509 residence time, etc. (Williams and Williams, 1997; Das and Tiwari, 2018a). Furthermore, using  
510 a particular type of catalyst and reactor design could influence the reaction rate and product  
511 distribution.

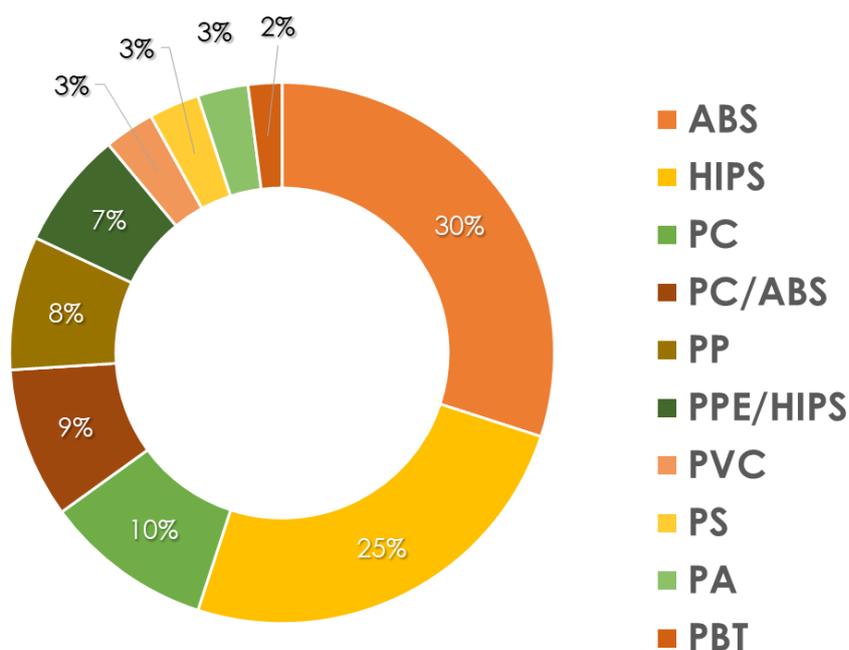
512 The impact of time and temperature on pyrolytic product distribution has been studied  
513 extensively (Ma et al., 2002; López et al., 2011a; Xue et al., 2015; Singh and Ruj, 2016; Das  
514 and Tiwari, 2018a, b). Pyrolysis temperatures of plastics were determined based on the material  
515 degradation temperatures. Degradation temperatures of plastics have been evaluated using  
516 thermogravimetric analysis (TGA) (Das and Tiwari, 2017). It was found out that the  
517 degradation temperature of plastics increases with an increase in heating rate (Das and Tiwari,  
518 2017). TGA coupled with Fourier transform infrared spectroscopy (TG-FTIR) as well as  
519 pyrolysis coupled with GCMS (Py-GC/MS) have been used to determine real-time

520 compositions of evolved gases during plastics' degradation under thermal stress (Fries et al.,  
521 2013; Jin et al., 2016).

522 The feasibility of pyrolysis technology to convert waste plastics into valuable products has  
523 been studied extensively and was adopted for industrial scale production. Hence, polyolefins  
524 pyrolysis can produce more than 80% of liquid oil, which can be easily blended with  
525 conventional oil (Das and Tiwari, 2018b). The quality of the liquid product can be improved  
526 by post pyrolysis distillation to produce petroleum derivatives, including gasoline and diesel  
527 grade fuel (Sharma et al., 2014). Dr Heinrich W. Smuda developed the Smuda process for the  
528 pyrolysis of polyolefins waste to produce fuel at the temperature range of 300 – 450°C in  
529 presence of catalyst made by silicates of iron, cobalt, nickel, magnesium, cadmium, copper,  
530 chromium and zinc catalyst (Smuda, 2001). The Smuda process can tolerate high levels of non-  
531 polyolefin plastics, such as PET, in which under heat decarboxylation can produce benzoic  
532 acid and benzoate (Scheirs and Kaminsky, 2006). The PET increases the aromatic content of  
533 the fuel oil. However, the PET is not considered in the pyrolysis process due to the formation  
534 of troublesome terephthalic acid (TPA) that makes solid deposits in the downstream pipelines  
535 and condensers. The presence of oxygen in the PET molecules results in the acidic component  
536 of the liquid oil. Likewise, PVC plastics in the feed causes hydrochloric acid (HCl) production  
537 (Williams and Williams, 1999). Material selectivity influences the product distribution of any  
538 pyrolysis process.

539 The e-waste plastic stream is composed of different types of plastic, such as ABS, PS and PC  
540 etc. (Fig. 7). Pyrolysis of polycarbonate (PC) produces phenolic components (Antonakou et  
541 al., 2014) and pyrolysis of ABS and PS results in aromatic hydrocarbons, like styrene, ethyl  
542 benzene (Rutkowski and Levin, 1986; Chaukura et al., 2016). PCBs have plastics as well as  
543 organic epoxy in addition to its metallic fraction. Evangelopoulos et al. (Evangelopoulos et al.,  
544 2015) investigated the degradation behaviour of PCBs in a temperature range of 400 – 900°C

545 by TGA and Py-GC/MS. It was observed that PCBs' decomposition starts at ~120°C and  
 546 around 20 – 25 % of volatile matters was evolved at different temperature programs. Epoxy  
 547 resins present in the PCBs decomposed along with other non-metallic components. The py-  
 548 GC/MS detected a wide range of organic compounds that entailed brominated components (e.g.  
 549 bromomethane, bromophenol), hydrocarbons, phenolic compounds and furans (e.g.  
 550 benzofuran, 2methyl-benzofuran). Brominated molecules were produced due to the presence  
 551 of significant amount of BFRs in the PCBs. It should be noted that a detailed analysis of the  
 552 pyrolysis products from the pyrolysis of individual types of e-waste plastics with or without  
 553 BFR is still lacking. Availability of such data would have a great influence in future  
 554 development of processes for the disposal and recycling of e-waste plastics.

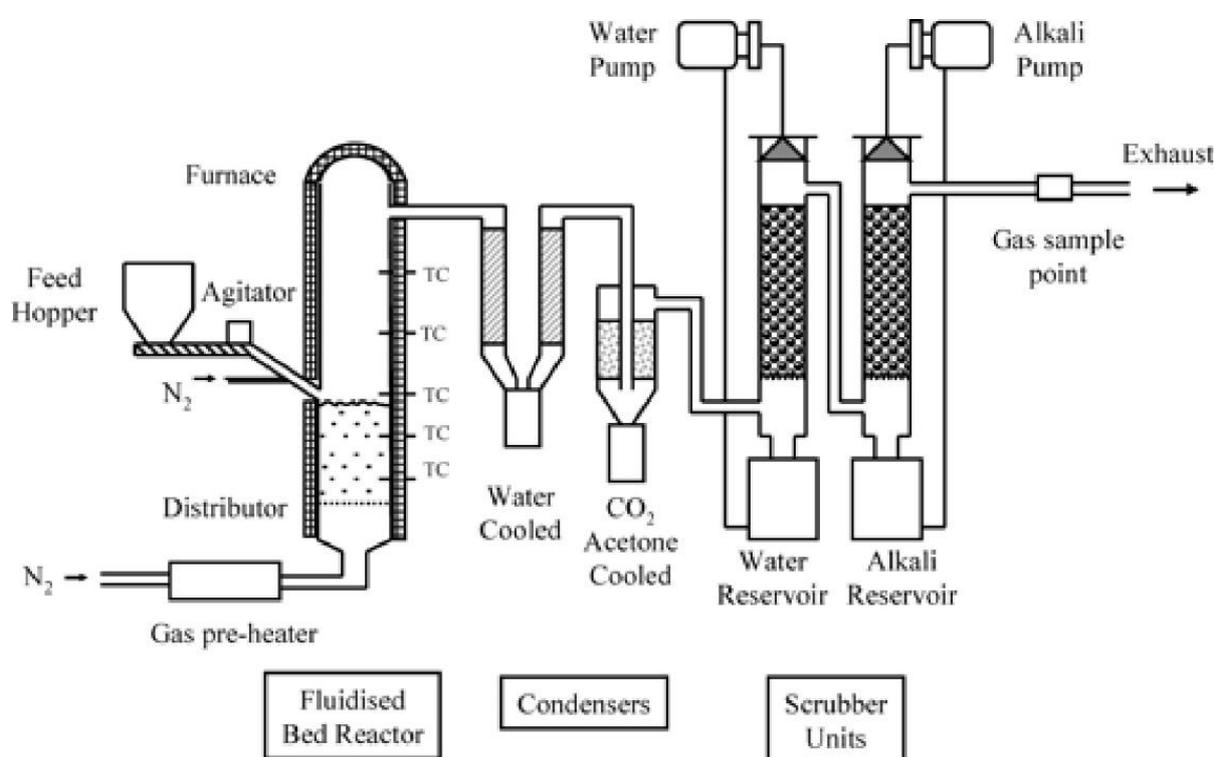


555

556 **Fig. 7: Typical composition of e-waste plastics in UK, 2006 (Keith Freegard; Alston et al.,**  
 557 **2011)**

558 Hall and Williams (2006) performed pyrolysis of old computer monitor casing composed of  
 559 ABS and PVC in a fast fluidised bed pyrolysis setup at 500°C. The pyrolysis reactor was  
 560 externally heated by an electrical furnace and the fluidized media (N<sub>2</sub> gas) was preheated up to

561 450°C. To assist the fluidization, the feedstock was mixed with sand particles (300-425  $\mu\text{m}$ )  
 562 supported over a sieve plate. A schematic representation of the setup is displayed in Fig. 8. The  
 563 fast pyrolysis of halogenated plastics produces halogenated organic components and hydrogen  
 564 halides. These molecules are unwanted in the plastic derived oil for its usage as fuel. De-  
 565 halogenation of the plastic sample seems to be a pre-requisite for fast pyrolysis although fast  
 566 pyrolysis with catalyst can still be utilized for simultaneous degradation and de-halogenation  
 567 of e-waste plastics (Sakata et al., 2003).



568  
 569 **Fig. 8: Schematic representation of the fluidized bed pyrolysis reactor. Reprinted**  
 570 **(adapted) with permission from (Energy Fuels 2006, 20, 4, 1536-1549). Copyright (2006)**  
 571 **American Chemical Society (Hall and Williams, 2006)**

### 572 5.3 Catalytic pyrolysis of plastics

573 In conventional catalytic pyrolysis, catalysts are used to enhance the production of specific  
 574 chemical components or to reduce the energy or time needed for degradation. A wide range of  
 575 catalysts were mentioned in the literature, most of these catalysts are used extensively in the

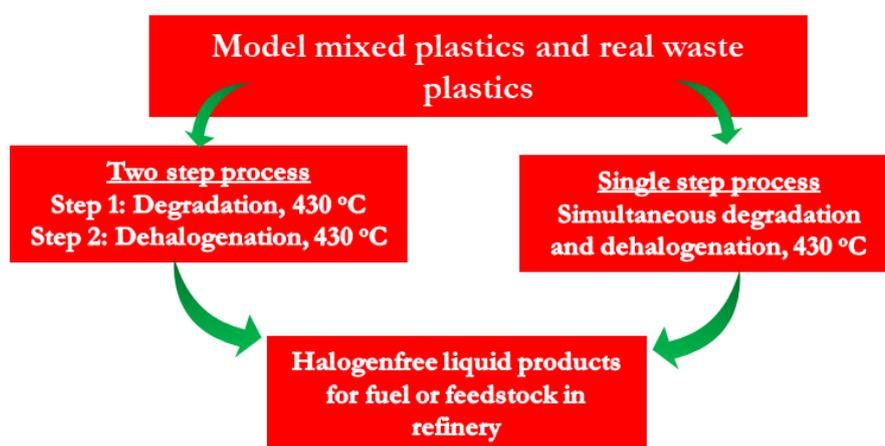
576 industry. The catalysts were categorised into homogeneous catalysts, acidic or non-acidic  
577 mesoporous materials, zeolites, metallic oxides, smectite clays as well as their pillared  
578 derivatives, etc. (Brebu et al., 2005; Lopez-Urionabarrenechea et al., 2012; De Stefanis et al.,  
579 2013b). Zeolites (ZSM5, HZSM etc.) are effective in plastics degradation as discussed in  
580 numerous past studies (George Manos, 2000; Ranbir Bagri, 2002).

581 López et al. (2011b) even used red mud, a Bauxite by-product waste from alumina production  
582 industry, as a catalyst for waste plastics pyrolysis as it favours hydrogenation reactions, but the  
583 high catalyst activity was only found at high temperatures ( $>500^{\circ}\text{C}$ ). On the other hand, catalyst  
584 like ZSM-5 was found to be active at lower temperature ( $440^{\circ}\text{C}$ ) and also to promote the  
585 production of lighter hydrocarbons (gas/liquid) with high aromaticity. Still regarding  
586 nanoporous aluminosilicates, De Stefanis et al. (2013a) reported three possible catalysts from  
587 restructured smectite clays: saponite, montmorillonite and beidellite. Catalysts were  
588 substantiated for their performance in the catalytic pyrolysis of a medium-density polyethylene.  
589 Catalysts were able to reduce the temperature of cracking down to  $300^{\circ}\text{C}$ , as compared to  
590  $650^{\circ}\text{C}$  or more for non-catalysed pyrolysis. In comparison to zeolites, clay based catalysts were  
591 found superior in producing liquid hydrocarbon from plastic wastes as they favour the  
592 production of liquid hydrocarbons in the gasoline and diesel range liquid from the polyethylene  
593 plastics.

### 594 *5.3.1 Bromine fixation from BFR containing e-waste plastics degradation*

595 Hall and Williams (2007) performed pyrolysis experiments with brominated ABS plastics  
596 originating from old computer monitor casings in a fluidised bed reactor system heated using  
597 an externally heated furnace, an air preheater ( $450^{\circ}\text{C}$ ) for fluidizing the fine ( $300 - 425 \mu\text{m}$ )  
598 sand particles used as bed material. The reactor was externally attached with condensers and  
599 scrubbing systems. They successfully converted the Br-ABS waste into more than 91% of oil.  
600 98% of the bromide was found in oil fraction and no bromine was found in the solid char one.

601 In catalytic pyrolysis, it is possible to fixate the bromine into different product stream (Ma et  
602 al., 2016b). Hence, catalytic pyrolysis is also utilized for simultaneous de-halogenation and  
603 degradation of e-waste plastics. Sakata et al. (2003) proposed iron oxide and calcium carbonate  
604 as the catalyst/sorbent for dehalogenation process. The process can follow two approaches (Fig.  
605 9). One approach advocated the degradation of plastics followed by dehalogenation of the  
606 halogenated products. In the other approach, both degradation and dehalogenation occurs  
607 simultaneously in presence of a suitable catalyst.



608

609 **Fig. 9: Two steps and single step dehalogenation and degradation of halogenated**  
610 **plastics (Sakata et al., 2003)**

611 Areprasert and Khaobang (2018) investigated the utilization of char obtained from e-waste as  
612 a green catalyst in the process of simultaneous debromination and pyrolysis of ABS/PC, PCB  
613 from e-waste. Although it is difficult to separate out Br from the pyrolysis product stream, the  
614 use of catalyst, one can modify brominated molecules from one stream (for example gas) in  
615 order to shift it to another stream (for example liquid). Chen et al. (2020) use Fe-Ni/MCM-41  
616 catalyst to recover the Br free oil fraction from the pyrolysis of BFR added e-waste plastics.  
617 Presence of Fe in the catalyst significantly reduces the HBr in the oil fraction whereas Ni helps  
618 in the reduction of  $SbBr_3$  in the oil. Ma et al. (2016b) observed a 50% reduction of Bromine  
619 content in the oil product in presence of zeolite catalysts compared with the non-catalytic

620 thermal pyrolysis. Addition of catalyst resulted in decrease of bromine content in the oil but  
621 simultaneously increased in wax and char residue. Table 4 compares the reduction of Bromine  
622 content in the oil fraction using different catalysts when compared with non-catalytic pyrolysis.  
623 PCB pyrolysis is an energy intensive process since their thermal decomposition is endothermic.  
624 Guo et al. (2014) were able to recover 10.17 wt% gas, 18.23% of oil/tar and 71.60% of solid  
625 residue by doing the low temperature (~500°C) pyrolysis of FR4 (epoxy composite) type PCBs.  
626 The calorific values of gas and tar samples are 2.38 MJ/kg and 4.5 MJ/kg respectively, which  
627 amounted around 35% of the total energy consumption for the pyrolysis. Gases such as CO,  
628 CO<sub>2</sub> and 2-methyl propene, were major components of the gaseous fraction. Regarding the tar  
629 fraction, it consisted of mostly phenols and alkyl aromatics along with brominated  
630 hydrocarbons.

631

632 **Table 4: Effect of catalyst in the reduction of Br from the pyrolysis liquid product compare to the non-catalytic pyrolysis liquid product**

Catalyst	Material	% reduction of Br from the non-catalytic pyrolysis	Reference
Y-Zeolite	Waste ABS+PC (80:20) with BFR	75%	Areeprasert and Khaobang (2018)
	PCB with BFR	8.1%	
ZSM-5	Waste ABS+PC (80:20) with BFR	75%	
	PCB with BFR	7.7%	
Bio-char (BC)	Waste ABS+PC (80:20) with BFR	60%	
	PCB with BFR	54%	
Electronic waste char (EWC)	Waste ABS+PC (80:20) with BFR	81%	
	PCB with BFR	58.6%	
Iron oxide loaded Y-Zeolite (Fe/YZ)	Waste ABS+PC (80:20) with BFR	81%	
	PCB with BFR	19%	
Iron oxide loaded ZSM-5 (Fe/ZSM-5)	Waste ABS+PC (80:20) with BFR	89.1%	
	PCB with BFR	46.3%	
Iron oxide loaded biochar (Fe/BC)	Waste ABS+PC (80:20) with BFR	90.5%	
	PCB with BFR	58.6%	
Iron oxide loaded electronic waste char (Fe/EWC)	Waste ABS+PC (80:20) with BFR	98.1%	
	PCB with BFR	70.9%	
Fe-Ni/MCM-41	Waste ABS with TBPPA+Sb <sub>2</sub> O <sub>3</sub>	~60%	Chen et al. (2020)
Zeolite catalyst (HY)		~42%	
Zeolite catalyst (H $\beta$ )		~50%	
Zeolite catalyst (HZSM5)	Br-ABS	~39%	Ma et al. (2016b)
MCM-41 (All silica)		~11%	
Al <sub>2</sub> O <sub>3</sub>		~40%	

## 634 **5.4 Effect of pyrolysis reactor configuration**

635 We have seen that pyrolysis is a possible solution for e-waste plastics degradation and de-  
636 halogenation. As discussed in the previous section, thermal treatment of e-waste plastics with  
637 BFR can be carried out in three ways: Firstly, dehalogenation is followed by pyrolysis of e-  
638 waste plastics; secondly, both dehalogenation and pyrolysis are performed simultaneously;  
639 thirdly, contaminated plastics undergo pyrolysis which is followed by a product up-gradation  
640 step to produce more useful products without toxins (Yang et al., 2013). For these approaches,  
641 different reactor configurations were used including batch reactor, semi-batch reactor, catalytic  
642 bed reactor, two-stage drop down reactor, fluidized bed reactor, rotary kiln reactor, screw kiln  
643 reactor, etc. Industrially, batch, fluidized bed and rotary kiln reactors are commonly considered  
644 for waste plastic pyrolysis.

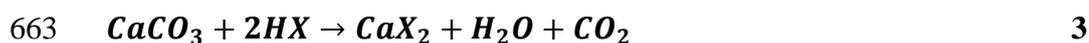
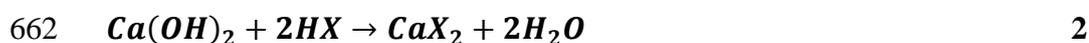
### 645 *5.4.1 Batch/semi-batch reactors*

646 Batch/semi-batch reactors are often used in the laboratory scale studies as they enable to easily  
647 maintain reaction conditions, such as temperature and pressure. For example, Hall and  
648 Williams (2008) performed catalytic pyrolysis in a batch reactor and examined the potentials  
649 of zeolite based catalyst in the process of removing brominated organic compounds from the  
650 oil products. They reported that zeolites: (i) significantly reduced the brominated organic  
651 components within the pyrolysis oil when treating BFR containing ABS and HIPS; (ii) but at  
652 the same time however, deteriorated the overall product quality by reducing the production of  
653 valuable chemicals, such as styrene and cumene.

### 654 *5.4.2 Fluidized bed reactors*

655 Jung et al. (2012) mixed shredded particles of Br-ABS from e-waste plastics with Calcium-  
656 based additives, such as calcium oxide, calcium hydroxide and oyster shells, and carried out  
657 the pyrolysis experiment in a fluidized bed reactor. The Ca-based absorbents were able to  
658 neutralize the hydrogen halide (X) formed due to the pyrolysis at 400°C of halogen containing

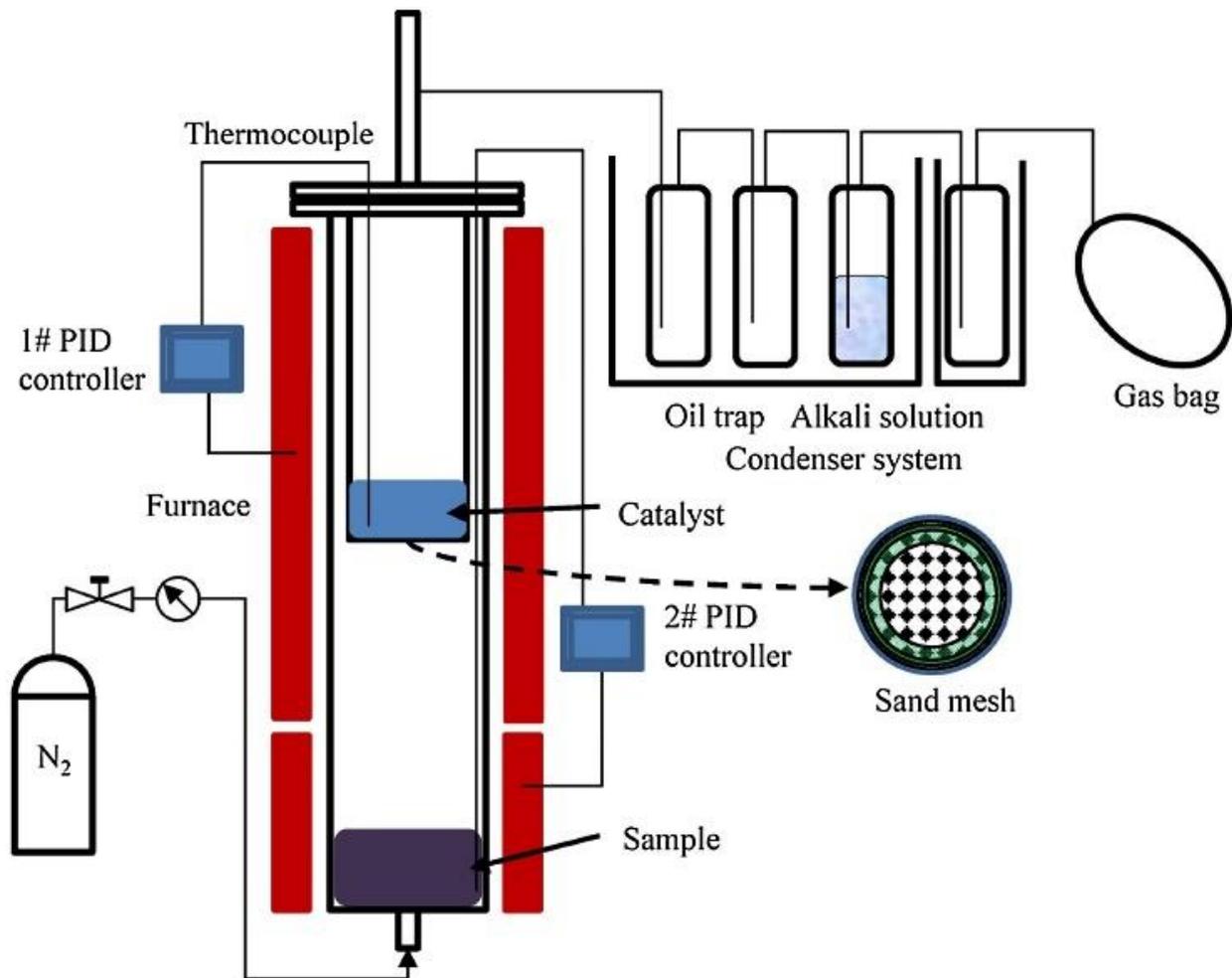
659 plastics (Br, Cl). The following reactions (Eq. 1 – Eq. 3) explain the reaction mechanism of the  
660 dehalogenation process.



664 Where X = Cl or Br

### 665 *5.4.3 Two stage pyrolysis reactors*

666 Two-stage reactors were used in which the pyrolysis reaction occurs in the first stage and the  
667 evolve gases passes through a catalytic bed in the second stage (Williams and Chishti, 2000;  
668 Ratnasari et al., 2017). Ratnasari et al. (2017) performed pyrolysis experiments in a two stage  
669 pyrolysis unit where in the second stage, a multi-layered structured mesoporous (MCM41)  
670 catalyst stacked on top of a micro-porous catalyst (ZSM5) layer to ensure more gasoline type  
671 hydrocarbon production from waste plastics. Two stages reactors are also utilized for the  
672 catalytic pyrolysis and bromine removal of the non-metallic fractions of waste PCBs. Ma and  
673 Kamo (2018) applied low cost Fe and Ni catalysts in a two stage fixed bed reactor for the  
674 pyrolysis of waste PCBs and reported that Fe particles have excellent bromine removal  
675 efficiencies from the pyrolysis product. The schematic representation of the two stage fixed  
676 bed pyrolysis setup is shown in Fig. 10.



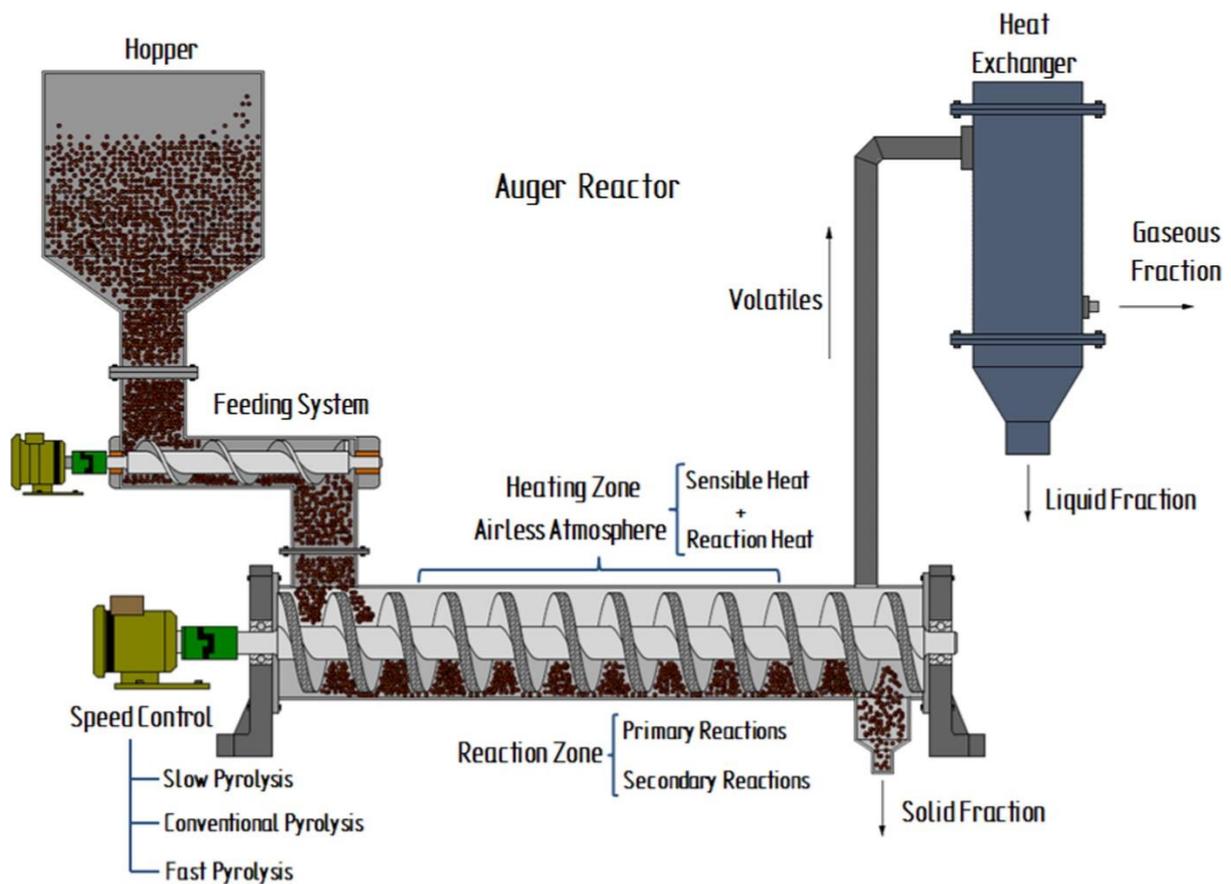
677

678 **Fig. 10: Schematic representation of the two-stage fixed-bed reactor system.**(Ma and  
 679 **Kamo, 2018)** [Reprinted from the article: *C. Ma and T. Kamo, Journal of Analytical and*  
 680 *Applied Pyrolysis, 134, (2018) 614, with permission from Elsevier]*

681 *5.4.4 Auger (screw kiln) reactor*

682 As reported recently, low temperature pyrolysis of carbonaceous material, such as plastics,  
 683 with long holding times undergoes consecutive degradation to produce lighter hydrocarbon  
 684 liquid fractions (Das and Tiwari, 2018b). However, at high temperature, ultra-pyrolysis  
 685 (flash/fast pyrolysis) indulges more production of gaseous hydrocarbon (Alvarez et al., 2015;  
 686 Lopez et al., 2017). Slow pyrolysis experiments were conducted mostly in batch or semi-batch  
 687 reactors. For continuous production, a screw kiln reactors/auger reactors can be used for low  
 688 to moderate temperature pyrolysis. Auger reactors use a screw to convey the feedstock down

689 the length of the externally heated tube (Campuzano et al., 2019). The temperature of the  
690 reactor can be programmed to vary along the length of the reactor tube. A typical auger reactor  
691 used for the pyrolysis of biomass is shown in Fig. 11 (Campuzano et al., 2019).



692

693 **Fig. 11: Single-auger reactor for pyrolysis of biomass** [Reprinted from the article:  
694 *Campuzano, Felipe Brown, Robert C. Martínez, Juan Daniel, Auger reactors for pyrolysis*  
695 *of biomass and wastes, Renewable and Sustainable Energy Reviews, 102, (2019) 372, with*  
696 **permission from Elsevier**

#### 697 5.4.5 Microwave assisted pyrolysis

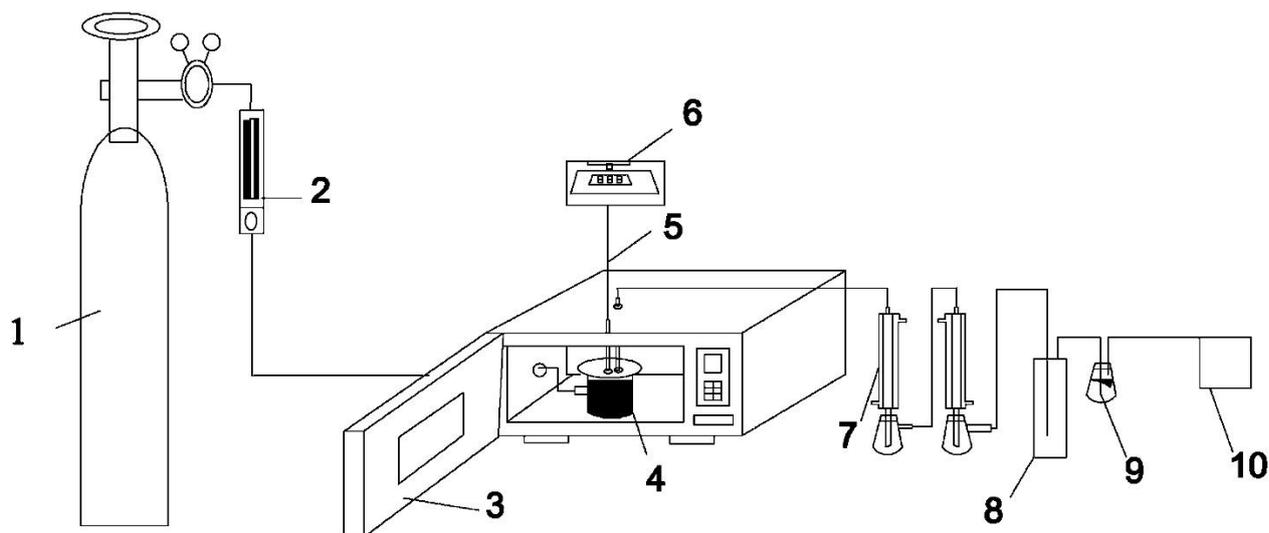
698 In microwave pyrolysis, microwaves are used as the energy source. Microwave are  
699 electromagnetic waves with wavelength ranging between 1 mm and 1 m (Undri et al., 2013).  
700 Materials like water, biomass, metals and carbon particles, are considered good microwave  
701 absorbers (dielectric materials). Polymers and plastics are transparent to microwave because  
702 they have low microwave absorption capacity (Cheng and Hu, 2010). However, these latter

703 materials can undergo pyrolysis by mixing them with dielectric ones, such as carbon particles  
704 or metal particles, in a microwave reactor. The control of pyrolysis temperature in microwave  
705 heating is however tricky due to the formation of hot spots during heating caused by localized  
706 microwave field that are due to the difference in dielectric properties of the various material  
707 and large wavelength of the radiation (Undri et al., 2013).

708 Microwave heating has been used for pyrolysis of biomass (Zhao et al., 2012; Zhang et al.,  
709 2017), waste plastics (Ludlow-Palafox and Chase, 2001), scrap tyres (Undri et al., 2013) and  
710 electronic waste (Sun et al., 2011). Aishwarya and Sindhu (2016) successfully carried out the  
711 pyrolysis of simulated plastic mixtures in a microwave assisted pyrolyser which had a power  
712 of 5 kW and was integrated with 4 magnetron generating microwaves continuously. Ludlow-  
713 Palafox and Chase (2001) successfully recovered aluminium and hydrocarbons from high  
714 density polyethylene and aluminium/polymer laminates (empty toothpaste tubes) by  
715 microwave induced pyrolysis in a semi-batch reactor using carbon particles as microwave  
716 absorbing materials. Hussain et al. (2012) used a microwave heating aluminium coil reactor  
717 for the pyrolysis of waste polystyrene into useful products. The heating was controlled by  
718 changing the size and shape of the metal reactor. Major factors affecting the microwave  
719 pyrolysis include the feedstock's properties, feeding pattern, heating program, microwave  
720 power, microwave power delivery, reactor design, susceptor type, catalytic properties of the  
721 susceptors and other reaction conditions. A typical microwave assisted pyrolysis setup is shown  
722 in Fig. 12 (Sun et al., 2011).

723

724



725

726 **Fig. 12: Diagram of the reactor system for microwave-induced pyrolysis of WPCBs: (1)**  
 727 **nitrogen cylinder, (2) rotameter, (3) microwave oven, (4) quartz reactor, (5)**  
 728 **thermocouple, (6) data collection, (7) condensing system, (8) glass wool trap, (9) deionized**  
 729 **water, (10) gas bag [Reprinted (adapted) with permission from (J. Sun, W. Wang, Z. Liu**  
 730 **and C. Ma, Industrial & Engineering Chemistry Research, 50, (2011) 11763.). Copyright**  
 731 **(2011) American Chemical Society."]**

## 732 6 Conclusion and outlooks

733 The recovery of toxic free plastics from e-waste plastics is an interesting field of waste  
 734 utilization and conversion. An extensive amount of studies of thermochemical conversion of  
 735 waste plastics have been carried out in recent years and many significant technological  
 736 advances have been achieved. However, a pyrolytic solution is still lacking that is capable of  
 737 dealing with waste quantities as large as the ones that can be treated using conventional waste  
 738 treatments, such as incineration and land filling. Major hurdle for plastic pyrolysis is the non-  
 739 homogeneity of plastic waste. Plastics like PVC and PET in the feedstock can lead to different  
 740 types of end products compared with polyolefin based plastics. On the other hand, plastic  
 741 wastes from WEEEs contain various types of plastics including styrene based plastics (ABS,  
 742 HIPS), polycarbonates, polyamides and polyolefins containing environmentally harmful  
 743 toxins, such as BFRs and heavy metals. Special attention is needed to recover the non-toxic

744 plastics from such e-waste plastics. Extraction processes of BFRs from the latter have been  
745 studied extensively with different solvents, such as methanol, propanol, hexane, etc., with good  
746 extraction efficiencies. However, it is advisable to do extractions of toxins in a sustainable way  
747 by using green technology, such as using supercritical CO<sub>2</sub> as solvent, bio solvents, ionic  
748 liquids, etc.

749 Pyrolysis of e-waste plastics have been performed particularly with various catalyst based on  
750 different metals, such as Ni, Fe, Ca, Mg etc, which might help in reducing the brominated  
751 organic hydrocarbon content in pyrolysis products. Pyrolysis is one of the most recommended  
752 technique in the treatment of e-waste plastics to convert them into value added products,  
753 however complete detoxification of e-waste plastics by pyrolysis remains the limiting factor.

754 The scope of utilizing thermochemical conversion of e-waste plastic into oil and chemicals is  
755 significant and helps to deal with the massive and global problem of plastic as well as e-wastes.

756 The pros

#### 757 **Declaration of competing interest**

758 The Authors have no conflict of interest between them.

#### 759 **Acknowledgement:**

760 Authors would like to thank financial support from National Research Foundation, Prime  
761 Minister's Office, Singapore, the Ministry of National Development, Singapore, and National  
762 Environment Agency, Ministry of the Environment and Water Resource, Singapore under the  
763 Closing the Waste Loop R&D Initiative as part of the Urban Solutions & Sustainability –  
764 Integration Fund (Award No. USS-IF-2018-4).

765

766

767 **References**

- 768 Achilias, D.S., Antonakou, E.V., Koutsokosta, E., Lappas, A.A., 2009. Chemical recycling of  
769 polymers from Waste Electric and Electronic Equipment. *Journal of Applied Polymer Science*  
770 114, 212-221.
- 771 Achilias, D.S., Roupakias, C., Megalokonomos, P., Lappas, A.A., Antonakou, E.V., 2007.  
772 Chemical recycling of plastic waste made from polyethylene (LDPE and HDPE) and  
773 polypropylene. *Journal of Hazardous materials* 149, 536-542.
- 774 Adrados, A., de Marco, I., Caballero, B.M., Lopez, A., Laresgoiti, M.F., Torres, A., 2012.  
775 Pyrolysis of plastic packaging waste: A comparison of plastic residuals from material recovery  
776 facilities with simulated plastic waste. *Waste Manag* 32, 826-832.
- 777 Agency, I.E., 2014. *Key World Energy Statistics*. OECD Publishing, Paris.
- 778 Aishwarya, K.N., Sindhu, N., 2016. Microwave Assisted Pyrolysis of Plastic Waste. *Procedia*  
779 *Technology* 25, 990-997.
- 780 Al-Salem, S.M., Lettieri, P., Baeyens, J., 2009. Recycling and recovery routes of plastic solid  
781 waste (PSW): a review. *Waste Manag* 29, 2625-2643.
- 782 Alston, S.M., Clark, A.D., Arnold, J.C., Stein, B.K., 2011. Environmental Impact of Pyrolysis  
783 of Mixed WEEE Plastics Part 1: Experimental Pyrolysis Data. *Environmental Science &*  
784 *Technology* 45, 9380-9385.
- 785 Altarawneh, M., Saeed, A., Al-Harashseh, M., Dlugogorski, B.Z., 2019. Thermal  
786 decomposition of brominated flame retardants (BFRs): Products and mechanisms. *Progress in*  
787 *Energy and Combustion Science* 70, 212-259.
- 788 Altwaiq, A.m., Wolf, M., van Eldik, R., 2003. Extraction of brominated flame retardants from  
789 polymeric waste material using different solvents and supercritical carbon dioxide. *Analytica*  
790 *Chimica Acta* 491, 111-123.
- 791 Alvarez, J., Amutio, M., Lopez, G., Barbarias, I., Bilbao, J., Olazar, M., 2015. Sewage sludge  
792 valorization by flash pyrolysis in a conical spouted bed reactor. *Chemical Engineering Journal*  
793 273, 173-183.
- 794 Antonakou, E.V., Kalogiannis, K.G., Stefanidis, S.D., Karakoulia, S.A., Triantafyllidis, K.S.,  
795 Lappas, A.A., Achilias, D.S., 2014. Catalytic and thermal pyrolysis of polycarbonate in a fixed-  
796 bed reactor: The effect of catalysts on products yields and composition. *Polymer Degradation*  
797 *and Stability* 110, 482-491.
- 798 Areeprasert, C., Khaobang, C., 2018. Pyrolysis and catalytic reforming of ABS/PC and PCB  
799 using biochar and e-waste char as alternative green catalysts for oil and metal recovery. *Fuel*  
800 *Processing Technology* 182, 26-36.
- 801 Arvanitoyannis, I.S., 2013. 14 - Waste Management for Polymers in Food Packaging  
802 Industries. in: Ebnesajjad, S. (Ed.). *Plastic Films in Food Packaging*. William Andrew  
803 Publishing, Oxford, pp. 249-310.
- 804 Baldé, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., 2017. The Global E-waste Monitor  
805 2017: Quantities, Flows, and Resources. International Telecommunication Union.
- 806 Ben Said, A., Guinot, C., Ruiz, J.C., Grandjean, A., Dole, P., Joly, C., Chalamet, Y., 2017.  
807 Modeling of supercritical CO<sub>2</sub> extraction of contaminants from post-consumer polypropylene:  
808 Solubilities and diffusion coefficients in swollen polymer at varying pressure and temperature  
809 conditions. *Chem. Eng. Res. Des.* 117, 95-109.
- 810 Brebu, M., Bhaskar, T., Murai, K., Muto, A., Sakata, Y., Uddin, M.A., 2005. Removal of  
811 nitrogen, bromine, and chlorine from PP/PE/PS/PVC/ABS-Br pyrolysis liquid products using  
812 Fe- and Ca-based catalysts. *Polymer Degradation and Stability* 87, 225-230.

813 Brennan, L.B., Isaac, D.H., Arnold, J.C., 2002. Recycling of acrylonitrile–butadiene–styrene  
814 and high-impact polystyrene from waste computer equipment. *Journal of Applied Polymer*  
815 *Science* 86, 572-578.

816 Buekens, A., 2006. Introduction to feedstock recycling of plastics. John Wiley & Sons, Ltd,  
817 pp. 1-41.

818 Campuzano, F., Brown, R.C., Martínez, J.D., 2019. Auger reactors for pyrolysis of biomass  
819 and wastes. *Renewable and Sustainable Energy Reviews* 102, 372-409.

820 Cao, P., Fujimori, T., Juhasz, A., Takaoka, M., Oshita, K., 2020. Bioaccessibility and human  
821 health risk assessment of metal(loid)s in soil from an e-waste open burning site in  
822 Agbogbloshie, Accra, Ghana. *Chemosphere* 240, 124909.

823 Chandrasekaran, S.R., Avasarala, S., Murali, D., Rajagopalan, N., Sharma, B.K., 2018.  
824 Materials and Energy Recovery from E-Waste Plastics. *ACS Sustainable Chemistry &*  
825 *Engineering* 6, 4594-4602.

826 Chaukura, N., Gwenzi, W., Bunhu, T., Ruziwa, D.T., Pumure, I., 2016. Potential uses and  
827 value-added products derived from waste polystyrene in developing countries: A review.  
828 *Resour. Conserv. Recy* 107, 157-165.

829 Chen, T., Yu, J., Ma, C., Bikane, K., Sun, L., 2020. Catalytic performance and debromination  
830 of Fe–Ni bimetallic MCM-41 catalyst for the two-stage pyrolysis of waste computer casing  
831 plastic. *Chemosphere* 248, 125964.

832 Chen, Z., Yang, M., Shi, Q., Kuang, X., Qi, H.J., Wang, T., 2019. Recycling Waste Circuit  
833 Board Efficiently and Environmentally Friendly through Small-Molecule Assisted Dissolution.  
834 *Sci Rep* 9, 17902.

835 Cheng, H., Hu, Y., 2010. Municipal solid waste (MSW) as a renewable source of energy:  
836 Current and future practices in China. *Bioresource Technology* 101, 3816-3824.

837 Cherif Lahimer, M., Ayed, N., Horriche, J., Belgaied, S., 2017. Characterization of plastic  
838 packaging additives: Food contact, stability and toxicity. *Arabian Journal of Chemistry* 10,  
839 S1938-S1954.

840 Choi, S., Choi, H.M., 2019. Eco-friendly, Expeditious Depolymerization of PET in the Blend  
841 Fabrics by Using a Bio-based Deep Eutectic Solvent under Microwave Irradiation for  
842 Composition Identification. *Fiber. Polym.* 20, 752-759.

843 Coates, G.W., Getzler, Y., Chemical recycling to monomer for an ideal, circular polymer  
844 economy. *Nature Reviews Materials*.

845 Costiuc, L., Patachia, S., Baltas, L., Tiorean, M., 2011. Investigation on Energy Density of  
846 Plastic Waste Materials. The 26th International Conference on Solid Waste Technology and  
847 Management, pp. 930-939.

848 Covaci, A., Harrad, S., Abdallah, M.A.E., Ali, N., Law, R.J., Herzke, D., de Wit, C.A., 2011.  
849 Novel brominated flame retardants: A review of their analysis, environmental fate and  
850 behaviour. *Environment International* 37, 532-556.

851 Coyne, D., 2018. World Energy 2018-2050: World Energy Annual Report (Part 1). Peak Oil  
852 Barral.

853 Cui, J., Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: A review.  
854 *Journal of Hazardous Materials* 158, 228-256.

855 Damrongsiri, S., Vassanadumrongdee, S., Tanwattana, P., 2016. Heavy metal contamination  
856 characteristic of soil in WEEE (waste electrical and electronic equipment) dismantling  
857 community: a case study of Bangkok, Thailand. *Environmental Science and Pollution Research*  
858 23, 17026-17034.

859 Das, A., Vidyadhar, A., Mehrotra, S.P., 2009. A novel flowsheet for the recovery of metal  
860 values from waste printed circuit boards. *Resources, Conservation and Recycling* 53, 464-469.

861 Das, P., Tiwari, P., 2017. Thermal degradation kinetics of plastics and model selection.  
862 *Thermochimica Acta* 654, 191-202.

863 Das, P., Tiwari, P., 2018a. The effect of slow pyrolysis on the conversion of packaging waste  
864 plastics (PE and PP) into fuel. *Waste Management* 79, 615-624.

865 Das, P., Tiwari, P., 2018b. Valorization of packaging plastic waste by slow pyrolysis.  
866 *Resources, Conservation and Recycling* 128, 69-77.

867 De Stefanis, A., Cafarelli, P., Gallese, F., Borsella, E., Nana, A., Perez, G., 2013a. Catalytic  
868 pyrolysis of polyethylene: A comparison between pillared and restructured clays. *Journal of*  
869 *Analytical and Applied Pyrolysis* 104, 479-484.

870 De Stefanis, A., Cafarelli, P., Gallese, F., Borsella, E., Nana, A., Perez, G., 2013b. Catalytic  
871 pyrolysis of polyethylene: A comparison between pillared and restructured clays. *Journal of*  
872 *Analytical and Applied Pyrolysis*.

873 Debnath, B., Chowdhury, R., Ghosh, S.K., 2018. Sustainability of metal recovery from E-  
874 waste. *Frontiers of Environmental Science & Engineering* 12, 2.

875 Diaz, L.F., Golueke, C.G., Savage, G.M., Eggerth, L.L., 2020. *Composting and Recycling*  
876 *Municipal Solid Waste*. CRC Press.

877 Duan, H., Li, J., Liu, Y., Yamazaki, N., Jiang, W., 2011. Characterization and Inventory of  
878 PCDD/Fs and PBDD/Fs Emissions from the Incineration of Waste Printed Circuit Board.  
879 *Environmental Science & Technology* 45, 6322-6328.

880 E.U., 2015. COMMISSION DELEGATED DIRECTIVE (EU) 2015/863. in: Commission, E.  
881 (Ed.). 2015/861, Official Journal of the European Union L137.

882 Egerer, K., Brandl, F., Golzari, N., Beuermann, S., 2019. Recycling of Printed Circuit Boards  
883 Employing Supercritical Carbon Dioxide. *Materials Science Forum* 959, 100-106.

884 Europe, P., 2018. *Plastics- the Fact 2018: An analysis of European plastic production demand*  
885 *and waste data*.

886 Evangelopoulos, P., Arato, S., Persson, H., Kantarelis, E., Yang, W., 2019. Reduction of  
887 brominated flame retardants (BFRs) in plastics from waste electrical and electronic equipment  
888 (WEEE) by solvent extraction and the influence on their thermal decomposition. *Waste*  
889 *Management* 94, 165-171.

890 Evangelopoulos, P., Kantarelis, E., Yang, W., 2015. Investigation of the thermal  
891 decomposition of printed circuit boards (PCBs) via thermogravimetric analysis (TGA) and  
892 analytical pyrolysis (Py-GC/MS). *Journal of Analytical and Applied Pyrolysis* 115, 337-343.

893 Forum, W.E., 2019. *A New Circular Vision for Electronics - Time for a Global Reboot*.  
894 *Platform for Accelerating the Circular Economy (PACE)*, Davos, Switzerland.

895 Fries, E., Dekiff, J.H., Willmeyer, J., Nuelle, M.-T., Ebert, M., Remy, D., 2013. Identification  
896 of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and  
897 scanning electron microscopy. *Environmental Science: Processes & Impacts* 15, 1949-1956.

898 Furuuchi, M., Gotoh, K., 1992. Shape separation of particles. *Powder technology* 73, 1-9.

899 Furuuchi, M., Yamada, C., Gotoh, K., 1993. Shape separation of particulates by a rotating  
900 horizontal sieve drum. *Powder technology* 75, 113-118.

901 Gamse, T., Steinkellner, F., Marr, R., Alessi, P., Kikic, I., 2000. Solubility Studies of Organic  
902 Flame Retardants in Supercritical CO<sub>2</sub>. *Industrial & Engineering Chemistry Research* 39,  
903 4888-4890.

904 George Manos, A.G., and John Dwyer, 2000. Catalytic Degradation of High-Density  
905 Polyethylene over Different  
906 Zeolitic Structures. *Industrial & Engineering Chemistry Research* 39, 1198-1208.

907 Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made.  
908 *Sci. Adv.* 3.

909 Ghosh, B., Ghosh, M.K., Parhi, P., Mukherjee, P.S., Mishra, B.K., 2015. Waste Printed Circuit  
910 Boards recycling: an extensive assessment of current status. *Journal of Cleaner Production* 94,  
911 5-19.

912 Global, B., 2019. BP Statistical Review of World Energy.

913 Grant, K., Goldizen, F.C., Sly, P.D., Brune, M.-N., Neira, M., van den Berg, M., Norman, R.E.,  
914 2013. Health consequences of exposure to e-waste: a systematic review. *The Lancet Global*  
915 *Health* 1, e350-e361.

916 Guo, X., Qin, F.G., Yang, X., Jiang, R., 2014. Study on low-temperature pyrolysis of large-  
917 size printed circuit boards. *Journal of analytical and applied pyrolysis* 105, 151-156.

918 Hall, W.J., Williams, P.T., 2006. Fast Pyrolysis of Halogenated Plastics Recovered from Waste  
919 Computers. *Energy & Fuels* 20, 1536-1549.

920 Hall, W.J., Williams, P.T., 2007. Analysis of products from the pyrolysis of plastics recovered  
921 from the commercial scale recycling of waste electrical and electronic equipment. *Journal of*  
922 *Analytical and Applied Pyrolysis* 79, 375-386.

923 Hall, W.J., Williams, P.T., 2008. Removal of organobromine compounds from the pyrolysis  
924 oils of flame retarded plastics using zeolite catalysts. *Journal of Analytical and Applied*  
925 *Pyrolysis* 81, 139-147.

926 He, M., Wang, X., Wu, F., Fu, Z., 2012. Antimony pollution in China. *Science of The Total*  
927 *Environment* 421-422, 41-50.

928 Hsu, E., Barmak, K., West, A.C., Park, A.-H.A., 2019. Advancements in the treatment and  
929 processing of electronic waste with sustainability: a review of metal extraction and recovery  
930 technologies. *Green Chemistry* 21, 919-936.

931 Hurley, R., Woodward, J., Rothwell, J.J., 2018. Microplastic contamination of river beds  
932 significantly reduced by catchment-wide flooding. *Nature Geoscience* 11, 251-257.

933 Hussain, Z., Khan, K.M., Perveen, S., Hussain, K., Voelter, W., 2012. The conversion of waste  
934 polystyrene into useful hydrocarbons by microwave-metal interaction pyrolysis. *Fuel*  
935 *Processing Technology* 94, 145-150.

936 Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R.,  
937 Law, K.L., 2015. Plastic waste inputs from land into the ocean. *Science* 347, 768-771.

938 Jefferson, M., 2016. A global energy assessment. *Wiley Interdisciplinary Reviews: Energy and*  
939 *Environment* 5, 7-15.

940 Jehanno, C., Perez-Madriral, M.M., Demarteau, J., Sardon, H., Dove, A.P., 2019.  
941 Organocatalysis for depolymerisation. *Polym. Chem.* 10, 172-186.

942 Jin, W., Shen, D., Liu, Q., Xiao, R., 2016. Evaluation of the co-pyrolysis of lignin with plastic  
943 polymers by TG-FTIR and Py-GC/MS. *Polymer Degradation and Stability* 133, 65-74.

944 Joshi, R., Ahmed, S., 2016. Status and challenges of municipal solid waste management in  
945 India: A review. *Cogent Environmental Science* 2.

946 Jung, S.-H., Kim, S.-J., Kim, J.-S., 2012. Thermal degradation of acrylonitrile-butadiene-  
947 styrene (ABS) containing flame retardants using a fluidized bed reactor: The effects of Ca-  
948 based additives on halogen removal. *Fuel Processing Technology* 96, 265-270.

949 Kaminsky, W., Schlesselmann, B., Simon, C., 1995. Olefins from polyolefins and mixed  
950 plastic by pyrolysis. *Journal of Analytical and Applied Pyrolysis* 32, 19-27.

951 Keith Freegard, G.T.R.M., Develop a Process to Separate Brominated Flame Retardants from  
952 WEEE Polymers Final Report. UK Waste & Resources Action Programme: Banbury, , UK,  
953 2007.

954 Kiddee, P., Naidu, R., Wong, M.H., 2013. Electronic waste management approaches: An  
955 overview. *Waste Management* 33, 1237-1250.

956 Kurose, K., Okuda, T., Nishijima, W., Okada, M., 2006. Heavy metals removal from  
957 automobile shredder residues (ASR). *Journal of Hazardous Materials* 137, 1618-1623.

958 Lateef, H., Grimes, S.M., Morton, R., Mehta, L., 2008. Extraction of components of composite  
959 materials: ionic liquids in the extraction of flame retardants from plastics. *Journal of Chemical*  
960 *Technology & Biotechnology* 83, 541-545.

961 Lazarevic, D., Aoustin, E., Buclet, N., Brandt, N., 2010. Plastic waste management in the  
962 context of a European recycling society: Comparing results and uncertainties in a life cycle  
963 perspective. *Resour. Conserv. Recy* 55, 246-259.

964 Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017.  
965 River plastic emissions to the world's oceans. *Nature Communications* 8, 15611.

966 Li, J., Dong, Z., Wang, Y., Bao, J., Yan, Y., Liu, A., Jin, J., 2018. Human exposure to  
967 brominated flame retardants through dust in different indoor environments: Identifying the  
968 sources of concentration differences in hair from men and women. *Chemosphere* 205, 71-79.

969 Li, J., Lu, H., Guo, J., Xu, Z., Zhou, Y., 2007. *Recycle Technology for Recovering Resources  
970 and Products from Waste Printed Circuit Boards*. *Environmental Science & Technology* 41,  
971 1995-2000.

972 Li, Y., Wang, T., Hashi, Y., Li, H., Lin, J.M., 2009. Determination of brominated flame  
973 retardants in electrical and electronic equipments with microwave-assisted extraction and gas  
974 chromatography-mass spectrometry. *Talanta* 78, 1429-1435.

975 Liu, Y., Liu, Y., 2005. Novel Incineration Technology Integrated with Drying, Pyrolysis,  
976 Gasification, and Combustion of MSW and Ashes Vitrification. *Environmental Science &  
977 Technology* 39, 3855-3863.

978 Liu, Y., Wang, Q., Fei, G., Chen, Y., 2006. Preparation of polyamide resin-encapsulated  
979 melamine cyanurate/melamine phosphate composite flame retardants and the fire-resistance to  
980 glass fiber-reinforced polyamide 6. *Journal of Applied Polymer Science* 102, 1773-1779.

981 Lopez-Uriónabarrenechea, A., de Marco, I., Caballero, B.M., Laresgoiti, M.F., Adrados, A.,  
982 2012. Catalytic stepwise pyrolysis of packaging plastic waste. *Journal of Analytical and  
983 Applied Pyrolysis* 96, 54-62.

984 López, A., de Marco, I., Caballero, B.M., Laresgoiti, M.F., Adrados, A., 2011a. Influence of  
985 time and temperature on pyrolysis of plastic wastes in a semi-batch reactor. *Chemical  
986 Engineering Journal* 173, 62-71.

987 López, A., de Marco, I., Caballero, B.M., Laresgoiti, M.F., Adrados, A., Aranzabal, A., 2011b.  
988 Catalytic pyrolysis of plastic wastes with two different types of catalysts: ZSM-5 zeolite and  
989 Red Mud. *Applied Catalysis B: Environmental* 104, 211-219.

990 Lopez, G., Alvarez, J., Amutio, M., Mkhize, N.M., Danon, B., van der Gryp, P., Görgens, J.F.,  
991 Bilbao, J., Olazar, M., 2017. Waste truck-tyre processing by flash pyrolysis in a conical spouted  
992 bed reactor. *Energy Conversion and Management* 142, 523-532.

993 Ludlow-Palafox, C., Chase, H.A., 2001. Microwave-induced pyrolysis of plastic wastes.  
994 *Industrial Engineerin Chemistry Research* 40, 4749-4756.

995 Luo, C., Liu, C., Wang, Y., Liu, X., Li, F., Zhang, G., Li, X., 2011. Heavy metal contamination  
996 in soils and vegetables near an e-waste processing site, south China. *Journal of Hazardous  
997 Materials* 186, 481-490.

998 Lyon, R.E., Hackett, S.M., Walters, R.N., 1998. Heats of Combustion of high-temperature  
999 polymers.

1000 Ma, C., Kamo, T., 2018. Two-stage catalytic pyrolysis and debromination of printed circuit  
1001 boards: Effect of zero-valent Fe and Ni metals. *Journal of Analytical and Applied Pyrolysis*  
1002 134, 614-620.

1003 Ma, C., Yu, J., Wang, B., Song, Z., Xiang, J., Hu, S., Su, S., Sun, L., 2016a. Chemical recycling  
1004 of brominated flame retarded plastics from e-waste for clean fuels production: A review.  
1005 *Renewable and Sustainable Energy Reviews* 61, 433-450.

1006 Ma, C., Yu, J., Wang, B., Song, Z., Zhou, F., Xiang, J., Hu, S., Sun, L., 2016b. Influence of  
1007 Zeolites and Mesoporous Catalysts on Catalytic Pyrolysis of Brominated Acrylonitrile–  
1008 Butadiene–Styrene (Br-ABS). *Energy & Fuels* 30, 4635-4643.

1009 Ma, S., Lu, J., Gao, J., 2002. Study of the Low Temperature pyrolysis of PVC. *Energy and  
1010 Fuel* 16, 338-342.

1011 Malliari, E., Kalantzi, O.-I., 2017. Children's exposure to brominated flame retardants in indoor  
1012 environments - A review. *Environment International* 108, 146-169.

1013 Meier-Staude, R., Koehnlechner, R., 2000. Electrostatic separation of conductor/non-  
1014 conductor mixtures in operational practice[Elektrostatische Trennung von Leiter-  
1015 /Nichtleitergemischen in der betrieblichen Praxis]. *AUFBEREIT TECH MINER PROCESS.*  
1016 41, 118-123.

1017 Muenhor, D., Harrad, S., Ali, N., Covaci, A., 2010. Brominated flame retardants (BFRs) in air  
1018 and dust from electronic waste storage facilities in Thailand. *Environment International* 36,  
1019 690-698.

1020 Nakajima, K., Kawakami, T., Ueno, T., Onishi, H., 2002. Method for treating thermoplastic  
1021 resin composition containing flame retardant. U. S. Patent, United States.

1022 Nnorom, I.C., Osibanjo, O., 2009. Toxicity characterization of waste mobile phone plastics.  
1023 *Journal of Hazardous Materials* 161, 183-188.

1024 Oh, C.J., Lee, S.O., Yang, H.S., Ha, T.J., Kim, M.J., 2003. Selective leaching of valuable  
1025 metals from waste printed circuit boards. *Journal of the Air & Waste Management Association*  
1026 53, 897-902.

1027 Othman, N., Sidek, L.M., Basri, N.E.A., Yunus, M.N.M., Othman, N.A., 2009. Electronic  
1028 plastic waste management in malaysia: the potential of waste to energy conversion. 2009 3rd  
1029 International Conference on Energy and Environment (ICEE), pp. 337-342.

1030 Peng, S., Chen, L., Li, L., Xie, M., Huang, H., Liu, X., 2010. Debromination of flame-retarded  
1031 TV housing plastic waste. *J. Mater. Cycles Waste Manag.* 12, 103-107.

1032 Qian, X., Song, L., Bihe, Y., Yu, B., Shi, Y., Hu, Y., Yuen, R.K.K., 2014. Organic/inorganic  
1033 flame retardants containing phosphorus, nitrogen and silicon: Preparation and their  
1034 performance on the flame retardancy of epoxy resins as a novel intumescent flame retardant  
1035 system. *Materials Chemistry and Physics* 143, 1243-1252.

1036 Ranbir Bagri, P.T.W., 2002. Catalytic pyrolysis of polyethylene. *Journal of Analytical and*  
1037 *Applied Pyrolysis* 63, 29-41.

1038 Ratnasari, D.K., Nahil, M.A., Williams, P.T., 2017. Catalytic pyrolysis of waste plastics using  
1039 staged catalysis for production of gasoline range hydrocarbon oils. *Journal of Analytical and*  
1040 *Applied Pyrolysis* 124, 631-637.

1041 Rigamonti, L., Grosso, M., Møller, J., Martinez Sanchez, V., Magnani, S., Christensen, T.H.,  
1042 2014. Environmental evaluation of plastic waste management scenarios. *Resources,*  
1043 *Conservation and Recycling* 85, 42-53.

1044 Robinson, B.H., 2009. E-waste: An assessment of global production and environmental  
1045 impacts. *Science of The Total Environment* 408, 183-191.

1046 Romarís-Hortas, V., Moreda-Piñeiro, A., Bermejo-Barrera, P., 2009. Microwave assisted  
1047 extraction of iodine and bromine from edible seaweed for inductively coupled plasma-mass  
1048 spectrometry determination. *Talanta* 79, 947-952.

1049 Rutkowski, J.V., Levin, B.C., 1986. Acrylonitrile-butadiene-styrene copolymers (ABS):  
1050 Pyrolysis and combustion products and their toxicity—a review of the literature. *Fire and*  
1051 *Materials* 10, 93-105.

1052 Sakata, Y., Bhaskar, T., Uddin, M.A., Muto, A., Matsui, T., 2003. Development of a catalytic  
1053 dehalogenation (Cl, Br) process for municipal waste plastic-derived oil. *Journal of Material*  
1054 *Cycles and Waste Management* 5, 113-124.

1055 Scheirs, J., Kaminsky, W., 2006. Feedstock recycling and pyrolysis of waste plastics. John  
1056 Wiley & Sons Chichester, UK.

1057 Schubert, G., 1991. AUFBEREITUNG DER NE-METALLSCHROTTE UND NE-  
1058 METALLHALTIGEN ABFALLE. I. Aufbereitungs-Technik 32.

1059 Sharma, B.K., Moser, B.R., Vermillion, K.E., Doll, K.M., Rajagopalan, N., 2014. Production,  
1060 characterization and fuel properties of alternative diesel fuel from pyrolysis of waste plastic  
1061 grocery bags. *Fuel Processing Technology* 122, 79-90.

1062 Shuey, S.A., Taylor, P., 2005. Review of Pyrometallurgical Treatment of Electronic Scrap.  
1063 *Mining Engineering* 57, 67-70.

1064 Singh, H., Jain, A., 2009. Ignition, combustion, toxicity, and fire retardancy of polyurethane  
1065 foams: a comprehensive review. *Journal of Applied Polymer Science* 111, 1115-1143.

1066 Singh, R.K., Ruj, B., 2016. Time and temperature depended fuel gas generation from pyrolysis  
1067 of real world municipal plastic waste. *Fuel* 174, 164-171.

1068 Smuda, H., 2001. Method of obtaining liquid fuels from polyolefine wastes. Google Patents.

1069 Stenvall, E., Tostar, S., Boldizar, A., Foreman, M.R.S., Möller, K., 2013. An analysis of the  
1070 composition and metal contamination of plastics from waste electrical and electronic  
1071 equipment (WEEE). *Waste Management* 33, 915-922.

1072 Sun, J., Wang, W., Liu, Z., Ma, C., 2011. Recycling of Waste Printed Circuit Boards by  
1073 Microwave-Induced Pyrolysis and Featured Mechanical Processing. *Industrial & Engineering*  
1074 *Chemistry Research* 50, 11763-11769.

1075 Suzuki, M., Nakajima, K., Onishi, H., 2002. Method for treating flame retardant resin  
1076 composition. U. S. Patent, United States.

1077 Tang, X., Shen, C., Shi, D., Cheema, S.A., Khan, M.I., Zhang, C., Chen, Y., 2010. Heavy metal  
1078 and persistent organic compound contamination in soil from Wenling: An emerging e-waste  
1079 recycling city in Taizhou area, China. *Journal of Hazardous Materials* 173, 653-660.

1080 Tange, L., Drohmann, D., 2005. Waste electrical and electronic equipment plastics with  
1081 brominated flame retardants – from legislation to separate treatment – thermal processes.  
1082 *Polymer Degradation and Stability* 88, 35-40.

1083 Tsydenova, O., Bengtsson, M., 2011. Chemical hazards associated with treatment of waste  
1084 electrical and electronic equipment. *Waste Management* 31, 45-58.

1085 Tue, N.M., Goto, A., Takahashi, S., Itai, T., Asante, K.A., Nomiya, K., Tanabe, S., Kunisue,  
1086 T., 2017. Soil contamination by halogenated polycyclic aromatic hydrocarbons from open  
1087 burning of e-waste in Agbogbloshie (Accra, Ghana). *Journal of Material Cycles and Waste*  
1088 *Management* 19, 1324-1332.

1089 Undri, A., Meini, S., Rosi, L., Frediani, M., Frediani, P., 2013. Microwave pyrolysis of  
1090 polymeric materials: Waste tires treatment and characterization of the value-added products.  
1091 *Journal of Analytical and Applied Pyrolysis* 103, 149-158.

1092 Vandenburg, H.J., Clifford, A.A., Bartle, K.D., Zhu, S.A., Carroll, J., Newton, I.D., Garden,  
1093 L.M., 1998. Factors Affecting High-Pressure Solvent Extraction (Accelerated Solvent  
1094 Extraction) of Additives from Polymers. *Analytical Chemistry* 70, 1943-1948.

1095 Vats, M., Singh, S., 2014. E-Waste characteristic and its disposal. *International Journal of*  
1096 *ecological science and environmental engineering* 1, 49-61.

1097 Vehlow, J., Bergfeldt, B., Hunsinger, H., Scifert, H., Mark, F.E., 2003. Bromine in waste  
1098 incineration partitioning and influence on metal volatilisation. *Environmental Science and*  
1099 *Pollution Research* 10, 329-334.

1100 Vehlow, J., Bergfeldt, B., Jay, K., Seifert, H., Wanke, T., Mark, F.E., 2000. Thermal treatment  
1101 of electrical and electronic waste plastics. *Waste Management and Research* 18, 131-140.

1102 Veit, H.M., Diehl, T.R., Salami, A.P., Rodrigues, J.S., Bernardes, A.M., Tenório, J.A.S., 2005.  
1103 Utilization of magnetic and electrostatic separation in the recycling of printed circuit boards  
1104 scrap. *Waste Management* 25, 67-74.

1105 Veregue, F.R., da Silva, C.T.P., Moises, M.P., Meneguim, J.G., Guilherme, M.R., Arroyo, P.A.,  
1106 Favaro, S.L., Radovanovic, E., Giroto, E.M., Rinaldi, A.W., 2018. Ultrasmall Cobalt  
1107 Nanoparticles as a Catalyst for PET Glycolysis: A Green Protocol for Pure Hydroxyethyl

1108 Terephthalate Precipitation without Water. *Acs Sustainable Chemistry & Engineering* 6,  
1109 12017-12024.

1110 Vesnin, R.L., Alalykin, A.A., Vokhmyanin, M.A., 2020. POLYETHYLENE  
1111 TEREPHTHALATE WASTE RECYCLING TECHNOLOGY TO PRODUCE  
1112 TEREPHTHALIC ACID AMIDE. *Izv. Vyss. Uchebnykh Zaved. Khim. Khimichesk. Tekhnol.*  
1113 63, 99-104.

1114 Vilaplana, F., Karlsson, P., Ribes-Greus, A., Ivarsson, P., Karlsson, S., 2008. Analysis of  
1115 brominated flame retardants in styrenic polymers: Comparison of the extraction efficiency of  
1116 ultrasonication, microwave-assisted extraction and pressurised liquid extraction. *Journal of*  
1117 *Chromatography A* 1196-1197, 139-146.

1118 Wäger, P.A., Hischer, R., Eugster, M., 2011. Environmental impacts of the Swiss collection  
1119 and recovery systems for Waste Electrical and Electronic Equipment (WEEE): A follow-up.  
1120 *Science of The Total Environment* 409, 1746-1756.

1121 Walters, R.N., Hackett, S.M., Lyon, R.E., Heats of combustion of high temperature polymers.  
1122 Wang, H., Hirahara, M., Goto, M., Hirose, T., 2004. Extraction of flame retardants from  
1123 electronic printed circuit board by supercritical carbon dioxide. *The Journal of Supercritical*  
1124 *Fluids* 29, 251-256.

1125 Wang, L.-C., Hsi, H.-C., Wang, Y.-F., Lin, S.-L., Chang-Chien, G.-P., 2010. Distribution of  
1126 polybrominated diphenyl ethers (PBDEs) and polybrominated dibenzo-p-dioxins and  
1127 dibenzofurans (PBDD/Fs) in municipal solid waste incinerators. *Environ. Pollut.* 158, 1595-  
1128 1602.

1129 Wang, T., 2018. Forecast of electronic waste generated worldwide from 2010 to 2018 (in  
1130 million metric tons). *Statista*.

1131 Wang, Z., Zhang, B., Guan, D., 2016. Take responsibility for electronic-waste disposal. *Nature*  
1132 *News* 536, 23.

1133 Weber, R., Kuch, B., 2003. Relevance of BFRs and thermal conditions on the formation  
1134 pathways of brominated and brominated-chlorinated dibenzodioxins and dibenzofurans.  
1135 *Environment International* 29, 699-710.

1136 Williams, E.A., Williams, P.T., 1997. Analysis of products derived from the fast pyrolysis.  
1137 *Journal of Analytical and Applied Pyrolysis* 40 - 41, 347-363.

1138 Williams, P.T., Chishti, H.M., 2000. Two stage pyrolysis of oil shale using a zeolite catalyst.  
1139 *Journal of Analytical and Applied Pyrolysis* 55, 217-234.

1140 Williams, P.T., Williams, E.A., 1999. Interaction of plastics in mixed-plastics pyrolysis.  
1141 *Energy and Fuels* 13, 188-196.

1142 Wilson, R., Veasey, T., Squires, D., 1994. The application of mineral processing techniques  
1143 for the recovery of metal from post-consumer wastes. *Minerals Engineering* 7, 975-984.

1144 Wu, Q., Leung, J.Y.S., Geng, X., Chen, S., Huang, X., Li, H., Huang, Z., Zhu, L., Chen, J., Lu,  
1145 Y., 2015. Heavy metal contamination of soil and water in the vicinity of an abandoned e-waste  
1146 recycling site: Implications for dissemination of heavy metals. *Science of The Total*  
1147 *Environment* 506-507, 217-225.

1148 Xue, Y., Zhou, S., Brown, R.C., Kelkar, A., Bai, X., 2015. Fast pyrolysis of biomass and waste  
1149 plastic in a fluidized bed reactor. *Fuel* 156, 40-46.

1150 Yang, X., Sun, L., Xiang, J., Hu, S., Su, S., 2013. Pyrolysis and dehalogenation of plastics from  
1151 waste electrical and electronic equipment (WEEE): A review. *Waste Management* 33, 462-  
1152 473.

1153 Yildirim, E., Onwudili, J.A., Williams, P.T., 2014. Recovery of carbon fibres and production of  
1154 high quality fuel gas from the chemical recycling of carbon fibre reinforced plastic wastes. *The*  
1155 *Journal of Supercritical Fluids* 92, 107-114.

1156 Zhang, C.-C., Zhang, F.-S., 2012a. Removal of brominated flame retardant from electrical and  
1157 electronic waste plastic by solvothermal technique. *Journal of hazardous materials* 221, 193-  
1158 198.

1159 Zhang, C.-C., Zhang, F.-S., 2020. Enhanced dehalogenation and coupled recovery of complex  
1160 electronic display housing plastics by sub/supercritical CO<sub>2</sub>. *Journal of Hazardous Materials*  
1161 382, 121140.

1162 Zhang, C.C., Zhang, F.S., 2012b. Removal of brominated flame retardant from electrical and  
1163 electronic waste plastic by solvothermal technique. *J Hazard Mater* 221-222, 193-198.

1164 Zhang, M., Buekens, A., Li, X., 2016. Brominated flame retardants and the formation of  
1165 dioxins and furans in fires and combustion. *Journal of Hazardous Materials* 304, 26-39.

1166 Zhang, T., Ruan, J., Zhang, B., Lu, S., Gao, C., Huang, L., Bai, X., Xie, L., Gui, M., Qiu, R.-  
1167 l., 2019. Heavy metals in human urine, foods and drinking water from an e-waste dismantling  
1168 area: Identification of exposure sources and metal-induced health risk. *Ecotoxicology and*  
1169 *Environmental Safety* 169, 707-713.

1170 Zhang, Y., Chen, P., Liu, S., Peng, P., Min, M., Cheng, Y., Anderson, E., Zhou, N., Fan, L.,  
1171 Liu, C., Chen, G., Liu, Y., Lei, H., Li, B., Ruan, R., 2017. Effects of feedstock characteristics  
1172 on microwave-assisted pyrolysis – A review. *Bioresource Technology* 230, 143-151.

1173 Zhang, Y., Liu, S., Xie, H., Zeng, X., Li, J., 2012. Current Status on Leaching Precious Metals  
1174 from Waste Printed Circuit Boards. *Procedia Environmental Sciences* 16, 560-568.

1175 Zhao, X., Wang, M., Liu, H., Li, L., Ma, C., Song, Z., 2012. A microwave reactor for  
1176 characterization of pyrolyzed biomass. *Bioresource Technology* 104, 673-678.

1177 Zhou, C., Fang, W., Xu, W., Cao, A., Wang, R., 2014. Characteristics and the recovery  
1178 potential of plastic wastes obtained from landfill mining. *Journal of Cleaner Production*.

1179 Zhu, J., Hirai, Y., Sakai, S.-i., Zheng, M., 2008. Potential source and emission analysis of  
1180 polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans in China. *Chemosphere*  
1181 73, S72-S77.

1182