

World Sustainability Series

Walter Leal Filho  
Jelena Barbir  
Nhan Huu Nguyen  
Reinhard Saborowski *Editors*

# Innovative Approaches to Handle Plastic Waste and Foster Bio-based Plastics Production

 Springer

# **World Sustainability Series**

## **Series Editor**

Walter Leal Filho, European School of Sustainability Science and Research, Research and Transfer Centre “Sustainable Development and Climate Change Management”, Hamburg University of Applied Sciences, Hamburg, Germany

Due to its scope and nature, sustainable development is a matter which is very interdisciplinary, and draws from knowledge and inputs from the social sciences and environmental sciences on the one hand, but also from physical sciences and arts on the other. As such, there is a perceived need to foster integrative approaches, whereby the combination of inputs from various fields may contribute to a better understanding of what sustainability is, and means to people. But despite the need for and the relevance of integrative approaches towards sustainable development, there is a paucity of literature which address matters related to sustainability in an integrated way.

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Prior to publication, the works published in this book are initially assessed and reviewed by an in-house editor. If suitable for publication, manuscripts are sent for further review, which includes a combined effort by the editorial board and appointed subject experts, who provide independent peer-review. The feedback obtained in this way was communicated to authors, and with manuscripts checked upon return before finally accepted. The peer-reviewed nature of the books in the “World Sustainability Series” means that contributions to them have, over many years, been officially accepted for tenure and promotion purposes.

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Nhan Huu Nguyen · Reinhard Saborowski  
Editors

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# Preface

Addressing the global challenge of plastic waste requires innovative approaches, both in managing existing waste and in developing sustainable materials. The strategies can be broadly categorised into two main areas: (a) handling plastic waste and (b) fostering bio-based plastics production. Both are equally important. Advanced mechanical and chemical recycling methods can improve the efficiency and effectiveness of plastic recycling, allowing for the recovery of higher-quality materials. Chemical recycling, for instance, breaks down plastics into their molecular components, which can be used to produce new plastics. On the other hand, research into additives that enhance the biodegradation of conventional plastics could make these materials more compatible with natural decomposition processes, though this approach is still in the early stages of development and requires careful consideration of its environmental impacts.

Technologies that convert plastic waste into fuel or energy through processes like pyrolysis are gaining traction. These methods can help reduce landfill waste and produce valuable resources, though they must be managed to minimize emissions. In addition, projects like The Ocean Cleanup aim to remove plastic waste from oceans using advanced collection systems. While not a solution to plastic pollution at its source, these efforts are useful for mitigating the existing impact on marine ecosystems. The promotion of business models and consumer practices that eliminate waste can also significantly reduce plastic pollution. Circular economy principles focus on designing products and systems that reuse materials, effectively minimising waste.

Moreover, bioplastics made from renewable resources like corn starch, sugarcane, or cellulose are being increasingly developed to replace conventional plastics. These materials can reduce dependence on fossil fuels and are often biodegradable or compostable. Advances in genetic engineering may enable the production of bioplastics from microorganisms. For example, bacteria can be engineered to produce PHA (polyhydroxyalkanoates), a type of bioplastic that is fully biodegradable in natural environments.

Success in these areas will require coordinated efforts across sectors and disciplines, as well as significant investment in research, development, and public engagement.

There is a perceived need for publications which document and showcase innovative approaches and strategies to tackle the plastic waste challenge. Against this backdrop and in order to facilitate a broad discussion on the contribution of innovative approaches to handle plastic and foster bioplastics use, this book is being produced. Produced as an output of the Horizon 2020 project “Bioplastics Europe”, the book gathers inputs from universities and research organisations working on matters related to plastic waste management and bioplastic production, in a variety of contexts. It also provides a platform for the dissemination of information on the latest initiatives, paving the way for technology transfer and networking. Furthermore, the book intends to provide a fertile basis upon which universities, research centres and practitioners, may cooperate more closely in this key area. Last but not least, a further aim of the book is to present methodological approaches and experiences deriving from case studies and projects, which aim to show how research to handle plastic-based pollution and many related problems may be implemented across a range of disciplines. Thanks to its scope and interdisciplinarity, this book makes an excellent reading to everyone interested on handling the many challenges posed by plastics in our modern society.

We thank the authors for sharing their knowledge and their experience by means of their chapters, and those colleagues who have contributed to it by assisting with the reviews. Thanks to its design and the contributions by experts from various areas, it provides a welcome contribution to the literature on plastic waste, and it may inspire further works in this field.

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# Contents

<b>Screening of the Regulations and Legislations that Control the Chemical Content of Plastics Through Their Lifecycle</b> .....	1
Ayah Alassali, Despoina Barouta, Zhi Kai Chong, and Kerstin Kuchta	
<b>The Rise of 3D Printing in Healthcare and Implications for Future Plastic Waste: Constructing a Circular Economy Roadmap to Ensure Responsible Innovation</b> .....	51
Elen J. Parry, Carly A. Fletcher, Rhiannon Hunt, and Craig E. Banks	
<b>Distributed Recycling of Biobased Thermoplastics</b> .....	69
Freddys R. Beltrán, Ignacio Bernabé, María U. de la Orden, and Joaquín Martínez Urreaga	
<b>Saving Plastics in Almere: Making Valuable Use of Mix Plastic Waste with the Green Plastic Factory</b> .....	85
Evert-Jan Velzing and Malou van der Vegt	
<b>Toxicity of (Bio)plastics—A Challenge for Product Development</b> .....	101
Silja Denise Kröger, Nicholas Ernst Johnson, Jelena Barbir, and Gesine Witt	
<b>Innovative Approaches to Managing Single-Use-Plastic Waste in Sri Lanka</b> .....	117
Randika Jayasinghe, Nuwan Gunarathne, and R. M. N. Sulochani	
<b>Understanding Inter-Organizational Dynamics to Boost Circular Bioeconomy in the Bio-based Plastics Industry</b> .....	139
Eleonora Foschi, Genc Alimehmeti, and Angelo Paletta	
<b>Contribution of Digital Transformation in Municipal Solid Waste Management: Insights from a Case Study</b> .....	165
Luigi Mersico, Selena Aureli, and Angelo Paletta	

<b>Development of Agar-Polylactic Acid Thermoplastic by an Extrusion Method and Injection Molding</b> .....	183
Dina Fransiska, Hari Eko Irianto, Nurhayati, Akbar Hanif Dawam Abdullah, Rossy Choerun Nissa, Bakti Berlyanto Sedayu, Arif Rahman Hakim, Mochamad Chalid, Azizah Intan Pangesty, Dedi Priadi, Firda Aulya Syamani, and Agusman	
<b>Fabricating Bioplastics from Kombucha: Ingredients and Characterization for Fashion and Textile Applications</b> .....	197
Rajkishore Nayak, Donna Cleveland, Giang Tran, Frances Joseph, and Vicki Little	
<b>Sustainable Livelihoods Through Reduced Plastic Waste: Collaborative Community-Based Sustainability-Oriented Innovation</b> .....	219
Donna Cleveland, Frances Joseph, Vicki Little, and Rajkishore Nayak	
<b>Environmental Pressures and Plastic Packaging Reduction Practices: An Exploratory in the Vietnamese Food Industry</b> .....	237
Hung Nguyen, Majo George, Lam Nguyen, and Mohammadreza Akbari	
<b>Sustainability Oriented Business Model Innovation in the Nascent Bio-Plastic Industry: A Case Study of Galaxy Biotech in Vietnam</b> .....	257
Thi Huong Nhu Do, Daniel Fuller, Duc Trinh Tran, Nhan Nguyen, and Diem Chau Do	
<b>Transforming Waste into Value: A Case Study of Reform Plastic in Vietnam</b> .....	277
Aemin Nasir, Manjit Singh Sandhu, and Kasia Weina	
<b>The Hospitality Green Experience: A Case Study in Corporate Sustainability Efforts in Vietnam</b> .....	297
Jung Woo Han, Santiago Velasquez, Nuno F. Ribeiro, and Kasia Weina	
<b>Transitioning Towards Plastic Circularity: A Case of <i>Refill</i> in Vietnam</b> .....	313
Manjit Singh Sandhu, Burkhard Schrage, Nguyen Nhan, and Daniel Fuller	
<b>Comparison of PLA/PBAT Electrospun Layer and Commercial PP Facemask Layer: Morphology, Diameter and Tensile Strength</b> .....	329
N. Ain Syakirah, D. Fadilah, N. Teramoto, C. Liza, and M. Mariatti	
<b>Approaches for Environmental Impact Assessment of Bio-Based Plastics, Microplastics, and Nanoplastics Applied to Aquatic Environments</b> .....	345
Arantxa Ballesteros, Javier Alcodori, and Carlos Fito	

<b>How the Entrepreneurial Ecosystem Supports the Development of Green Startups: The Case of Green Joy in Vietnam</b> .....	369
Cat-My Dang, Thanh-Thao Luong, Que N. Tran, and Chuyen T. Nguyen	
<b>Bio-Based Plastics: Challenge or Reality? Perspectives and Constraints of Their Exploitation as Sustainable Alternative to Fossil Plastics</b> .....	387
Sarai Agustin-Salazar, Lucia Conzatti, Roberto Utzeri, Lorena Affatato, Maria Gelli, Michela Tassistro, Iliaria Schizzi, Francesca Spanò, Pierfrancesco Cerruti, Paola Stagnaro, and Gabriella Santagata	
<b>Innovative Plastic Waste Sorting Technologies: Advancing Towards Sustainable Recycling</b> .....	407
Ana Compadre, Alejandro Aragón-Gutiérrez, Gatien Fleury, Antoine Bourely, and Miriam Gallur-Blanca	
<b>Plastics and Human Health: How Perception of Human Health Risks Can Reduce Plastics Consumption?</b> .....	427
Malin Francke, Vaishali Arora, Andrea Dobri, and Jelena Barbir	
<b>Uptake of Microparticles from Bio-Based Biodegradable Plastics by Aquatic Invertebrates</b> .....	443
Lukas Miksch, Ann-Christin Scheer, Lars Gutow, and Reinhard Saborowski	
<b>The Utilization of Coconut Coir Powder in Low-Density Polyethylene (LDPE) Plastic Mulch to Enhance Biodegradability and Resistance to Ultraviolet Light Exposure</b> .....	459
Ilham Andreansyah, Puji Rizana Ayu Mentari, Putri Amanda, Resti Marlina, Yeyen Nurhamiyah, Firda Aulya Syamani, and Herliati	
<b>Implementing Ecopreneurship with Ecobricks in Bandung City Indonesia: How Well We Manage the Plastic Waste?</b> .....	473
Ratna Lindawati Lubis	
<b>Correction to: Transforming Waste into Value: A Case Study of Reform Plastic in Vietnam</b> .....	C1
Aemin Nasir, Manjit Singh Sandhu, and Kasia Weina	

# Screening of the Regulations and Legislations that Control the Chemical Content of Plastics Through Their Lifecycle



Ayah Alassali, Despoina Barouta, Zhi Kai Chong, and Kerstin Kuchta

**Abstract** The mechanical recycling of plastic waste plays a crucial role in advancing the circular economy, ensuring that valuable resources within the waste stream are preserved for extended periods. However, the sustainable, economic, and environmentally responsible management of plastic waste remains a significant challenge, particularly when plastics are sourced from contaminated streams, such as those originating from electronic waste (e-plastics). These materials often contain a wide range of chemical substances, some of which can pose considerable environmental and health risks. Therefore, assessing the degree of contamination in plastic waste is essential to ensure a safe and sustainable life cycle for plastics. Regulatory frameworks aim to address this issue by establishing guidelines and limitations on the use of hazardous chemicals, as well as providing standards for the proper treatment of contaminated waste streams. This paper offers a comprehensive review of the regulations and legislation governing the chemical content of plastics throughout their life cycle—spanning from production to waste disposal and recycling. The objective is to deepen the understanding of the challenges and limitations associated with the recycling of e-plastics and to highlight the importance of these regulatory measures in achieving sustainable plastic waste management.

**Keywords** Plastic recycling · Contaminated plastics · Plastic additives · Hazardous substances

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# 1 Introduction

The lifecycle of plastics encompasses the entire sequence of stages, from raw material extraction and material production to product manufacturing, consumer use, waste disposal, and ultimately end-of-life (EoL) treatment, which includes options such as incineration, mechanical and chemical recycling, and landfilling. Plastics are highly versatile materials, prized for their ability to be molded into a wide variety of products, each with unique properties and applications. This versatility is largely due to the diverse range of additives incorporated during the compounding stage, which enhance the material's performance and enable the tailoring of specific characteristics to meet the demands of various industries (Andrady 2015). Every additive type and concentration can influence the quality and appearance of plastics. The ultimate aim is to have products with a quality that is sufficient for their applications. For instance, stabilisers and antioxidants protect plastics against degradation caused by heat or UV light, pigments and colorants improve the appearance, fillers and plasticisers enhance the mechanical properties and increase the material's flexibility, and flame retardants act against fire propagation (Ambrogi et al. 2017; Andrady 2015).

The most common additives used in e-plastics are plasticisers, fillers and reinforcements, pigments, heat stabilisers, and flame-retardants (FRs). Flame-retardants are found in plastics that are exposed to heat sources (e.g. cables and connectors) and their presence is essential to maintain safety (Delva et al. 2018).

Several of the additives that are used in e-plastics obtain harmful properties. Hence, they are labelled as hazardous, bio-accumulative, persistent, carcinogenic, etc. For instance, brominated flame retardants (BFRs) and chlorinated flame retardants (CFRs) can be toxic, bio-accumulative and persistent (Barouta et al. 2022; Haarman and Gasser 2016). Two main international regulations responded to the potential danger of toxic BFRs, targeting their production, utilisation and end-of-life management. These regulations are the Stockholm Convention of Persistent Pollutants (Stockholm Convention on Persistent Organic Pollutants 2015b), and the EU RoHS Directive on the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment ("Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment" 2003).

Additionally, e-plastics can also contain potentially toxic elements (PTEs), heavy metals (e.g. Pb, Cr, Cd, Hg) and organic compounds (e.g. phthalates plasticisers and Short-chain chlorinated paraffins (SCCPs)), which are restricted due to the risk they pose to human health and the environment (Alassali et al. 2019; Andersson et al. 2019). The presence of these substances can hinder the mechanical recycling of e-plastics and hence resulting in reduced recycling quotas (Alassali et al. 2019).

Generally, the EoL treatment of electrical waste (e-waste) strongly considers the recovery of critical raw materials (CRMs) and precious metals like gold, silver, cobalt and lithium (Arduin et al. 2020). Nonetheless, e-waste contains 20–25 wt.% of plastic, which is most of the times not recovered. The recovery and recycling of e-plastics can increase the overall circularity of e-waste. Namely, 2.6 million tonnes

of e-plastics are annually generated in Europe, while 1.3 million tonnes are officially collected, and 1.0 million tonnes is sent for recycling. The fate of the remaining 1.3 million tons is undefined and can be informally transboundary moved to developing countries (Alassali et al. 2019; Cardamone et al. 2021).

Overall, various laws exist in order to control the quality of the product throughout and after its lifecycle. The chemical composition is regulated through the product's lifecycle and at its end-of-life by numerous policies (Stenmarck et al. 2017). The foremost goal of policies is to protect the human health and the environment, while ensuring a safe and sustainable product. However, the strictness of the existing regulations differs depending on the applications of the product (e.g. food packaging and toys have stricter threshold values of chemical substances to prevent ingestion). In this paper, regulations that are controlling the recyclability of e-plastics are analysed and discussed. The aim is to provide an understanding to the current state of e-plastic recyclability and to extrapolate the future trends.

## 2 Regulations Controlling the Recycling of Electrical Waste Plastics

### 2.1 REACH Regulation

The REACH regulation (Regulation No 1 907/2006) corresponds to Registration, Evaluation, Authorisation and Restriction of Chemicals. With the objective of ensuring that all substances are produced, manufactured and consumed safely (for products manufactured in the EU or imported to its markets), REACH came in force in 2007 (Stenmarck et al. 2017). In line with REACH, manufactured or imported substances—with volumes of 1 tonne or more per year—have to be registered to ECHA (the European Chemical's Agency). Otherwise, they can't be put on the EU markets. As a result, the potential risks presented by the substance could be controlled. According to REACH (Annex XIII), substances may be identified as Substances of Very High Concern (SVHC) if they are (a) carcinogenic, mutagenic or reproduction toxic chemicals (CMR), (b) persistent, bio-accumulative and toxic chemical (PBT), (c) very persistent or very bio-accumulative or toxic chemical (vPvB) or (d) can cause equivalent concern like endocrine disrupting action. Once a substance is identified as SVHC, it will be included in the Candidate list of SVHC for Authorisation. The potential follow-up is to be included in the Authorisation List (Annex XIV) and afterwards to the Restriction list (Annex XVII). Substances on the candidate list can be used in mixtures, blends, and objects. Yet, it is compulsory to provide information to ECHA and to the consumers about their application in products, especially when the concentrations exceed 0.1 wt.%. The identification of SVHC and the notification is essential for the application of the concept of circular economy on materials. The aim is to substitute the SVHC with safer alternatives, which can be continuously circulated and consumed without any health or environmental risks.

In 2016, ECHA and 21 industrial organisations joined forces to assess additives in plastics and their migration potentials. The task, which lasted until December 2018, produced a summary for over 400 additives in plastics consumed extensively in the EU to develop a method for comparing the discharge potential of additives of concern (European Chemicals Agency (ECHA) 2019b).

Although REACH does not apply to the waste material, plastic recyclers must comply with the REACH regulation when material reuse and mechanical recycling are considered (Jepsen et al. 2012). As was explained above, for plastic waste containing SVHCs, information should be provided when the material contains SVHCs in concentrations exceeding 0.1 wt.% (Klaschka 2017). However, the identification of SVHC in post-consumer and post-industrial plastics is very challenging for the recyclers. Waste handlers do not have any legal obligation to communicate the chemical composition of waste to the recyclers. The analysis of the receiving waste demands significant investments (Tandt et al. 2021).

## 2.2 RoHS Legislation

All products in the EU market put after 01/07/2006 must comply with the RoHS legislation (“Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment” 2003; Gensch et al. 2014). The list included 6 substances in the directive known as RoHS 2 and more 4 were added in RoHS 3 (“Commission Delegated Directive (EU) 2015/863” 2015). All the listed substances (see Table 1), and those which are going to be listed, are already included in the REACH general regulation with the same limitations.

The RoHS directive plays a significant role in recycling by regulating the chemical content of recycled plastics used in the production of electronic equipment. For recyclers, identifying all the chemicals present in plastics can be a complex task. Additionally, there is ongoing discussion regarding seven other substances currently being examined and assessed by RoHS for potential inclusion in the updated RoHS 4 list. These substances under consideration are: *beryllium*, *cobalt* (in the forms of dichloride and sulfate), *diantimony trioxide (ATO)*, *indium phosphide*, *medium-chain chlorinated paraffin (MCCPs)*, *nickel* (in the forms of sulfate and sulfamate), and *tetrabromobisphenol A (TBBPA)*.

A possible restriction of *TBBPA* and *ATO* is concerning e-waste recyclers, since they are two of the most widely used additives and this decision will result in a further decrease in the recycling quota (Institute for Applied Ecology 2019).

**Table 1** Substances restricted by RoHS

Substance	Limit (by weight in homogenous material)		Applications	Characteristics
	%	mg kg <sup>-1</sup>		
Mercury (Hg)	0.1	1000	Batteries, switches, thermostats, fluorescent lamps	Known as human carcinogen
Hexavalent Chromium (Cr VI)	0.1	1000	Chrome plating, dyes, pigments	Toxic effects in multiple organ systems. Some forms of Cr are not toxic
Cadmium (Cd)	0.01	100	Electronic equipment, coatings, pigments	Known to be carcinogen, affects multiple organs
Lead (Pb)	0.1	1000	Solder, lead-acid batteries, electronic components, cable sheathing	Known to be human carcinogen, affects the nervous and renal system
Polybrominated Diphenyl Ethers (PBDE)	0.1	1000	BFRs. Added to plastic enclosures	Known as human carcinogen and endocrine disruptor, very persistent in the environment, long range environmental transport, bioaccumulative and toxic
Polybrominated Biphenyls (PBB)	0.1	1000	BFR. Computer monitor, TV plastic enclosures	
Bis(2-Ethylhexyl) phthalate (DEHP)	0.1	1000	To soften PVC, vinyl insulation, electrical wires, medical tubing	Carcinogen, disturbs the immune and reproduction systems
Benzyl butyl phthalate (BBP)	0.1	1000	To soften PVC, vinyl insulation, electrical cables	Toxic for reproduction, endocrine disruptor, aquatic acute and chronic toxic
Dibutyl phthalate (DBP)	0.1	1000	To soften PVC, vinyl insulation, electrical wires	Category 1B reproductive toxicant (CLP), endocrine disruptor, aquatic acute toxic
Diisobutyl phthalate (DIBP)	0.1	1000		Endocrine-disrupting properties, with probable severe effects on health and the environment

### 2.3 CLP Regulation

The merged version of the Regulation EC No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 incorporates all of the

adjustments and corrigenda to the CLP Regulation until the date marked in the regulation (“Regulation EC No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006” 2008b). The harmonised criteria for classification and labelling, together with general principles of their application, were developed within the United Nations (UN). The outcome is called the *Globally Harmonised System of Classification and Labelling of Chemicals (GHS)*. One of the main goals of the CLP Regulation is to determine whether a substance or mixture of substances have characteristics that lead to their classification as hazardous. Waste is not included. However, the hazardous properties applicable to waste are linked to the CLP measures. Furthermore, the classification of substances under CLP can be relevant for waste classification (European Commission 2014). To ensure consistency in substances’ regulation, ECHA is responsible for implementing the REACH and CLP regulation. The obligation of CLP for all suppliers is to classify, label, and package substances or the mixture of substances (European Chemicals Agency (ECHA) 2019a).

Once hazardous properties are identified and the substance or the mixture is accordingly classified, all responsible parties in the value-chain (i.e. manufacturers, importers, and distributors of substances, as well as producers and importers of articles) required to communicate the known hazards of these chemical substances or mixtures to other actors in the supply chain. Hazard labelling is very important to alert about the existence of risks that require proper handling and management (European Chemicals Agency (ECHA) 2019a).

## 2.4 The Stockholm Convention

The Stockholm Convention on Persistent Organic Pollutants is a global treaty to protect human health and the environment from chemicals that remain in the environment for prolonged periods and get widely geographically distributed and have dangerous effects on human health or on the environment. The Stockholm Convention was adopted on 22 May 2001 in Stockholm, Sweden. The Convention came into force on 17 May 2004 (Stockholm convention 2018).

The main provisions are to reduce or prevent releases from unintentionally produced POPs that are listed in Annex C of the Convention (Article 5), by using the best available techniques and practices. Also, in Article 6 the convention is concerned with providing measures to eliminate releases from stockpile and wastes by developing appropriate strategies of identification and management of materials with the safest and most efficient manner. Wastes containing POPs should be collected and sorted in an environmentally sound manner. They could be disposed of after destroying the persistent pollutants (Stockholm convention 2018) (see Table 2).

Additionally, materials containing POPs should not be subject to recovery, reuse or recycling. In the third paragraph of Article 7, it was clearly stated that the recovery

**Table 2** Substances classified as POPs and could be found in the plastic waste (European Parliament 2018)

Substance	Concentration limit referred to in Article 7(4)(a)
Hexabromocyclododecane (HBCDD)	1000 mg kg <sup>-1</sup> or 0.1% (as a waste). Concentrations ≤100 mg kg <sup>-1</sup> (0.01 wt.%) when it occurs in substances, preparations, articles or as constituents of the flame retarded articles
Hexabromobiphenyl (HBB)	50 mg kg <sup>-1</sup> or 0.005%
Hexabromodiphenyl ether and heptabromodiphenyl ether (HexaBDE, HeptaBDE) Tetrabromodiphenyl ether and Pentabromodiphenyl ether (TetraBDE, PendaBDE)	The sum should not exceed 0.1 wt.%. Products placed on the market since 16.08.2010 are not allowed to contain ≥0.001 wt.% of these substances. Exception on articles manufactured from recycled materials; the permitted concentration < 0.1%
Hexachlorobutadiene (HCBD)	100 mg kg <sup>-1</sup> or 0.01%
Mirex	50 mg kg <sup>-1</sup> or 0.005%
Pentachlorobenzene (PeCB)	50 mg kg <sup>-1</sup> or 0.005%
Polychlorinated naphthalenes (PCNs, group of 75 possible chlorinated naphthalenes)	10 mg kg <sup>-1</sup> in waste. Placing on the market and use of articles produced before or on 10.07.2012 containing this substance is allowed until 10.01.2013
Short-chain chlorinated paraffin (SCCPs)	10,000 mg kg <sup>-1</sup> or 1% in waste
Polychlorinated biphenyls (PCBs) and Polychlorinated terphenyls (PCTs)	15 μg kg <sup>-1</sup>
Perfluorooctanesulfonic acid, its salts and perfluorooctanesulfonyl fluoride (PFOS/PFOS-F)	50 μg kg <sup>-1</sup> or 0.005% as waste Article 4(1)(b) controls the concentrations of PFOS in substances or mixtures to be ≤10 mg kg <sup>-1</sup> (0.001 wt.%)

operation of the POP substances should be prohibited (Stockholm Convention on Persistent Organic Pollutants 2015a). Nevertheless, products composed of recycled plastics are allowed to contain concentrations not exceeding 0.1 wt.% of the restricted BFRs (namely PBDEs). This responsibility was established to enable the extension of recycling of plastics containing restricted substances. Accordingly, the recycling operations are possible on wastes containing restricted substances, only if the concentrations are less than 0.1 wt.%. However, when the products are not derived from recycled materials, the threshold limits should not exceed 0.001% (threshold concentration for substances and preparations should be lowered to 10 mg kg<sup>-1</sup> or 0.001 wt.% in POPs Regulation).

## **2.5 *Directive 2008/98/EC on Waste (Waste Framework Directive or WFD) and Directive 2012/19/EU on e-waste***

Waste will be classified as hazardous if it displays one or more of the hazardous properties listed in the WFD Annex III of the “Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives” 2008a. The hazardous properties are: explosive, oxidising, highly flammable, flammable, irritant, harmful, toxic, carcinogenic, corrosive, infectious, toxic for reproduction, mutagenic, sensitising, producing toxic gases, eco-toxic or waste capable of producing substances possessing any of the above characteristics. The Commission Regulation No. 1357/2014, which was published in 2014, replaced the Annex III of the WFD and harmonised it with the CLP regulation. Consequently, 15 hazard classes (HP) are available for the classification of waste (European Commission 2014). Each of the classes corresponds to a different concentration limit (%). Hence, for waste containing substances that are classified as hazardous under the CLP is considered hazardous waste.

The Waste Framework Directive (WFD) is the main legislative document on waste at the EU level. The legislation also determines that hazardous waste must only be treated in special treatment facilities that have obtained a special permit, in line with Articles 23 to 25 of the WFD.

The directive does not specify recycling targets for plastic waste. However, recycling is generally discussed. By 2020, the preparation for re-use and recycling of waste shall reach 50% by mass for households and other similar waste, and 70% for construction and demolition waste. Waste can be classified as hazardous or non-hazardous. Nonetheless, only a small fraction of plastic waste is classified as hazardous, since there is no List of Waste (LoW) entry for all kinds of hazardous plastic waste. The WFD can be seen as a directive encouraging recycling (Stangenberg et al. 2004).

The Annex VIII of the e-waste directive (2012/19/EU) states that all the e-plastic containing brominated flame retardants (BRFs) should not be considered for the mechanical recycling. These fractions should be treated separately (by incineration). Due to the high costs associated with identifying the BFRs, CELENEC states that e-plastics containing bromine in concentrations exceeding 2,000 ppm should be separated and specially treated (Wagner and Schlummer 2020).

## **2.6 *Basel Convention***

Basel Convention is an international treaty functioning under the United Nations. The main objective of this treaty is to control the transboundary movements of hazardous waste and their treatment. Hence, the aim of minimising the related human health and environmental risks generated from waste disposal is concurrently met. Accordingly, the Basel Convention has compiled lists, included in Annexes I and VIII, where they

**Table 3** Annex I: Categories of waste to be controlled (UNEP 2019)

Code	Description
<i>Waste streams</i>	
Y10	Waste substances and articles containing or contaminated with polychlorinated biphenyls (PCBs) and/or polychlorinated terphenyls (PCTs) and/or polybrominated biphenyls (PBBs)
<i>Wastes having as constituents:</i>	
Y21	Hexavalent chromium compounds
Y23	Zinc compounds
Y26	Cadmium; cadmium compounds
Y27	Antimony; antimony compounds
Y31	Lead; lead compounds
Y37	Organic phosphorus compounds
Y39	Phenols; phenol compounds including chlorophenols
Y40	Ethers
Y41	Halogenated organic solvents
Y42	Organic solvents excluding halogenated solvents
Y45	Organohalogen compounds other than substances referred to in this Annex (e.g. Y39, Y41, Y42, Y43, Y44)

classify waste hazardousness and specify the categories that should be controlled. Tables 3 and 4 present the e-waste related waste streams and that are mentioned in Annex I and Annex VIII.

## 2.7 Rotterdam Convention

The Rotterdam Convention was established as a regulation aiming at protecting the environment and human health while contributing to a quality-enhanced consumption of chemicals of interest. This shall be achieved by promoting shared responsibility within the international trade of some hazardous substances. The Prior Informed Consent (PIC) approach together with the information exchange are the two most significant provisions in the Rotterdam Convention.

The convention may affect the export and/or import of plastic waste for recycling if the plastic waste contains any chemicals listed in the Rotterdam convention. Annex III includes particularly pesticides and some industrial chemicals (e.g. particular flame retardants such as OctaBDE and PentaBDE) (Stangenberg et al. 2004).

**Table 4** Annex IX: Hazardous waste (UNEP 2019)

Code	Description
<i>A1 metal and metal-bearing wastes</i>	
A1020	Waste (excluding metal waste in massive form) having as constituents or contaminants, any of the following: <ul style="list-style-type: none"> <li>• Antimony; antimony compounds</li> <li>• Beryllium; beryllium compounds</li> <li>• Cadmium; cadmium compounds</li> <li>• Lead; lead compounds</li> <li>• Selenium; selenium compounds</li> <li>• Tellurium; tellurium compounds</li> </ul>
A1040	Wastes having as constituents any of the following: <ul style="list-style-type: none"> <li>• Metal carbonyls</li> <li>• Hexavalent chromium compounds</li> </ul>
A1190	Waste metal cables coated or insulated with plastics containing or contaminated with coal tar, PCB, lead, cadmium, other organohalogen compounds or other Annex I constituents to an extent that they exhibit Annex III characteristics
<i>A3 wastes containing principally organic constituents, which may contain metals and inorganic materials</i>	
A3180	Wastes, substances and articles containing, consisting of or contaminated with polychlorinated biphenyl (PCB), poly-chlorinated terphenyl (PCT), polychlorinated naphthalene (PCN) or polybrominated biphenyl (PBB), or any other polybrominated analogues of these compounds, at a concentration level of 50 mg/kg or more
<i>A4 wastes which may contain either inorganic or organic constituents</i>	
A4130 Waste	Waste packages and containers containing Annex I substances in concentrations sufficient to exhibit Annex III hazard characteristics

### 3 Future Perspectives

There are current and future activities arranged to increase recyclability of plastic waste. Yet, when considering the health and environmental measures, the recyclability of plastic waste can be significantly lowered. There are various measures to be considered at different levels and stages in the lifecycle of the plastic products. There are continuous discussions about investigating and assessing new chemicals in the waste fractions or the material to be recycled. Among which are: new candidates to Persistent Organic Pollutants (POPs) regulation, beryllium, cobalt (dichloride and sulphate), diantimony trioxide ( $Sb_2O_3$ ), indium phosphide, Medium-Chain Chlorinated Paraffins (MCCPs), nickel (sulphate and sulfamate), tetrabromobisphenol A (TBBPA) and titanium dioxide ( $TiO_2$ ). Table 5 summarises some of the threshold limits for some metal additives, either in new products or waste streams, which could be considered in the future. All in all, although new legislations are necessary to govern the quality of the produced recyclates, harmonisation has to be well thought of (Stenmarck et al. 2017).

**Table 5** Elemental additives in plastics and their function, applications, hazard statement and regulated limits

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit			References
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)	
Titanium dioxide	Pigment (white colour), UV absorber, filler. TiO <sub>2</sub> is the most widely used in the plastic industry	H351, H332, H319, H335, H372, H371, H350, H302, H315, H319, H335, H413, H320, H372, H334, H336	Polyolefin, PVC, ABS, PS	White EEE	Substance Evaluation—CoRAP (REACH)	1%			The European Chemicals Agency (ECHA) (2019)
Bromine	Included as a substance in BFRs and other FRs	H330, H314, H400			(EU) 2018/669 classification, labelling and packaging of substances and mixtures, CELENEC	0.50%		0.2% OR 2000 mg/kg (CELENEC)	The European Chemicals Agency (ECHA) (2019)

(continued)

**Table 5** (continued)

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit			References	
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)		Others
Chlorine	Included as a substance in CFRs and other FRs	H270, H315, H319, H331, H335, H400			(EU) 2018/669 classification, labelling and packaging of substances and mixtures			3.5%		(Chemical Inspection and Regulation Service (CIRS) (2016)

(continued)

**Table 5** (continued)

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit			References
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)	
Lead and its compounds	Stabiliser		PVC (stabiliser), all plastics (pigment)	Electronic toys, casing for TV and OC	Restriction list Annex XVII (REACH)	0.05% Articles supplied to the general public, and articles or accessible parts that may, during normal or reasonably foreseeable conditions of use, be placed in the mouth by children			Stenmark et al. (2017), The European Chemicals Agency (ECHA) (2019)

(continued)

Table 5 (continued)

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit			References	
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)		Others
Lead sulphates	Pigment	H350, H360, H373, H400, H410, H317, H334	HDPE, LDPE, PVC, PP	Mobile phones	Restriction list Annex XVII (REACH)	Banned for uses in paints		0.25%		The European Chemicals Agency (ECHA) (2019)

(continued)

**Table 5** (continued)

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit			References	
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)		Others
Lead chromate	Pigment	H350, H360, H373, H400, H410,	All plastics		Authorisation list SVHCs (REACH), Annex XIV authorisation list (REACH), Annex VI of Regulation (EC) No 1272/2008 (CLP Regulation)			0.10%		Stenmark et al. (2017), The European Chemicals Agency (ECHA) (2019)

(continued)

Table 5 (continued)

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit			References
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)	
Lead carbonates	Pigment	H302, H332, H360, H373, H400, H410			Restriction list Annex XVII (REACH)	Banned for use in paints		0.25%	The European Chemicals Agency (ECHA) (2019)

(continued)

**Table 5** (continued)

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit			References
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)	
Lead chromate molybdate sulphate red (C.I. Pigment Red 104)	Pigment	H350, H360, H373, H400, H410, H351	All plastics	Mobile phones	Authorisation list SVHCs (REACH) until 5/21/2015, Annex XIV authorisation list (REACH), Annex VI of Regulation (EC) No 1272/2008 (CLP Regulation)	lead sulphates are banned for use in paints		0.10%	Stenmark et al. (2017), The European Chemicals Agency (ECHA) (2019)

(continued)

Table 5 (continued)

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit			References
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)	
Lead sulfochromate yellow (C.I. Pigment Yellow 34)	Pigment, bright lasting colours	H350, H360, H373, H400, H410, H317, H334,	HDPE, LDPE, PVC, PP	Mobile phones	Authorisation list SVHCs (REACH), Annex XIV authorisation list (REACH), Annex VI of Regulation (EC) No 1272/2008 (CLP Regulation)			0.10%	Stenmark et al. (2017), The European Chemicals Agency (ECHA) (2019)

(continued)

Table 5 (continued)

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit				References
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)	Others	
Lead	As a powder	H360, H362, H372, H350, H411, H400, H410, H332, H302, H360, H302, H351, H372		Solder, lead-acid batteries, electronic components, cable sheathing, x-ray shielding, glass of cathode-ray tubes	Annex VI of Regulation (EC) No 1272/2008 (CLP Regulation), authorisation list SVHCs (REACH), restriction list Annex XVII (REACH) but the restrictions do not related with EEE		0.10%	0.10%		The European Chemicals Agency (ECHA) (2019)

(continued)

Table 5 (continued)

Substance	Function	Hazard Statement Codes (CLP)	Plastic type	Product group	Regulation	Limit			References
						REACH (annex XVII restricted sub.)	RoHS	Commission regulation (EU) No 1357/2014, 2018/C 124/01 (the lowest limit)	
Cadmium	Metal coatings, as a substance in pigments	H400, H410, H330, H341, H350, H361, H372, H250, H335		Electronic equipment, car batteries, metal coatings, as a substance in pigments, Electrical batteries	Authorisation list SVHCs (REACH), Annex XIV authorisation list (REACH), Annex VI of Regulation (EC) No 1272/2008 (CLP Regulation)		0.01%	0.10%	The European Chemicals Agency (ECHA) (2019)

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