Appendix 11:

Reviews of available knowledge and guidance documents on POPs monitoring and control in plastics

Assessment of state of knowledge and gaps on sampling and analysis of POPs and POPs candidates in plastic pellets in major use sectors

Part A: Assessment of available guidance documents for practical understanding and controlling POPs in plastics

Part B: State of knowledge and gaps on sampling and analysis of POPs and POP candidates in major plastic use categories and related recycled pellets, including practical guidance to monitor POPs in plastics for a better control

Assessment of state of knowledge and gaps on sampling and analysis of POPs and POPs candidates in plastic pellets in major use sectors

Part A: Assessment of available guidance documents for practical understanding and controlling POPs in plastics

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Abbreviations and Acronyms

BAT	Best available technique
BC	Basel Convention
BEP	Best environmental practice
BFR	Brominated flame retardants
BRS	Basel, Rotterdam, and Stockholm (conventions)
CEN	European Committee for Standardization
CoC	Chemical of concern
CPs	Chlorinated paraffins
COP	Conference of Parties
DecaBDE	Decabromodiphenyl ether
ECHA	European Chemical Agency
EDC	Endocrine disrupting chemicals
EEE	Electrical and electronic equipment
EPS	Expanded polystyrene
ESM	Environmentally sound management
EU	European Union
FCC	Food contact chemicals
FCCdb	Food contact chemicals data base
GEF	Global Environment Facility
GMP	Global Monitoring Plan
HBCD	Hexabromocyclododecane
HBB	Hexabromobiphenyl
HIPS	High impact polystyrene
INC	Intergovernmental Negotiating Committee
IPCP	International Panel on Chemical Pollution
IPEN	International Pollutant Elimination Network
ISO	International Organization for Standardization
LCCPs	Long-chain chlorinated paraffins
MCCPs	Medium-chain chlorinated paraffins
MEAs	Multilateral Environmental Agreements
PAH	Polycyclic aromatic hydrocarbons
PBDDs	Polybrominated dibenzo-*p*-dioxins
PBDEs	Polybrominated diphenyl ethers
PBDFs	Polybrominated dibenzofurans
PCDDs	Polychlorinated dibenzo-*p*-dioxins
PCDFs	Polychlorinated dibenzofurans
PCNs	Polychlorinated naphthalenes
PFASs	Per- and polyfluoroalkyl substances
PFOS	Perfluorooctanesulfonic acid
PFOA	Perfluorooctanoic acid
POPs	Persistent organic pollutants

POPRC	POPs Review Committee
PUR	Polyurethane
PVC	Polyvinyl chloride
SAICM	Strategic Approach to International Chemicals Management
SC	Stockholm Convention
SCCPs	Short-chain chlorinated paraffins
SIDS	Small Island Developing States
UN	United Nations
UNEP	United Nations Environment Programme
WEEE	Waste Electrical and Electronic Equipment
XPS	Extruded polystyrene

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Executive Summary

In recent years, a range of plastic additives have been listed as Persistent Organic Pollutants (POPs) in the Stockholm Convention. These include Dechlorane Plus, hexabromocyclododecane (HBCD), hexabromobiphenyl (HBB), polybrominated diphenyl ether (PBDEs), short-chain chlorinated paraffins (SCCPs), and UV-328. Furthermore, other plastic-related chemicals such as PFOS, PFOA, and PFHxS found in side-chain fluoropolymers were added as POPs. This establishes a close association between the management of POPs and plastics. Consequently, the activities and guidance documents provided by the Stockholm Convention hold relevance for the management of POPs-containing plastic fractions. Similarly, the Basel Convention focuses on the control of POPs-containing waste, including POPs-containing plastic waste.

Within the framework of these two Conventions, a range of guidelines and guidance documents have been developed to facilitate the life cycle management of POPs plastic additives and other plastic-related POPs. The categories of guidance documents that aid in the life cycle management of plastic additive include:

- Guidance documents on alternatives to POPs plastic additives
- Inventory guidance documents for the POPs plastic additives, including affected plastic products and wastes
- Guidance documents on BAT/BEP for the production, use in production, and recycling of POP plastic additives
- Basel Convention guidelines covering the end-of-life management.

The current document briefly introduces the individual guidelines and guidance documents to provide an overview of the available information and support for controlling POPs in plastics.

For POPs additives with exemptions, the search for alternatives and information about them has a high priority to reduce and eliminate production. This is essential to prevent an increase in the quantity of POPs-containing plastic, which could adversely affect plastic recycling in the years and decades to come. Consequently, guidance documents on alternatives to decaBDE, SCCPs, and HBCD have been developed. These guidelines include not only chemical alternatives but also alternative materials, beyond plastics, that can substitute plastic without requiring flame retardants. Also, a general guidance document on considerations related to alternatives and substitutes for listed POPs and candidate chemicals have been published. This includes information on the identification and assessment of alternatives, as well as a compilation of tools for alternative assessment.

For all POPs listed until 2022, the Secretariat of the Basel, Rotterdam and Stockholm Conventions (BRS) has developed and published inventory guidance documents. Although primarily designed to facilitate inventory and management of individual POPs, these documents can also globally trigger the inventory of major plastic fraction impacted by POPs. This is particularly relevant in electrical and electronic equipment (EEE) and related waste (WEEE), plastics and synthetic textiles in the transport sector, and plastics in buildings and construction. The development of inventory of POPs can stimulate and facilitate the overall inventory of plastics in these sectors. In particular, the PBDE inventory guidance encourages and propose an approach to estimate the total amount of polymers in vehicles and the total amount of plastic in EEE/WEEE. Furthermore, UNEP has recently published a cross-sectoral inventory guidance for POPs and other chemicals of concern addressed in multilateral environmental agreements within these three major plastic use sectors. This publication aims to aid in the creation of sectoral inventories for POPs and other CoC, ultimately facilitating the development of comprehensive sectoral assessments. To facilitate the identification of products, waste, and stockpiles containing POPs, a monitoring guidance for POPs in products and recycling processes have been developed. This includes a step-by-step methodology to screen and analyse POPs in products (UNEP 2021a). Since most of POPs present in products are plastic additives or other POPs related to plastics, the POP monitoring guidance is highly relevant to monitor POPs in plastic and identify impacted products and recycling flows. Another set of guidance documents from the Stockholm Convention provide information on Best Available Techniques and Best Environmental Practices (BAT/BEP).

Since some of these BAT/BEP guidance documents specifically pertain to POPs plastic additives (PBDE, HBCD) or POPs related to plastics (PFOS and PFOA), these documents can support the control of the release of POPs related to plastic production, plating of plastics, and recycling of plastics. In particular, the PBDE BAT/BEP guidance provides detailed insights into techniques for separating PBDE-containing plastics from non-impacted plastic for a safe recycling of plastic derived from sources like WEEE and ELVs with separation of PBDE/BFR and non-contaminated plastic. Furthermore, the BAT/BEP guidance for unintentional POPs (UPOPs) is relevant for reducing emissions of dioxins, other UPOPs, and toxic releases from open burning and landfill fires, primarily fuelled by plastics. The implementation of the guidance can reduce toxic releases from plastic end-of-life management in particular in low-income countries.

Similarly, the environmentally sound management (ESM) of POPs plastic additives requires the ESM of the related plastic fractions and need to be embedded in the larger frame of the ESM of the plastic fractions within the waste sectors containing these POPs (WEEE, end-of-life vehicles and construction and demolition waste). The Basel Convention gives guidance for the ESM of POPs waste and technical guidelines for the individual POPs plastic additives have been developed. These guidelines are shortly introduced together with the general guidance on POPs managements. The Basel Convention sets low POP content limits in waste, which are defined in the technical guidelines. These low POP content limits determine whether a plastic waste fraction qualifies as POPs waste, necessitating ESM, or if it can be directly recycled without the need for separation of POPs. The established approach, including the development of guidance documents for the life cycle management of POPs in plastics and related implementation activities, could possibly be extended in the frame of a plastic treaty to other CoCs considering the lessons learned by the implementation of the Basel, Rotterdam, and Stockholm Conventions.

The report also reviewed documents which have been compiled to support the development of an international legally binding instrument on plastic pollution and contain information on chemicals in plastics. Among these documents is the UNEP report titled “Chemicals in Plastics – A technical report”, which was published as an INF document for the 2nd meeting of the Intergovernmental Negotiating Committee on Plastic Pollution and offers an overview on chemicals in plastics. The study compiled 13,000 chemicals associating with plastics and estimates that only 7,000 have been screened for their hazardous properties, with over 3,200 displaying one or more hazardous properties. The report identifies ten groups of chemicals associated with plastics as being of major concern due to their known toxicity and release from plastics. The publication informs about chemical-related issues of plastic pollution and presents potential options to address these issues.

The report also shortly introduces the publication “Global Governance of Plastics and Associated Chemicals” of the BRS Secretariat, submitted to INC2. The main objective of this publication was to map the global governance of plastics and related chemicals, identify governance gaps, and identify complementarities with existing multilateral instruments, such as Basel, Rotterdam, Stockholm Conventions, in context of ongoing intergovernmental efforts to combat plastic pollution. The report compiled a list of 128 substances regulated by the Stockholm Convention, Minamata Convention, and Montreal Protocol that are relevant to plastics and emphasized that these substances account for

1% of chemicals associated with plastics, while 24% (3076) of chemicals of potential concern remain unregulated internationally.

The report also assesses other documents on chemicals in plastic published in the frame of the development of the international treaty and shortly introduce to the relevant content.

1 Introduction

1.1 Background and objective of this report

All plastics are made of chemicals, including basic polymers, solvents, and additives such as plasticizers, flame retardants, stabilizers, or pigments that contribute to the material's functionality. The increased global production and consumption of plastics have correspondingly led to an increase in the production of plastic additives (*ca*. 4% of total polymer production) and other plastic-related chemicals, like processing aids, has also increased, both in quantity and diversity. More than 13,000 chemicals are associated with plastics and plastic production across a wide range of applications. Among these, over 3,200 substances, including monomers, additives, processing aids, and non-intentionally added substances, are of potential concern due to their hazardous properties (United Nations Environment Programme (UNEP) and Basel, Rotterdam, and Stockholm [BRS] Secretariat 2023). Among these plastic-related chemicals, only 128 regulated internationally by the Stockholm and Minamata Conventions or the Montreal Protocol (BRS Secretariat 2023). Within these Multilateral Environmental Agreements (MEAs) (*i.e.* the Basel, Rotterdam and Stockholm Conventions), experiences have been gathered in managing the regulated chemicals and a range of guidance documents have been developed to facilitate the management. Furthermore, other publications containing information on POPs and other chemicals of concern (CoCs) have been published in such international frames.

The purpose of this report is to provide a comprehensive overview of key international documents with information on POPs and other chemicals of concern present in plastics. It also shortly inform on the related guidance documents or reports. Notably, recent UNEP reports have been published, offering an overview on chemicals in plastic (UNEP and BRS Secretariat 2023) as well as the status of internationally regulated chemicals in plastic (BRS Secretariat 2023) (see Chapter 2). Within the framework of the Stockholm Convention, major documents have been developed to inventory, manage, and monitor POPs in plastic. An overview on the major Stockholm Convention guidance documents containing pertinent information on POPs plastic additives or POPs related to plastics are introduced in Chapter 3 (Guidance on monitoring POPs in products; UNEP 2021a), Chapter 4 (Inventory guidance documents), Chapter 5 (Guidance on alternatives to POPs) and Chapter 6 (Guidance documents for Best Available Techniques and Best Environmental Practice (BAT/BEP)) for the management of POPs related to plastics.

Furthermore, within the Basel Convention (BC), guidelines and guidance documents have been developed for the management of plastic waste and the inventory of plastic (see Chapter 7). Also, technical guidelines for managing waste consisting or containing POPs used as plastic additives or POPs otherwise associated with plastics have been published and are shortly described in Section 7.2. This available information can contribute to the control of certain plastic waste containing POPs, including their recycling in different plastic applications where POPs have been used during production and are present in certain plastics in current use.

Moreover, under the Strategic Approach to International Chemicals Management (SAICM) process, some information documents have been published which contain specific information on chemicals in certain plastic use sectors, such as the electronics or building sectors (Section 8.2).

Furthermore, recognising the fragmented and inadequate global governance landscape to address plastic pollution, 175 Member States adopted Resolution 5/14 at the United Nations Environment Assembly (UNEA) session in March 2022. This decision marked the commencement of negotiations toward a global, legally binding treaty to end plastic pollution. It acknowledges the imperative of addressing governance gaps across the full life cycle of plastics and associated chemicals to prevent impacts on human health, human well-being, and the environment (BRS Secretariat 2023). Several documents related to the development of the plastic treaty address or mention chemicals in plastic. These documents are briefly introduced in Chapter 2 and Section 8.1.

Finally, major information on chemicals in plastic is available in scientific literature, which has been comprehensively reviewed in a recent technical report (UNEP and BRS Secretariat 2023; Section 2.1). A selection of review articles on this topic is shortly described in Section 9.2.

2 Major UNEP reports with the focus on chemicals in plastics

Two recent reports published by UNEP focus on chemicals in plastic with the objective to promote the international control of hazardous chemicals in plastic.

2.1 UNEP report "Chemical in plastic – a technical report"

The UNEP report titled *"Chemical in plastic – a technical report"*[1] (UNEP and BRS Secretariat 2023) aims to inform about the chemical-related challenges associated with plastic pollution and options to address them. It also aims to support the negotiation process to develop the international legally binding instrument on plastic pollution based on UNEA resolution 5/14[2] (UNEP 2022a; see also Chapter 8 of this report). The report outlines a set of credible and publicly available scientific studies and initiatives focused on chemicals in plastics and the science-policy interface. The report highlights that among the total 13,000 chemicals associating with plastics, only a few have been widely studied. Among these, 7,000 chemicals associated with plastics have been screened for their hazardous properties, showing that over 3,200 of them have one or more hazardous properties (UNEP and BRS Secretariat 2023).

According to the UNEP report, ten groups of chemicals associated with plastics have been identified as major concerns due to their known toxicity and the potential for release from plastics. These groups include specific flame retardants, ultraviolet light stabilizers, per- and polyfluoroalkyl substances (PFASs), phthalates, bisphenols, certain alkylphenols and alkylphenol ethoxylates, biocides, metals and metalloids, polycyclic aromatic hydrocarbons (PAHs), and non-intentionally added substances (NIAS) such as polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/PCDFs) or other contaminants in new products made from recycled plastics (Figure 1; UNEP and BRS Secretariat 2023).

The report further identifies ten priority use sectors where CoCs in plastic products can lead to either high likelihoods of ecosystem and human exposures or exposures of vulnerable populations such as children (UNEP and BRS Secretariat 2023). These sectors include toys and other children's products, packaging (including food contact materials), electrical and electronic equipment (EEE), vehicles, synthetic textiles and related materials, furniture, building materials, medical devices, personal care and household products, and plastics used in agricultural, aquaculture, and fisheries (UNEP and BRS Secretariat 2023).

The report documents that a variety of chemical substances employed in plastic production may be released throughout the entire life cycle of the plastic, posing risks to human health (through exposure of workers and consumers via inhalation of air or consumption of contaminated food and drinking water), the environment (via release into the air, soil, or water), and recycling systems. Furthermore,

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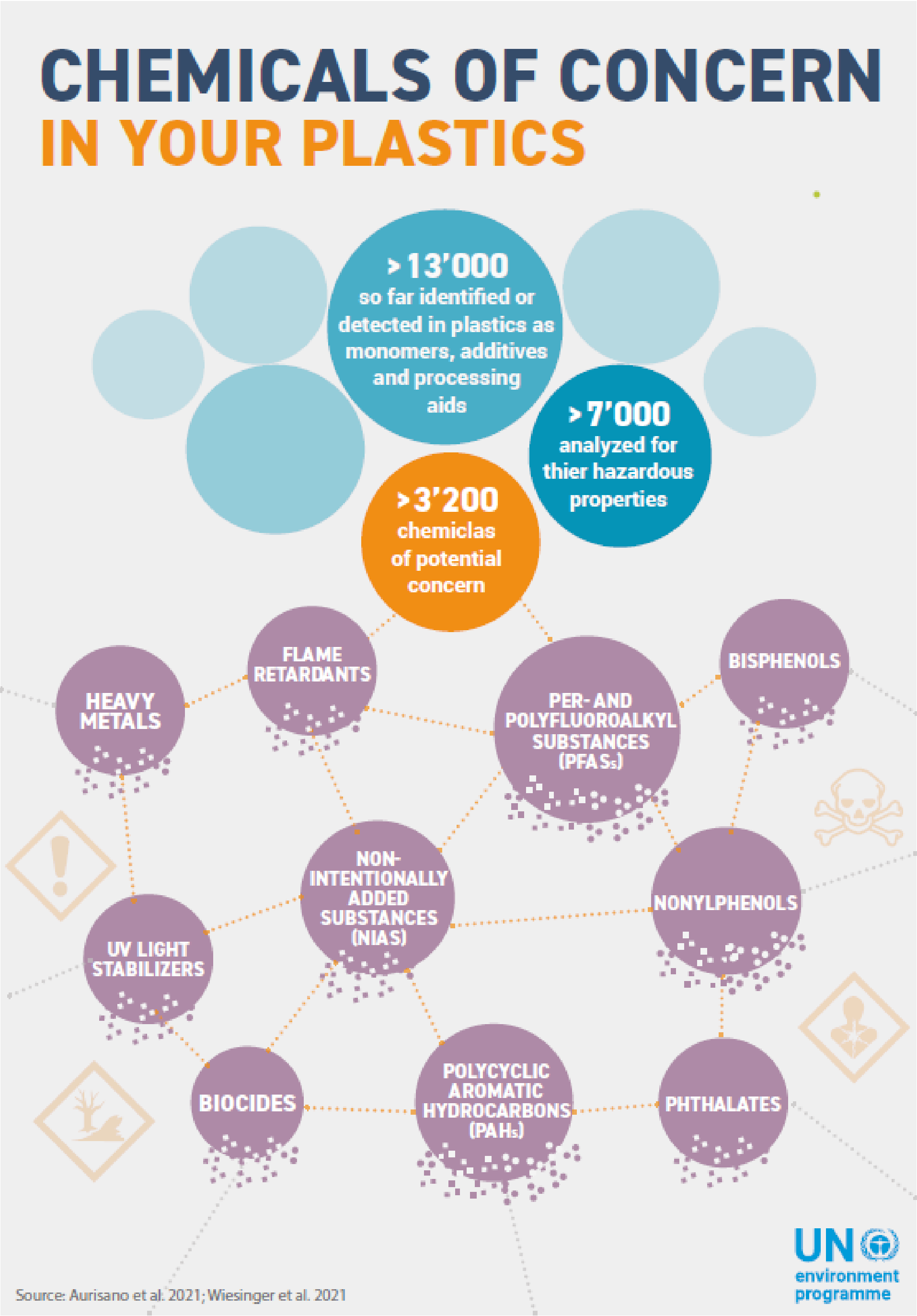
[1] https://www.unep.org/resources/report/chemicals-plastics-technical-report

[2] https://www.unep.org/about-un-environment/inc-plastic-pollution

organisms can be exposed to plastic-associated chemicals after ingesting plastic debris or through exposure in aquatic and terrestrial environments (UNEP and BRS Secretariat 2023).



Source: Aurisano et al. 2021; Wiesinger et al. 2021

Figure 1: Overview of chemicals associated with plastics, including ten groups of chemicals identified as chemical groups of concern (UNEP and BRS Secretariat 2023)

The report highlights that the huge volume and variety of plastics and associated chemicals produced, used, and released to the environment worldwide have resulted in transboundary pollution that can have adverse effects on human health and the environment, including by exacerbating climate change and biodiversity loss (UNEP and BRS Secretariat 2023). Without the implementation of globally coordinated measures, the increasing production of plastics and associated chemicals will result in increasing pollution levels and associated environmental, social, and economic costs (UNEP and BRS Secretariat 2023). The report concludes that several important challenges need to be addressed. It recommends actions to reduce the chemical-related impacts of plastic pollution and calls for significant efforts to build appropriate capacity buildings to reduce these impacts worldwide (especially in developing countries). The proposed actions and challenges can be found in the executive summary of the report.

As supplementary material, the report includes as Annex an Excel list[3] of plastic associated chemicals. The list contains more than 13,000 unique chemical substances, including plastic additives, processing aids, monomers, and other plastic-related chemicals identified across various sectors.

2.2 Report on global governance of plastics and associated chemicals

The report titled "*Global governance of plastics and associated chemicals*" aimed to map the global governance of plastics and related chemicals, identify governance gaps, and identify complementarities with existing multilateral instruments (Basel, Rotterdam, Stockholm Conventions) in context of ongoing intergovernmental efforts to end plastic pollution (BRS Secretariat 2023). The report also discusses the role of international sustainability criteria for plastics and related chemicals.

The report builds on UNEA Resolution 5/14, which reaffirmed "the importance of cooperation, coordination, and complementarity among relevant regional and international conventions and instruments" (BRS Secretariat 2023). The report focuses on mapping the global governance landscape of plastics and their associated chemicals to understand the governance gaps and possible mechanisms to 1) address the full life cycle of plastics, 2) prevent adverse effects on human health and the environment, and 3) "promote sustainable production and consumption of plastics, including, among others, product design, and environmentally sound waste management, including through resource efficiency and circular economy approaches" (BRS Secretariat 2023).

The intention of this report is to clarify the currently available policy options that meet general circularity approaches. However, the full life cycle of plastics and associated chemicals still remains undefined, including the approaches that may be considered as promoting circularity thereof.

The report highlights that the current governance landscape is insufficient to achieve the goal of ending plastic pollution. It provides suggestions for potential mechanisms to close the governance gaps across the full life cycle of plastics and associated chemicals, including by strengthening existing MEAs and by introducing new measures in the global plastics agreement. The report discusses the role of possible criteria to be used as control measures to close the governance gaps. This includes criteria for elimination of chemicals and polymers of concern used in plastics based on examples from existing frameworks as well as a novel idea of introducing criteria for sustainable design of plastics that needs to feature non-toxicity as a central criterion (BRS Website)[4].

The authors conclude that several aspects of plastic pollution have been addressed by different MEAs, including the Basel, Rotterdam, Stockholm, and Minamata conventions. Notably, particular progress has been achieved under the Basel Convention by including mixed plastics as waste in 2019. However, measures focusing on upstream activities remain limited. Additionally, the Stockholm Convention has listed a range of plastic additives as POPs.

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[3] Compilation of chemicals identified as associated with plastics, either known for use in plastic production or detected in plastic materials https://wedocs.unep.org/handle/20.500.11822/40858

[4] https://www.basel.int/Implementation/Plasticwaste/Cooperationwithothers/tabid/8335/Default.aspx

The reports highlights an important governance gap regarding polymers of concern that remain unaddressed by existing MEAs (BRS Secretariat 2023). The document also stresses the difficulty in comprehensively assessing the entire life cycle of plastics or polymers and the chemicals they contain.

As mentioned above, the report describes the interrelationships between the MEAs and their considerations of plastics and associated chemicals. The document stresses the relevance of the Basel Convention, which is currently the only MEA directly addressing plastic in its Annexes and in the regulatory frame (BRS Secretariat 2023). The report underscores the need of a plastics framework to complement activities under the BRS Conventions, spanning the chemicals, material, and dematerialization phases, while building on these conventions to address the full life cycle of plastics and associated chemicals.

The report compiles a list of 128 substances regulated by the Stockholm Convention, Minamata Convention, and Montreal Protocol, all of which hold relevance to plastics (Figure 2; compiled in Annex VI of the BRS Secretariat 2023 report). It accentuates that these regulated substances account for only 1% of chemicals associated with plastics, while 24% (3076) of chemicals of potential concern remain unregulated internationally. This assessment is based on the two review articles of Aurisano *et al*. (2021) and Wiesinger *et al*. (2021) and compiled in the UNEP report on chemicals in plastic (UNEP and BRS Secretariat 2023; see also Chapter 2.1).

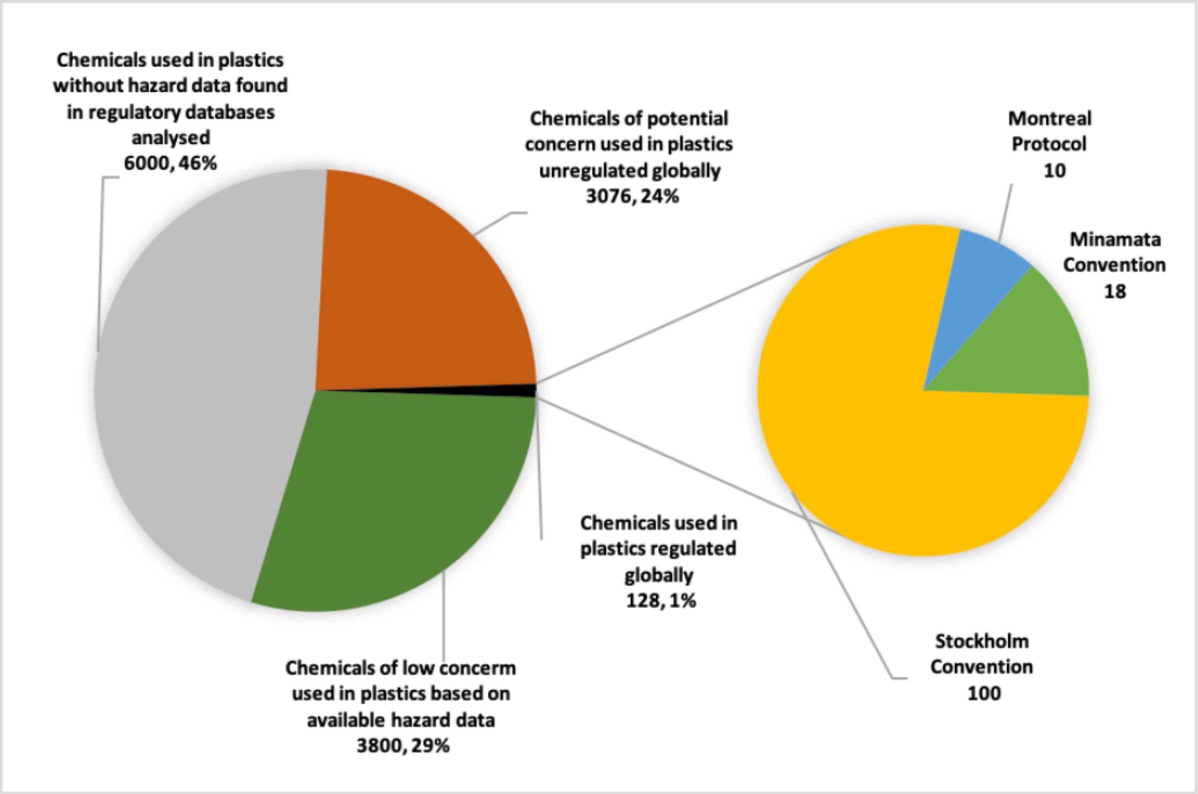

Figure 2: Number of CoCs addressed internationally in the Montreal Protocol and Stockholm and Minamata Convention compared to chemicals of potential concern and other chemicals in plastic (BRS Secretariat 2023 based on Wiesinger *et al*. (2021) and Aurisano *et al*. (2021))

3 Stockholm Convention guidance on monitoring POPs in products and recycling

Within the framework of the Stockholm Convention, a guidance on sampling, screening, and analysis of POPs in products and recycling has been developed over the last decade. The need for such guidance arose in 2009, when several POPs – primarily used as plastic additives in consumer products - were listed. These included tetra- to heptaBDE and HBB, which were commonly used in electrical and electronic equipment and related waste electrical and electronic equipment (EEE/WEEE), cars and other vehicles, building materials, synthetic carpets, textiles, and more. The guidance continues to evolve to encompass newly listed POPs, such as HBCD, SCCPs, decaBDE, and PFOA, as well as unintentional POPs (UNEP 2021a). As these products are normally not labelled, it becomes imperative to monitor POPs for the identification of stockpiles, products, and waste and to develop appropriate strategies for identification of products and wastes as required by Article 6 of the Convention. The identification of POPs in products and plastic waste becomes increasingly important for recycling of plastic towards a more circular economy. Furthermore, monitoring of POPs is also necessary to evaluate whether waste exceeds or falls bellow the low POPs content limits of the Basel Convention. This determination clarifies whether plastic waste qualifies as POP waste and needs ESM or is eligible for recycling. The provided guidance can facilitate the review and implementation of the national implementation plans (NIPs), as well as assist task teams responsible for conducting inventories and developing action plans for POPs in products. Furthermore, it can extend support to other stakeholders concerned with monitoring of POPs in products and plastic, encompassing customs, research institutions, and recyclers.

The document provides step-by-step guidance on monitoring of the POP content in products, encompassing sampling, screening, and analysis of the products. This guidance is specifically aimed at products in-use and in the recycling streams, particularly for the industrially and unintentionally released POPs listed in Annexes A, B, and C. This includes all POPs used (partly) as plastic additives or otherwise related to plastic. Notably, the recently listed POPs, UV-328 and Dechlorane Plus, are not yet considered in the guidance document. Since both are plastic additives still in production, they will likely be included in the next update of the guidance.

Additionally, the guidance includes technical information on extraction and clean-up of samples and information on sample preparation for the main matrices. Moreover, the guidance provides a basis for import control and possible monitoring at customs or at consumer protection level. The document intends to assist parties in enhancing and developing their inventories of industrial and unintentional POPs, including scenarios where a Tier III inventory component, including screening and instrumental analysis, might be useful or necessary (UNEP 2021a).

The guidance on monitoring POPs in products and recycling (UNEP 2021a) complements the "Guidance on the Global Monitoring Plan for POPs"[5], which focuses on the matrices for effectiveness evaluation (air, human milk/blood, and water) (UNEP 2013).

The POPs in products monitoring guidance (UNEP 2021a) can also provide support for emerging policy issues and other issues of concern of SAICM, in particular chemical in products, chemicals in the life cycle of electronics, or PFAS[6] (see also Section 8.2).

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[5] http://chm.pops.int/Implementation/GlobalMonitoringPlan/Overview/tabid/83/Default.aspx

[6] For example, all PFAS substances are considered an issue of concern, which is also reflected in the concern of the research community and the Madrid Statement (https://ehp.niehs.nih.gov/doi/10.1289/ehp.1509934)

The guidance does not aim to develop analytical standard procedures similar to *e.g.* ISO and CEN standards but stresses that POPs monitoring should be conducted according to international standard procedures and introduces to international standards for the monitoring of POPs in products where they are available (UNEP 2021a). However, for a range of POPs in plastic, other products, waste, and recycling, no ISO standard for sampling or analysis has been developed (UNEP 2021a). In these cases, the guidance incorporates clean-up, extraction, or measurement protocols from experienced laboratories to fill this gap (UNEP 2021a). Annex 3 of the guidance document contains an analytical method for instrumental analysis and chromatograms for each of the POPs relevant for products.

3.1 Compilation of products and recycling streams potentially containing POPs (Annex 1)

Annex 1 of the guidance lists products and major recycling streams which can contain POPs, accompanied by short descriptions to support screening and sampling procedures (UNEP 2021a). This includes major consumer products containing plastic additives (PBDEs, HBCD, SCCPs, HBB) or other plastic-related POPs (PFOS and PFOA and related compounds).

3.2 Compilation of best practice case studies on POPs in plastic (Annex 2)

In the SC guidance on monitoring POPs in products and recycling, case studies for major products or recycling streams possibly containing plastic additives and other industrial POPs are referenced in the respective chapters and in Annex 2 (UNEP 2021a). This gives an overview of best practice studies and can be consulted when *e.g.*, developing monitoring studies of POPs in plastics and other products.

By including a range of case studies on monitoring POPs in products in different countries and regions, the guidance endeavours to provide insights into previously conducted studies and their methodologies. These case studies could, for example, assist in selecting appropriate approaches and methods, including sample selection, screening methods, and analysis. Furthermore, the case studies might shed light on existing and missing information regarding POPs in products and recycled materials, helping countries avoid duplication of studies and the unnecessary use of resources and time.

3.3 Analytical procedures of POPs plastic additives or otherwise associated with plastic

Annex 3 of the guidance contains detailed description of analytical methods for instrumental measurements and quantification of industrial POPs in plastic and other products. This includes detailed instrumental settings, the specific mass parameters used for detecting each respective POP, and chromatograms for individual POPs and POPs groups.

3.4 Webinars introducing to the SC guidance document on monitoring POPs in products

The International Panel on Chemical Pollution (IPCP) organised three webinars on POPs in plastic and monitoring approaches (See Section 9.3). Within these sessions, two presentations introduced to the SC Guidance on monitoring POPs in products and recycling, with an emphasis on POPs in plastic products. Part 1[7] provides an introduction to the step-by-step approach to sampling and screening approaches described in the guidance. Part 2[8] provides an introduction to the information on extraction and instrumental analysis of POPs plastic additive in the guidance.

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[7] IPCP Webinar 19 May 2023 (0:04:19 to 0:24:43): https://www.youtube.com/watch?v=WOHifcF71Xo&t=8s

[8] IPCP Webinar 23 May 2023 (1:59:45 to 2:17:13): https://www.youtube.com/watch?v=hcjIe6QfUE0

4 Stockholm Convention POP inventory guidance documents related to plastics

The Stockholm Convention provides inventory guidance documents for individual POPs. These inventories primarily aim to understand the national situation regarding POPs in order to devise strategies for meeting the SC requirements for these chemicals, including supporting developing countries and updating NIPs. Objectives are detailed further in the general POP inventory guidance (UNEP 2020a).

A POP inventory compiles information on past and present production and current uses, stocks, and waste of a SC-listed chemicals within a country. Given that many POPs are used in products/articles long service-lifea comprehensive inventory should also estimate the amount of POP in the products/articles in the country along the whole life cycle, thus, contributing to the provisions of Article 6 of the convention on management of waste.

Many of the newly listed POP are or were primarily used as additives in plastics. Notewothy instances encompass halogenated flame retardants (decaBDE, c-PentaBDE, c-OctaBDE, HBCD, HBB, Dechlorane Plus, SCCPs), plasticizers for polyvinyl chloride (PVC) or rubber (SCCPs and POP candidate MCCPs), and UV stabilizers (UV-328). Furthermore, a large share of fluorinated POPs (PFOS, PFOA, PFHxS related compounds) were used as part of side-chain fluoropolymers (see IPCP Webinar presentations of Cousins[9] and Weber[10]). Additionally, a large share of PFOA has been used and released from fluoropolymer production resulting in large contaminated sites (Gebbink and van Leeuwen 2020; Lohmann *et al.*, 2020; Liu *et al.*, 2021; UNEP 2023a). Therefore, the inventory guidance documents are important to identify and understand the use of POPs in plastics. Subsequently, the related inventories are crucial to identify and manage products and waste containing POP-contaminated plastics and to enable an ESM in the end-of-life. In this context, POPs inventory activities can be used to assess the plastic fractions containing POPs, to improve, prioritise, and develop actions for the management of these plastics in end-of-life and recycling, and to stop or minimise the use of currently produced POPs (decaBDE, Dechlorane Plus, PFOA, SCCPs, UV-328) in the production of new plastic products. Furthermore, these inventories can promote comprehensive assessments of plastics and chemicals of concern in these plastic use sectors.

The following subchapters describe some relevant content and information of the respective inventory guidance documents relating to the individual POPs in plastics.

4.1 Stockholm Convention PBDE inventory guidance

PBDEs were major brominated flame retardants (BFRs) used in plastics, with a total production volume of 1.9 million tonnes, along with ongoing current production of decaBDE (Li *et al.* 2023; Weber 2023a; Weber 2023b). The *"Guidance on preparing inventories of PBDE including decaBDE"* (UNEP 2021b) guides the Parties through the process of developing an inventory for POP-BDEs listed under the convention including tetraBDE/pentaBDE (c-PentaBDE) and hexaBDE/heptaBDE (c-OctaBDE), listed in 2009, and decaBDE, listed in 2017.

The guidance provides an overview of plastic types (polymers) and information about the utilization of c-PentaBDE, c-OctaBDE, and decaBDE, along with their applications in the different sectors (building and construction, EEE/WEEE, transport and textiles). Additionally, the guidance includes

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[9] Webinar 25 April 2023; Introduction to fluorinated POPs related to polymers & plastics (from 2:38:56 to 3:26:33) https://www.youtube.com/watch?v=u5Ht6vg8Y04

[10] Webinar 19 May 2023; Monitoring of PFAS in products and recycling (from 3:10:08 to 3:43:23): https://www.youtube.com/watch?v=WOHifcF71Xo&t=8s

robust data on the amount of PBDE use in various polymers, products, components, and waste and recycling fractions. As an illustrative instance, Table 1 shows PBDE concentrations in polymers/plastic used in construction. Another example involves the best estimate calculation that vehicles produced before 2004 contain an average of 80 g decaBDE, with regional differences for c-PentaBDE in the United State, and vehicles produced between 2005 to 2016 average 20 g decaBDE (UNEP 2021b; Abbasi *et al*. 2019; Kajiwara *et al*. 2014). Moreover, the guidance highlights key information, including data needed for POP inventories and calculation formulas.

The guidance also informs that the use of HBB in plastic in vehicles and EEE was analogous to PBDEs. However, due to its small overall production (5,600 t) and its early discontinuation in 1976, EEE products containing HBB-treated plastic reached the end-of-life a long time ago, diminishing their relevance (UNEP 2021b).

Table 1: PBDEs concentration in polymers/plastic in construction (UNEP 2021b)

POP	Uses	Content (% wt)	References
DecaBDE, PentaBDE	Polyurethane (PUR) foam in insulation	4–13%	Leisewitz & Schwarz 2000
DecaBDE, PentaBDE	PUR foam fillers	22%	Leisewitz & Schwarz 2000
DecaBDE	PE insulating foam	20%	Morf *et al*. 2003
DecaBDE	PE and PP plastic sheeting	10%	Morf *et al*. 2003
DecaBDE, PentaBDE, HBCD	Roller blind and curtain	4%	Kajiwara *et al*. 2013
DecaBDE	Adhesive layer of reflective tapes	1–5%	Risk and Policy Analysts [RPA] 2014
DecaBDE, PentaBDE	Intumescent paint	2.5–10%	RPA 2014

In addition to the uses and their applications, the guidance provides numerous instructions from data collection to waste management. This includes information and monitoring data concerning PBDEs in EEE/WEEE and transport, and PBDEs in PUR foam and other polymers in construction.

Further information on general management and treatment of polymers generated from the main sectors are provided in order to achieve the successful implementation of the SC. The document provides an illustrative example: the recycling of a share of plastic containing decaBDE has impacted a multitude of plastic and polymer products including toys, food contact materials, and a wide range of other products (UNEP 2021b).

Given that the usage sectors of flame-retarded plastics (EEE, transport, and construction) constitute a considerable portion of the total plastic stock increasingly entering end-of-life, a PBDE inventory report can contribute in forming a comprehensive plastic inventory in these sectors, thereby improving overall plastic management. Therefore, the guidance suggests that, for each inventory, an estimation of total plastic volumes should be conducted for these sectors, considering the sectoral approach (see also Section 4.6 and Weber 2023a). For example, approximately 200 kg of polymers are contained in a mid-size car (UNEP 2021b). This value can be used to calculate the total amount of plastic/polymers in cars registered in the country and cars entering end-of-life. The calculated values provide information to the waste management sector and other stakeholders, shedding light on polymer management needs in transport. Similarly, the guidance highlights that EEE/WEEE contain an average of 20% plastic. Moreover, it details the share of plastic in different EEE/WEEE categories, facilitating the development of a plastic inventory for EEE and WEEE.

4.2 Stockholm Convention HBCD inventory guidance

HBCD, a significant flame retardant, was produced in a total volume of 703,000 t (Li *et al*. 2023), added to over 45 MT of polystyrene insulation in construction. The purpose the HBCD inventory document is to provide guidance to Parties on the establishment of inventories of HBCD and related contaminated plastic (UNEP 2021c). The guidance provides an overview of where HBCD was used and its applications in the different sectors (building and construction, EEE/WEEE, transport, *etc*). Moreover, the document provides guidance on acquiring information about stockpiles, import/export of products containing HBCD, management of waste containing HBCD, and addressing potentially contaminated sites.

The guidance informs that the major use of HBCD (approx. 90%) has been as additive flame-retardant used in construction in expanded and extruded polystyrene foams (EPS/XPS) from 1970 until 2021 when exemption on production and use stopped (UNEP 2021c). EPS and XPS materials are used in a variety of applications throughout the construction sector. In EPS, a HBCD concentration of 0.5−1% by weight is common (UNEP 2021c), while in XPS, the range is 1−3% (Morf *et al*. 2003). The specific concentration depends on the product fire safety requirements and the flammability standards in the countries. Due to the long service life of building insulation of 30 to 100 years (Charbonnet *et al*. 2020; Li *et al*. 2016) EPS/XPS containing HBCD will still be in use for the next decades and up to a century.

According to the guidance, HBCD was also used as flame retardant in high impact polystyrene (HIPS) in EEE and in polymer dispersions for textiles and synthetic fabrics, often in public space *e.g.*, for curtains, furniture, mattresses, and home textiles. EPS/XPS installed from 2014 to 2021 might include HBCD or alternative flame retardants depending on the substitution process in a country and new installed EPS/XPS from 2022 onwards does not contain HBCD. Also, decaBDE has been used to some extent in XPS foam as an alternative (Morf *et al*. 2003).

4.3 Stockholm Convention SCCP inventory guidance

Short-chain chlorinated paraffins (SCCPs) are the most extensively produced POPs, prominently used as plastic additives as flame retardants and/or plasticizers in PVC, rubber, and PUR foam. The purpose of the SCCP document is to provide Parties with guidance for formulating inventories of SCCPs and products and wastes containing SCCPs. A detailed inventory guidance has been developed for SCCPs (UNEP 2019a), including a short version (UNEP 2021d) to support the assessment and inventory of SCCPs.

Chlorinated paraffins (CPs) are produced in high volumes (around 1 million t/year) including approx. 400,000 t SCCPs. CPs are classified according to their chain length into short-chain CPs (SCCPs; C_{10} to C_{13}), medium-chain CPs (MCCPs[11]; C_{14} to C_{17}), and long-chain CPs (LCCPs; C≥18). SCCPs are listed since 2017 as POP in Annex A of the SC with various specific exemptions covering the major uses (UNEP 2019a)[12]. SCCPs can also exist as impurities in MCCP, LCCP, or other CP mixtures. Therefore, the guidance recommends analysing also the use of other CP mixtures and assessing their SCCP content (UNEP 2019a).

The SCCP inventory aims to identify major plastic and polymer products, stockpiles, and wastes containing or contaminated by SCCPs, enabling their ESM. Since there are only a few studies on

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[11] MCCPs are currently evaluated by the POPRC and meet the Annex D POP criteria. LCCPs is not listed in SC

[12] http://chm.pops.int/Implementation/Exemptions/SpecificExemptions/ChemicalslistedinAnnexA/tabid/4643/Default.aspx

SCCPs in wastes, the current SCCP inventory guidance does not contain impact factors of SCCPs in plastic wastes yet. However, the guidance delivers information on SCCPs in use and stocks, waste fractions containing SCCPs, indication on impacted recycling, and inform on waste categories according Basel Convention Annexes that might contain or might be contaminated with SCCPs.

The guidance also mention that due to the use of CP mixtures and the lack of labelling of products such as plastics, screening and monitoring is, however, needed for identification of SCCPs in plastics, other products, or waste (see POPs monitoring guidance UNEP 2021a; Chapter 3).

Table 2 shows SCCP (and MCCP) concentrations in polymers/plastic in construction.

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Table 2: SCCP concentration in polymers/plastic in construction (UNEP 2019a)

POP	Uses	Content (% wt)	References
SCCP/MCCP	PVC plastic sheeting	5%–20%	Morf *et al*. 2003; Chen *et al*. 2021
SCCP/MCCP	PVC hosepipes for plumbing	0.5%–10%	Chen *et al*. 2021
SCCP/MCCP	PVC flooring, roofing, wallpaper	0.5%–10%	Chen *et al*. 2021
SCCP/MCCP	Cables	0.5%–10%	Chen *et al*. 2021

4.4 Stockholm Convention inventory guidance for PFOS, PFOA, and PFHxS

The POP-PFAS inventory guidance (UNEP 2023a) aims to provide the information needed for key strategies and decisions related to the management of (1) PFOS, its salts and PFOSF, (2) PFOA, its salts and PFOA-related compounds, and (3) PFHxS, its salts and PFHxS-related compounds, and implementation of the obligations in the SC. The guidance aims to provide a basis for identification of the quantities of listed PFASs in this document that are produced, used, stored as stockpiles, and generated as waste in the country. It also seek to identify important economic sectors and operators and the type of actions required for those sectors, estimate the capacities needed for implementation, and identify sources that should be prioritised. Notably, a major use of PFOS, PFOA, and related substances (precursors) involves the manufacturing of sidechain fluorinated (SCF) polymers (UNEP 2023a). These SCF polymers (and other PFAS) are used on plastic fibres in carpets, furniture, textiles, even fast food paper wrappings to repel water, oil, and dirt (Glüge *et al*. 2020; UNEP 2023a).

The inventory of PFOS, PFOA, and PFHxS aims to identify major side-chain polymer products, stockpiles, and wastes containing and contaminated with these substances, enabling their ESM. Additionally, the inventory includes an overview of possible waste management practices for products/articles containing PFOS, PFOA, or PFHxS when they become waste. For PFOS and PFOA-related compounds there is a range of information about polymer products and applications while there is very limited information about PFHxS in polymers/plastics yet. The guidance also delivers some monitoring data *e.g.*, concentrations of PFOS and PFOA in different applications/products including polymers. However, screening and monitoring are needed for assessing and controlling PFOS/PFOA in polymers like synthetic carpets and textiles containing SCF polymers, which were major uses of PFOS and PFOA (UNEP 2023a)[13]. This monitoring is also crucial for safeguarding the recycling of these product categories (UNEP 2021a; Chapter 3).

4.5 SC inventory guidance for PCNs and open application of PCBs

The purpose the PCN inventory guidance is to provide Parties with guidance on establishing PCN inventories (UNEP 2021e). This guidance provides an overview of where PCNs were used and their applications (open applications, unintentional POPs) across different sectors (construction, plastic cables in EEE/WEEE, *etc*). Moreover, the document guides in obtaining information about stockpiles, import/export of PCN-containing uses within a country, and potentially contaminated sites.

PCBs and PCNs have been used in construction, particularly in polymer sealants, cables, coatings, paints, and adhesives (UNEP 2021e). The primary use period for open applications of PCBs spanned from the 1950s to 1975, whereas PCNs were mainly used from the 1930s to the 1960s (UNEP 2021e). PCBs sealants and paints are found in industrial, public, and residential buildings (UNEP 2021e). Overall, the use of PCBs in these applications was considerable higher than that of PCNs. It is estimated that approximately 21% of the total world PCB production was used in open applications (approx. 375,000 tonnes), mainly in polymer sealants and PVC paints/coatings in the construction sector (UNEP 2021e).

It is generally believed that new uses of open applications of PCBs were stopped in the 1970s. However, due to the long service life of these polymer products, PCBs are still present in the built environment (Weber *et al*. 2018).

The inventory of PCBs and PCNs aims to identify major plastic and polymer products containing or contaminated with PCBs and PCNs, along with stockpiles and wastes, enabling their ESM.

The use of PCBs and PCNs as plastic additives, sealants, paints, coatings, and adhesives has largely been substituted by SCCPs/MCCPs ~50 years ago (UNEP 2019a). Therefore, the development of inventories for PCNs and PCBs in open applications should be combined with SCCPs in these uses.

4.6 Stockholm Convention: Sectoral guidance on POPs and other Chemicals of Concern in EEE/WEEE, transport, and buildings

POPs are only one category of Chemicals of Concern (CoCs). Other CoCs are addressed, for example, by the Basel and Rotterdam Conventions, the Minamata Convention on Mercury, and the Montreal Protocol on Substances that Deplete the Ozone Layer. Moreover, a range of CoCs have been flagged under SAICM (see chapter 8.2) as “Emerging Policy Issues”, including endocrine-disrupting chemicals like major plastic additives such as phthalates or bisphenols (Weber 2023a). EEE, the transport sector, and the building sector are major plastic usage sectors containing both POPs and other CoCs. These sectors collectively account for more than 1/3 of all plastic usage (Plastics Europe

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[13] See IPCP Webinars Section 9.3 Weber 2023 (Monitoring of PFAS in products & recycling from 3:10:08 on https://www.youtube.com/watch?v=WOHifcF71Xo&t=3s) and Huang 2023 (from 2:08:28 onhttps://www.youtube.com/watch?v=o341GAxt2nY&t=26s)

2022), and this plastic is still present in products in use or at their end-of-life[14]. UNEP is promoting a synergistic approach for these key sectors. Consequently, sectoral guidance has been developed for inventories of POPs and other CoCs in buildings/construction, EEE, and vehicles (Weber 2023a). The objective of this guidance document is to facilitate a sectoral assessment of POPs and that information gathering for POP inventories is better coordinated with information on other CoCs. The sectoral approach should ensure that individual stakeholders in the different sectors or individual ministries are approached only from one inventory team for POP data which can save time and money in the inventory development process. Within these major use sectors, an overall plastic inventory should contain information on POPs and, as relevant, other CoCs present in plastic. Regarding the transport sector and EEE/WEEE, the recommendation to estimate the total plastic fraction in these uses has already been explained in the Section of the PBDE inventory (Section 4.1) (UNEP 2021b) and can be further elaborated upon during the development of inventories for these sectors (Weber 2023a). POPs and CoCs, such as phosphorous flame retardants, phthalates ,or certain blowing agents, which also function as greenhouse gases or ozone-depleting substances in polymer insulation used in buildings or the transport sector (F-gas bank), could be inclusively inventoried to facilitate sound environmental management (Weber 2023a).

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14 Since plastic in these three plastic use sectors have a long service life, the plastic stocks in these three sectors likely account more than 50% of all plastic stock in use.

5 Guidance documents on alternatives to listed POP plastic additives

Appropriate substitution of POPs by safer alternatives, chemical and non-chemical, represents the best and most effective way to eliminate them from articles and products, reduce contamination in recycling flows, and prevent human and environmental exposure. The term "alternative" is used to denote a chemical, material, product, product design, system, production process, or strategy that can replace listed persistent organic pollutants or candidate chemicals, or materials, products, product designs, systems, production processes, or strategies that rely on listed persistent organic pollutants or candidate chemicals, while maintaining an acceptable level of efficacy. Therefore, one of the essential aims of the Stockholm Convention is to support the transition to safer alternatives. According to Article 9, each Party to the Convention is to facilitate or undertake the exchange of information relevant to "*alternatives to persistent organic pollutants, including information relating to their risks as well as to their economic and social costs*". Furthermore, Article 11 stipulates that Parties, within their capabilities, are to "*encourage and/or undertake appropriate research, development, monitoring and cooperation pertaining to persistent organic pollutants and, where relevant, to their alternatives and to candidate persistent organic pollutants*".

Several plastic additives have been listed in the Stockholm Convention with exemptions, such as decaBDE, SCCPs, and HBCD. For these POPs additives, where alternatives were not available in multiple countries, the search for alternatives and information regarding them became a high priority. This effort aims to reduce and eliminate production, preventing the further increase of the amount of POPs contaminated plastic, which would negatively impact plastic recycling for the years and decades to come. Therefore, guidance documents on alternatives to the listed plastic additives decaBDE (Section 5.1), SCCPs (Section 5.2), and HBCD have been developed and published by the BRS Secretariat. Additionally, a general guidance on considerations related to alternatives and substitutes for listed POPs and candidate chemicals has been developed and published (UNEP 2009). This guidance includes information on identifying alternatives, assessing risks related to alternatives (including POP properties), and evaluating the social and economic aspects of alternatives, including cost analysis and benefit assessments (UNEP 2009).

5.1 Preliminary draft guidance on alternatives to decaBDE

When decaBDE was listed with a range of exemptions (Table 3), the BRS Secretariat published a guidance on available alternatives (UNEP 2019b). The guidance document compiles chemical alternatives and non-chemical alternatives to decaBDE, mainly for the uses listed as specific exemptions in Annex A to the Convention (Table 3), in order to support Parties in phasing-out the use of decaBDE in plastic production.

The information compiled in the guidance was mainly gathered in the POPRC, which has a mechanism in the risk management phase (Annex F) to compile information on available alternatives. Since decaBDE is mainly used and exempted as a plastic additive (see Table 3), the content of the alternative guidance is largely relevant for plastics. The guidance compiled information on alternatives covering the exempted additive uses, such as PUR foam insulation and plastics in EEE, vehicles, and aircraft. In particular for PUR foam insulation, non-plastic alternatives are also available, which could substitute not only POP/decaBDE but also the use of plastics altogether (e.g., stone wool, glass wool, organic insulation like). Likewise, within the textile industry, plastics like polyester, nylon, or cotton-nylon dominate usage (UNEP 2019b). Also for textiles the substitution includes alternatives to plastic fabrics, such as wool, which has inherently fire-resistant properties and, depending on the thickness of the weave, can meet fire safety requirements without additional chemical treatment (UNEP 2019b).

Table 3: Specific exemptions for decabromodiphenyl ether (BDE-209; c-DecaBDE) (UNEP 2019b)

Chemical	**Activity**	**Specific exemption**
Decabromodiphenyl ether (BDE-209) present in commercial decabromodiphenyl ether (CAS No: 1163-19-5)	Production	As allowed for the Parties listed in the Register
	Use	In accordance with Part IX of Annex A: • Parts for use in vehicles • Aircraft for which type approval has been applied for before December 2018 and has been received before December 2022 and spare parts for those aircraft* • Textile products that require anti-flammable characteristics, excluding clothing and toys • Additives in plastic housings and parts used for heating home appliances, irons, fans, immersion heaters that contain or are in direct contact with electrical parts or are required to comply with fire retardancy standards, at conc. <10% by weight of the part • Polyurethane foam for building insulation

*The specific exemptions for spare parts for aircraft for which type approval has been applied for before 12/2018 and has been received before 12/2022 shall expire at the end of the service life of those aircraft.

5.2 Preliminary draft guidance on alternatives to SCCPs

When SCCPs were listed with a range of exemptions (Table 1), the BRS published a guidance on available alternatives (UNEP 2019c) to support countries in phasing-out SCCPs in the production of plastics and other uses. This guidance document compiles chemical alternatives and non-chemical alternatives to SCCPs, mainly focusing on the uses listed as specific exemptions in Annex A of the Convention (Table 4). The guidance was developed based on information contained in the POPRC documents and other reports and information. Since SCCPs exemptions include their utilization as plastic additives, such as secondary plasticizers in flexible PVC (including tubes for outdoor decorative bulbs), as well as additives in rubber and adhesives (Table 1), the guidance has relevance for these large plastic applications. For these uses, alternative chemicals, materials, and techniques have been compiled (UNEP 2019c). Therefore, this guidance also contains information on alternative materials for some plastic uses. Also the paint applications of SCCPs are related to plastics such as paints and coatings based on chlorinated rubber, vinyl copolymers, and acrylic and information on alternatives are provided (UNEP 2019c).

Table 4: Specific exemptions listed for production and use of SCCPs (UNEP 2019c)

Chemical	**Activity**	**Specific exemptions**
Short-chain chlorinated paraffins (Alkanes, C_{10-13}, chloro): straight-chain chlorinated hydrocarbons with chain lengths ranging from C_{10} to C_{13} and a content of chlorine greater than 48% by weight. For example, the substances with the following CAS numbers may contain SCCPs: CAS No. 85535-84-8; CAS No. 68920-70-7; CAS No. 71011-12-6; CAS No. 85536-22-7; CAS No. 85681-73-8; CAS No. 108171-26-2.	Production	As allowed for the Parties listed in the Register
	Use	• Additives in the production of transmission belts in the natural and synthetic rubber industry • Spare parts of rubber conveyor belts in the mining and forestry industries • Leather industry, in particular fatliquoring in leather • Lubricant additives, in particular for engines of automobiles, electric generators and wind power facilities, and for drilling in oil & gas exploration, petroleum refinery to produce diesel oil • Tubes for outdoor decoration bulbs • Waterproofing and fire-retardant paints; Adhesives • Metal processing • Secondary plasticizers in flexible polyvinyl chloride, except in toys and children’s products

5.3 Guidance on alternatives to HBCD

When HBCD was listed with a range of exemptions, the BRS compiled information on available alternatives to support countries in the elimination of HBCD in the production of plastics (EPS/XPS and synthetic textiles) (UNEP 2019d). This guidance document compiles chemical and non-chemical alternatives to HBCD. This includes also alternatives to EPS/XPS insulation, such as mineral wool and natural fibre-based insulation materials. Various modern insulation materials are based on natural fibres, primarily plant fibres, and sometimes sheep wool. Some of these materials have been known for centuries but have experienced a resurgence in recent decades due to the growing interest in environmentally friendly building techniques (UNEP 2019d).

5.4 Publication on POPs phase-out opportunities

A publication regarding alternatives to POPs has been published, including the POPs plastic additives listed at that time (Stockholm Convention Regional Centre for Asia and Pacific 2014). This document not only presents information on POPs alternatives but also assembles a compilation of assessment tools for chemical alternatives and introduces to assessment approaches from entities such as the Lowell Center for Sustainable Production[15], USEPA, and GreenScreen[16]. Furthermore, it is linked to SUBSPORT[17] for safer alternatives, which contains over 40 case studies on alternatives to plastics, including plastics containing hazardous additives. This Stockholm Convention document has also compiled recommendations, such as the utilization and promotion of Green Chemistry/Sustainable Chemistry, the protection of recycling flows, and improvements of current approaches for controlling POPs in articles (UNEP 2014).

6 Stockholm Convention BAT/BEP guidance documents

In the frame of the Stockholm Convention, several guidance documents on best available techniques and best environmental practices (BAT/BEP) were developed to control POPs with exemptions in their production and use, as well as for unintentional POPs. BAT refers to the most effective and advanced activities, operational methods, and techniques for providing the basis for release limitations designed to prevent and generally to reduce releases of chemicals and their environmental impact. On the other hand, BEP describes the application of the most appropriate combination of environmental control measures and strategies.

Since some of these BAT/BEP guidance documents are for POPs plastic additives (PBDE, HBCD; Section 6.1 and 6.2) or have plastic related uses (PFOS and PFOA; Section 6.3), these documents can support the control of release of POPs related to plastic production, plastic plating, and plastic recycling. The importance of better control over plastic recycling has been revealed by a wide range of monitoring studies which have shown contamination of toys and food-contact materials by PBDEs (Chen et al. 2009; Ionas et al. 2014; Kuang et al. 2018; Kajiwara et al. 2022) and related brominated dioxins and furans (PBDD/PBDFs; Budin et al. 2020; Behnisch et al. 2023). When PBDEs were listed in 2009 with an exemption for recycling, recommendations were made to separate PBDE-containing plastics, and a BAT/BEP guidance document for PBDEs (Section 6.1) was developed, providing a comprehensive compilation of technologies to separate PBDE-containing plastics in recycling of

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[15] https://www.uml.edu/research/lowell-center/chemicals-materials-products/alternatives-assessment/alternativesassessment.aspx

[16] https://www.greenscreenchemicals.org/learn/gs-in-alternatives-assessment

[17] https://www.subsportplus.eu/

impacted plastic wastes from WEEE and ELVs, with applicability extending to other BFR-containing plastics. The BAT/BEP guidance on unintentional POPs is highly relevant for reducing releases of dioxins, other UPOPs, and other toxic emissions resulting from open burning and landfill fires primarily fuelled by plastics. This guidance can support the reduction of the burden of toxic releases from plastic end-of-life management, in particular in low-income countries (Section 6.4).

6.1 Stockholm Convention PBDE BAT/BEP guidance

When tetra- to heptaBDEs were listed in 2009 with exemptions for recycling of plastics containing PBDEs, a BAT/BEP guidance was developed to support the control of such recycling and to assist Parties in eventually phasing-out PBDEs from recycling streams of plastics (UNEP 2021f)[18]. Despite being listed in the SC, large volumes of PBDE-containing products will continue to be used in consumer articles before entering the recycling flows, as these are durable consumer and industrial products with relatively long service life (up to several decades for vehicles and plastic materials in buildings and construction).

In 2010, this became the first international guidance document for managing and recycling of plastic containing a POP and for understanding the challenges of reducing releases from uses/applications and recycling of plastics containing POPs, in this case, PBDEs. The guidance has been updated several times, and decaBDE was added after listing in 2017.

The document gives an introduction on commercial PBDE mixtures and their use in different plastic sectors and related products to inform the management of these products and control affected plastic recycling flows. The production and use of decaBDE are still allowed in specific exemptions for a limited number of applications, mainly for plastic products including EEE, plastic spare parts in vehicles, and PUR insulation foam in buildings and textiles. Therefore, the guidance outlines BAT and BEP for the use of decaBDE in production (UNEP 2021f).

The guidance describes BAT/BEP processes for screening and separation of plastic containing PBDEs, with the aim of eliminating them during recycling.

Recycling processes for both WEEE and end-of-life vehicles (ELV) manually separate POPs/BFR-containing plastics at the beginning of the treatment process or, as in most cases where mechanical recycling takes place, the separation of PBDEs along with other brominated flame retardant-containing plastics is conducted at the end of the recycling process, based on different methods described in the guidance, before the production of recycling pellets. The guidance document also shortly introduces to the destruction of PBDE-containing plastic in waste incinerators, recovery in cement kilns, and for selected metal industries, considering energy recovery options of plastic and destruction of POPs.

6.2 Stockholm Convention HBCD BAT/BEP guidance

The HBCD BAT/BEP guidance document (UNEP 2021g) has been developed and updated to guide Parties in their endeavour to prevent or reduce releases of HBCD resulting from the use under the specific exemptions listed in the Stockholm Convention, as well as the production and use of HBCD in EPS/XPS polymers in building insulation.

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[18] http://chm.pops.int/Implementation/NIPs/Guidance/GuidanceonBATBEPfortherecyclingofPBDEs/tabid/3172/Default.aspx

The guidance document provides specific BAT and BEP measures for using HBCD as a flame retardant in EPS and XPS in buildings. These measures include a description of the formulation of the production of EPS and XPS compounds, measures for reducing channelled emissions as well as preventing or reducing diffuse emissions, measures referring to water emissions, and minimization and control of emissions from storage (UNEP 2021g). BEP describe the application of the most appropriate combination of chemical management strategies and environmental control measures, including best practices for continuously enhancing environmental, health, and safety performance in producing and managing EPS/XPS containing HBCD (UNEP 2021g).

A short description explains the voluntary industry programme (Voluntary Emissions Control Action Programme - VECAP) with recommendations of best practices for the production of HBCD and use processes of HBCD in EPS/XPS and other uses (UNEP 2021g).

The guidance also contains an overview about the chemical alternatives to HBCD as a flame retardant in EPS/XPS with similar properties, as well as an overview of material substitutions for EPS/XPS insulation (UNEP 2021g).

6.3 Stockholm Convention PFOA and PFOS BAT/BEP guidance

This guidance document (UNEP 2021h)[19] has been developed and updated to guide Parties in their actions to prevent or reduce releases of PFOS and its salts, PFOSF, PFOA and its salts, and PFOA-related compounds from production and use under the specific exemptions and acceptable purposes listed in the convention. As PFOS and PFOA are also used in some plastic applications (e.g., production of fluoropolymers, production of side-chain fluorinated polymers, plating of plastics), this guidance can reduce releases of PFOS, PFOA, and related-compounds in these plastic related uses. The BAT/BEP guidance describes general principles and guidance on BAT/BEP for managing PFOS and PFOA and their related substances under the SC. Several environmental management techniques for manufacturing and use are determined as BEP as well general principles, measures, and safety precautions that apply to all types of chemicals and industries handling them.

It includes further information on available alternatives (substances and technologies) for the uses listed as specific exemptions and acceptable purposes under the convention which also includes alternatives to some fluorinated side-chain applications.

For PFOA exemptions have been listed for some fluoropolymer production where PFOA is still used in some countries “Manufacture of polytetrafluoroethylene (PTFE) and polyvinylidene fluoride (PVDF)”, “Manufacture of polyfluoroethylene propylene (FEP) for the production of high-voltage electrical wire and cables for power transmission” and “Manufacture of fluoroelastomers for the production of O-rings, v-belts and plastic accessories for car interiors”. For these processes this draft guidance has not yet defined BAT/BEP and inform that this will be added later.

6.4 Stockholm Convention BAT/BEP guidance for unintentional POPs

Plastic is a major fuel for open burning of waste, especially in low- and middle-income countries. Open burning is a major source of unintentional POPs release and a relevant source of release of black carbon (a light-absorbing, short-lived climate pollutant - SLCP), CO_2, and particulate matter. Therefore, for minimizing unintentional POPs release, the inventory and management of all plastic categories are of great importance and can be linked to POPs inventories.

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[19] http://chm.pops.int/Implementation/NIPs/Guidance/GuidanceonBATBEPfortheuseofPFOS/tabid/3170/Default.aspx

The "Guidelines on best available techniques and provisional guidance on best environmental practices relevant to Article 5 and Annex C of the Stockholm Convention on POPs"[20] (UNEP 2007) contains BAT/BEP for the control and minimization of unintentional POPs, in particular PCDD/PCDFs in large scale industrial processes where also plastic containing POPs is treated, recovered, or recycled, such as waste incinerators, cement kilns, industrial shredders, or metal industries (UNEP 2007 with updates of individual sections). The guideline also contains a section on controlling open burning and landfill fires relevant for plastic and related POPs and POP releases (UNEP 2007).

7 Basel Convention Technical Guidelines related to plastics

The Technical Working Group of the *"Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal"* has developed technical guidelines. The main objective of all these guidelines is to assist Parties, particularly developing countries, in the activities they must undertake for the environmentally sound management (ESM)[21] of the hazardous wastes they generate. These technical guidelines aim to provide guidance to countries that are in the process of building their capacity for environmentally sound and efficient waste management when in developing waste management plans or strategies. Since 2019, when POPs in plastics were addressed at the ninth meeting of the Conference of the Parties to the Basel Convention (COP9)[22], many projects on plastic waste have been implemented under the convention. The Basel Convention website stresses the synergies with the Stockholm Convention[23]. These synergies will become even more important in the future since two additional plastic additives have been listed as POPs (Dechlorane Plus and UV-328). These plastic additives will now be addressed by the Stockholm and Basel Conventions, and guidance documents for inventory development and waste management will be developed accordingly. All technical guidelines are available on the BRS website[24]. The main guidelines related to plastics and POPs are shortly introduced in this report.

7.1 Technical guidelines on the ESM of plastic wastes

The technical guidelines on the ESM of plastic wastes are the overarching guidelines of the Basel Convention for managing plastic in the end-of-life (UNEP 2023b). In the context of these guidelines, the term "plastic waste" covers those plastic wastes classified according to Basel Convention listing. Plastic wastes containing or contaminated with BFRs that are Stockholm Convention POPs fall under Annex I of the Basel Convention and are subject to control under the Basel Convention due to their POPs content. The limits for these POPs content are also defined in the Basel Convention by specific low POP content levels (UNEP 2023c). Furthermore, the guidelines cover plastic wastes that are extracted and/or separated from other waste streams that have plastic components or are partially or fully composed of plastic (*e.g.*, wastes collected from households, WEEE, ELVs, waste cables).

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[20] http://chm.pops.int/Implementation/BATandBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx

[21] ESM is a broad policy concept that is understood and implemented in various ways by different countries, stakeholders and organizations. The provisions and guidance documents pertaining to ESM of hazardous wastes as it applies to POP wastes within the Basel and Stockholm conventions, together with performance elements produced by the Organisation for Economic Co-operation and Development (OECD 2007)

[22] http://www.basel.int/Implementation/Plasticwaste/Overview/tabid/8347/Default.aspx

[23] Basel Convention (2021) Cooperation with others (on plastic waste) http://www.basel.int/Implementation/Plasticwaste/Cooperationwithothers/tabid/8335/Default.aspx

[24] http://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx

These technical guidelines present the overarching issues related to plastics which also consider POPs and substances of very high concern used as additives in plastics and listed by ECHA (UNEP 2023b). For CoCs in plastic, the guidelines refer to the UNEP report on Chemicals in Plastic (UNEP and BRS Secretariat 2023; Section 2.1), and the Report on global governance of plastics and associated chemicals (BRS Secretariat 2023; Section 2.2 of current report).

The guidelines appeal to avoid, reduce, and control, as far as possible, the impact of mechanical recycling and end-of-life contamination of plastic waste with POPs in terms of human health and the environment. To avoid contamination of subsequent recycling and manufacturing processes, plastics containing or contaminated with additives, processing aids, or other substances, especially POPs, should be removed. The guidelines require the identification, quality, and form of plastic waste, especially the content of CoCs such as POPs, should be known.

7.2 Technical guidelines on ESM of wastes for POPs management

A range of technical guidelines have been developed under the BC for POPs-containing waste, including those where POPs are used as plastic additives, as well as the related waste streams.

7.2.1 General technical guidelines on the ESM of POP wastes

The general technical guidelines on the ESM of wastes consisting of, containing, or contaminated with POPs aim to provide guidance for the proper management of these wastes (UNEP 2023c). One key aspect of these guidelines is the environmental sound management of waste containing POPs listed under the Stockholm Convention. Since a range of plastic additives have been listed as POPs in recent years, such as Dechlorane Plus, HBCD, HBB, PBDEs, SCCPs, and UV-328, as well as other plastic-related chemicals such as PFOS, PFOA, and PFHxS present in side-chain fluoropolymers (OECD 2022; UNEP 2023), the management of POPs waste is now closely linked to the management of plastic waste.

The purpose of these “umbrella” technical guidelines (UNEP 2023c) is:

- to provide overarching and common guidance on the ESM of POP wastes,
- to address the levels of destruction and irreversible transformation,
- to define the methods that are considered to constitute ESM of waste related provisions, and
- to define the concentration levels of “low POP content”.

Among these, the definition of low POPs limits is particularly crucial to categorize whether plastic waste containing POPs is considered POP waste. The setting of low POPs content limits for additives in plastics is an integral part of the regulatory frame of the ESM of plastics containing POPs. These limits impact the management of specific plastic fractions, such as those from certain WEEE. Currently, the low POPs content limits are provisional for major POPs additives in plastic, including PBDEs (50, 500, and 1000 mg/kg as a sum); for SCCPs (100, 1,500, and 10,000 mg/kg), and HBCD (100, 500 or 1000 mg/kg) (UNEP 2023c).

The respective technical guidelines for individual POPs (Section 7.2.2) provide information about the wastes, including plastic waste, affected by each respective POP to support their ESM.

7.2.2 Specific technical guidelines on the ESM of wastes containing individual POP

For industrial POPs, individual technical guidelines have been developed including POPs used as plastic additives (PBDEs, HBCD, SCCPs)[25] or other plastic-related POPs (PFOS, PFOA), and are available on the BRS website[26]:

- Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with hexabromocyclododecane (UNEP 2015);
- Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with hexabromodiphenyl ether and heptabromodiphenyl ether, or tetrabromodiphenyl ether and pentabromodiphenyl ether or decabromodiphenyl ether (UNEP 2019e);
- Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with short-chain chlorinated paraffins (UNEP 2019f);
- Technical guidelines on the environmentally sound management of wastes consisting of, containing, or contaminated with perfluorooctane sulfonic acid (PFOS), its salts and perfluorooctane sulfonyl fluoride (PFOSF), perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds, and perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS-related compounds (UNEP 2023i).

These specific technical guidelines share a common structure, containing detailed technical descriptions for each respective POP group. They provide guidance on waste types and entries, informing about plastic waste possibly containing the respective POP. They also contain a section on low POPs content limits for the respective POP, determining whether a plastic waste fraction falls into the category of POPs waste requiring ESM or remains below the threshold, allowing recycling from that perspective.

Environmentally sound waste disposal and (pre)treatment aim to prevent or reduce the releases of POPs into the environment. The ESM of plastic waste containing POPs can help prevent plastics containing POPs from being recycled into new plastic products, as frequently observed past 15 years (overview in UNEP 2021a).

7.3 Guidance on the development of inventories of hazardous wastes and plastic waste

Chemicals in plastic can only be controlled if the plastic waste is subjected to an ESM. A robust inventory of plastic and related hazardous additives is a basis for ESM and respective planning. Such inventories can be used to develop appropriate strategies and policies, including those for collecting and disposing of plastic waste. Moreover, they are an important input for the planning of facilities dedicated to recovery and final disposal, which require substantial financial investment and regular throughputs of wastes. The “Guidance on the development of inventories of hazardous wastes and plastic waste” of the Basel Convention (UNEP 2022b) aims to provide practical instructions to assist Parties and stakeholders in developing inventories of plastic waste. It is meant to be used in conjunction with the “Methodological guide for the development of inventories of hazardous wastes under the Basel Convention” (UNEP 2016). The main objective of developing a plastic waste

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[25] Please note that for the POPs listed in 05/2023 – Dechlorane Plus and UV-328 – no guidance has been developed yet.

[26] http://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx

inventory is to obtain information on the amount of plastic waste generated at a country level, as well as its disposal and transboundary movement. However, this guidance does not mention or address POPs or other hazardous chemicals in plastic at all and therefore does not support Parties in managing CoCs in plastic.

8 Documents in the international negotiations on a global agreement on plastics and in SAICM with specific information on chemicals in plastics

8.1 Documents from the international negotiations on a global agreement on plastics

At UNEA[27] 2022, governments officially adopted a mandate to begin negotiations on a global, legally binding agreement on plastics that would cover the entire life cycle of plastics, including production, design, and disposal.

The resolution (United Nations 2022), based on three initial draft resolutions from various nations, establishes an Intergovernmental Negotiating Committee (INC), which commenced its work in 2022, with the aim of finalizing a draft global, legally binding agreement by the end of 2024[28]. This treaty on plastics has enormous potential to guide the world towards reducing the impact of plastic production and pollution.

The above described documents "Chemicals in Plastic – A Technical Report" (Section 2.1; UNEP and BRS Secretariat 2023) and "Report on the global governance of plastics and associated chemicals" (Section 2.2; BRS Secretariat 2023), were also submitted by UNEP and the BRS Secretariat to INC2 of this process and included there as information documents (UNEP/PP/INC.2/INF/5 and part of UNEP/PP/INC.2/INF/7/Rev.1, respectively). Furthermore, certain other documents of this process contain information on POPs or chemicals in plastic and are shortly discussed herein.

8.1.1 Zero draft text of the international legally binding instrument on plastic pollution

A "Zero draft text of the international legally binding instrument on plastic pollution, including in the marine environment" has been published ahead of Third Session of the Intergovernmental Negotiating Committee on plastic pollution (INC3) (UNEP 2023d). The zero draft text contain in Part II a section on chemicals and polymers of concern. In this section three options are proposed to address chemicals of concern in the treaty including an annex for related details (UNEP 2023d).

The draft also includes a paragraph on "*Transparency, tracking, monitoring and labelling*" which "*require producers and importers to disclose harmonized information on the chemical composition of all plastics and plastic products throughout their life cycle*" (UNEP 2023d).

8.1.2 Document for "Potential options for elements towards an international legally binding instrument"

For the Second Session of the Intergovernmental Negotiating Committee on plastic pollution (INC2), the working document "*Potential options for elements towards an international legally binding instrument, based on a comprehensive approach that addresses the full life cycle of plastics as called*

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[27] The UN Environment Assembly (UNEA) is the UN's highest decision-making body in the field of environmental protection and sets the priorities for global environmental policy.

[28] https://www.unep.org/news-and-stories/story/what-you-need-know-about-plastic-pollution-resolution

for by United Nations Environment Assembly resolution 5/14" (UNEP/PP/INC.2/4; UNEP 2023e), proposes as a possible core obligation: banning, phasing-out, and/or reducing the production, consumption, and use of chemicals and polymers of concern (UNEP 2023e):

"*The committee may wish to consider including some or all of the following potential options for control measures and voluntary approaches:*

(a) Options for regulating chemicals and polymers of concern:

- *(i) Ban, phase-out, reduce or control specific polymers and CoCs, or groups of chemicals, based on criteria identified to determine polymers and chemicals of concern (list, phase-out date and criteria could be included in an annex to the instrument).*
- *(ii) Apply import and export requirements for listed polymers and chemicals to parties and non-parties on a non-discriminatory basis.*
- *(iii) Apply import and export requirements to parties and non-parties on a non-discriminatory basis.*

(b) Options for increasing transparency:

- *(i) Track types and volumes of polymers and chemicals applied in production, including through disclosure requirements for plastics throughout the supply chain, and plastic production, use and additives, consistent with national laws.*
- *(ii) Increase transparency through marking (digital watermarks, tracers) and harmonized product labelling, material safety data sheets, product passports and publicly available databases.*

(c) Options for accelerating and supporting the transition:

- *(i) Establish measures to foster innovation and incentivize alternative and substitutes, including through sustainable or green chemistry and chemical simplification.*
- (ii) *Incentivize research and development of sustainable additives and polymers*"

8.1.3 Document for "Additional information linked to potential options for elements towards an international legally binding instrument"

A second related INC2 document published as the information (INF) document "*Additional information linked to potential options for elements towards an international legally binding instrument*" (UNEP/PP/INC.2/INF/4; UNEP 2023f) compiles in Section II proposals contained in the submissions of Member States on the **possible contents of potential annexes** to the instrument.

One suggested potential annex is a "List of polymers, chemicals of concern; criteria for determining polymers and chemicals of concern; and possible dates for banning, phase-out, reduction or control" (UNEP 2023e). This potential annex is related to possible Core Obligation 3: banning, phasing-out, and/or reducing the production, consumption, and use of chemicals and polymers of concern. Specifically, it refers to options for regulating chemicals and polymers of concern, through "ban, phase-out, reduce or control specific polymers and chemicals of concern, or groups of chemicals, based on criteria identified to determine polymers and chemicals of concern" (UNEP 2023e see Section 8.1.2).

Potential criteria for determining polymers and CoCs were compiled (UNEP 2023f) as follows:

a. Harmfulness to the environment and/or human health, including chemicals or groups of chemicals with the following properties:

- (a) Carcinogenicity, mutagenicity, reproductive toxicity (including, for example, tris(2-chloroethyl) phosphate (TCEP) which can be used as a flame retardant in PUR, and lead and cadmium which are used as stabilizers in PVC);

(b) Endocrine disruptors (including, for example, phthalates which are often used as plasticizers, including DEHP, DBP, BBP, and DIBP);

(c) Substances of equivalent concern to the above, *e.g.*, those affecting the immune system, neurological system, or a specific organ (immunotoxicants, neurotoxins, or substances with specific target organ toxicity arising from a repeated exposure to a substance or mixture (STOT RE);

(d) Persistent, bioaccumulative, and toxic substances in the environment (PBT);

(e) Very persistent and very bioaccumulative substances (vPvB) (including, for example, BFRs as additives in plastics);

(f) Persistent, mobile, and toxic substances (PMT);

(g) Very persistent and very mobile substances (vPvM) (including, for example, PFAS found as contaminants in plastic packaging or BFRs as additives).

b. Hindrance of recyclability or circularity for safe and high-quality secondary materials, including:

(a) Polymers that cannot readily be recycled;

(b) Use of certain chemicals, groups of chemicals, polymers, and polymer mixes (to simplify product composition for enhanced reuse recyclability and develop non-toxic secondary markets);

(c) BFRs.

c. Risk of release, including due to slow or non-degradation in the environment, such as:

(a) Oxo-degradable plastic products;

(b) Certain single-use plastic products;

(c) Intentionally added microplastics.

d. Substances having ozone depleting effects and substances with global warming potential:

e. Polymers of high concern.

8.1.4 Report “Turning off the Tap - How the world can end plastic pollution and create a circular economy”

UNEP developed a report titled “Turning off the Tap - How the world can end plastic pollution and create a circular economy” (UNEP/PP/INC.2/INF/8; UNEP 2023g)[29]. The report contains a specific Topic Sheet: Criteria for Chemicals in Plastic[30] (UNEP 2023h). This Topic Sheet probes into the question: “What could criteria on chemicals in plastics look like?” The inquiry point to the UNEP report on “Chemicals in Plastic” (UNEP and BRS 2023; see Section 2.1) and highlights specific methodologies mentioned therein, including the strategies to avoid regrettable substitution, approach challenges from a holistic perspective, and adopt the precautionary principle. These approaches offer avenues to prioritise actions on 10 groups of chemicals associated with plastics identified as of major concern due to their known toxicity and potential to migrate from plastics (UNEP 2023h; Figure 1; UNEP and BRS Secretariat 2023).

These 10 groups of chemicals include:

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[29] https://www.unep.org/resources/turning-off-tap-end-plastic-pollution-create-circular-economy

[30] https://wedocs.unep.org/handle/20.500.11822/42234

- Specific flame retardants,
- Ultraviolet light stabilizers,
- Per- and polyfluoroalkyl substances (PFASs),
- Phthalates,
- Bisphenols,
- Alkylphenols and alkylphenol ethoxylates,
- Biocides, toxic metals, and metalloids,
- Polycyclic aromatic hydrocarbons (PAHs), and
- Other non-intentionally added substances, including unintentional POPs such as dioxins and furans.

Furthermore, the Topic Sheet[30] suggests that possible criteria for elimination or reduction of CoCs in plastic can focus on:

- Approach 1: Global negative list based on selection criteria.
- Approach 2: Global negative list based on existing regulatory lists of CoCs.
- Approach 3: Global positive list based on chemicals deemed safe.
- Approach 4: Hybrid of any approaches 1–3.

8.1.5 INF document of the Secretariat of the Convention on Biological Diversity

The Secretariat of the Convention on Biological Diversity submitted the INF document titled "*Work and guidance under the Convention on Biological Diversity of relevance for the deliberations of the second session of intergovernmental negotiating committee to develop an international legally binding instrument on plastic pollution, including in the marine environment*" to INC2 (UNEP/PP/INC.2/INF/6; Secretariat of the Convention on Biological Diversity 2023). The document stresses that "*ingestion of plastics is also of concern as it may provide a pathway for the transport of harmful chemicals into the food web*" by referencing to Annex of COP Decision 13/10. And calls to "Promote research on the potential trophic transfer of marine microdebris in food webs to determine whether there is a bioaccumulation effect for plastics and harmful chemicals" as suggested as a Priority actions for mitigating and preventing the impacts of marine debris on marine and coastal biodiversity and habitats by Annex of COP Decision 13/10 (Secretariat of the Convention on Biological Diversity 2023).

8.1.6 Scientists Coalition Policy Brief on the role of chemicals and polymers of concern

The Scientists' Coalition for an Effective Plastics Treaty (SCEPT) published a policy brief on the "Role of chemicals and polymers of concern in the global plastics treaty". The document targets policymakers involved in the INC for a plastic treaty. It provides arguments and insights into why and how plastic-related CoCs and polymers of concern should be integrated in the global plastics treaty (Wagner *et al.* 2023).

The policy brief stresses that "without comprehensive inclusion of plastic chemicals and polymers, the treaty's goal of protecting human health and the environment from negative impacts of plastics and to promote sustainable and consumption of plastics cannot be achieved".

Chemicals and polymers of concern are cross-cutting issues relevant for obligation options outlined in the UNEP option document (UNEP/PP/INC.2/4; See Section 8.1.1). The policy brief concludes that it is critical to include chemicals and polymers in the legally binding obligations set out in the plastic treaty to mitigate the global dispersal of hazardous substances, and that multiple opportunities exist to do so:

1. Creating a comprehensive, global inventory of plastic chemicals, polymers, and materials is a key prerequisite to reduce plastic pollution.

2. Science can provide comprehensive definitions regarding plastic chemicals and polymers.
3. The chemical complexity of plastics can be addressed by grouping chemicals based on their structure.
4. Groups of chemicals and polymers of concern can be phased-out based on existing frameworks using negative lists.
5. Positive lists of chemicals and polymers can be created based on safe-by-design criteria.
6. Negative and positive lists will promote the transition to a non-toxic plastic economy when combined with financial incentives.
7. The provisions on plastic chemicals and polymers should be legally binding, as well as adaptive and informed by independent science.

8.1.7 Contribution of IPEN on chemicals in plastic for the plastic treaty

The International Pollutant Elimination Network (IPEN) published a brief suggesting that the tackling of toxic chemicals should be considered as the top priority for the plastic treaty (IPEN 2023).

The brief suggests elements from the Stockholm Convention to be adapted to the Plastics Treaty (IPEN 2023):

- Specific criteria: persistence, bioaccumulation, potential for long-range environmental transport, and evidence of adverse effects to human health or the environment.
- Precautionary principle.
- Special considerations for vulnerable groups.
- Focus on elimination.
- Adaptation of scientific knowledge.

The brief recommends enhancing the identification and regulation of problematic chemicals under the Plastics Treaty by grouping of chemicals, transparency, and stockpile prevention. It also proposes a list of priority substances to tackle.

Additionally, it states that various approaches could be adopted, such as positive lists, negative lists, and a combination of the two as suggested by BRS Secretariat 2023 (See Section 2.2). However, the favoured approach is to combine a negative list with an approach that prohibits marketing chemicals when toxicity data is unavailable (IPEN 2023).

8.2 Documents from the SAICM process with specific information on chemicals in plastic

SAICM is a multi-stakeholder and multi-sectoral policy framework aimed at promoting chemical safety around the world. The overarching goal of SAICM was to achieve sound management of chemicals throughout their life cycles, which would result in the production and use of chemicals in a manner that significantly reduces negative impacts on the environment and human health by 2020.

8.2.1 Report “Chemicals of concern in the building and construction sector”

The building and construction sector is one of the most chemical-intensive downstream sectors of the chemical industry and represents the largest end market for chemicals, generating the highest chemical revenue (UNEP 2021i). The UNEP report “*Chemicals of Concern in the Building and Construction Sector*” has been published in the context of SAICM. It aims to provide an overview of the challenge posed by CoCs in products relevant to the building and construction sector (UNEP

2021i)[31]. The report outlines the relevance and linkages of CoCs with regards to the building life cycle and highlights existing gaps, challenges, and opportunities regarding the imperative of increasing circularity in the building and construction sector. The report aims at identifying selected CoCs that have relevance in the context of products of the building and construction sector. The scope of the analysis covers chemicals that have documented applications in products (including building materials) and formulations intended for permanent incorporation in the built environment, potentially causing concern during at least one life cycle stage of a building. Many of the compiled chemicals are related to plastic but also asbestos and heavy metals not related to plastic are addressed (UNEP 2021i). For chemicals that are currently addressed under multilateral environmental agreements (MEAs), such as the Stockholm Convention on POPs, the report includes fact sheets summarizing information on chemical identities, relevant applications, and potential alternatives (UNEP 2021i).

The major conclusions of the report are (UNEP 2021i):

- Nearly 30 CoCs are relevant in the context of products of the building and construction sector, as identified by the study, and the number of chemicals of potential concern is likely higher.
- Continued collaborative research and action will be needed to address the identified gaps and challenges in order to further protect human health and the environment from potential harmful impacts of chemicals of concern used in the sector and to shift the sector towards more sustainable patterns of consumption and production.
- Given the current trends in the building and construction sector and the increased focus on environmental concerns, including energy efficiency, the use of resources and health considerations should be used as a springboard to address the issue of chemicals of concern and to seize the opportunity this offers for sustainable development.

8.2.2 Chemicals of concern in electronics – Review of legislative and regulatory approaches

This report provides an overview on legislative and regulatory approaches to address the use of CoCs in electronics (UNEP 2020b).[32] The report informs that at the international level, several chemicals and chemical groups with documented uses in EEE have been designated for global elimination by MEAs. Examples for this are the listing of the plastic additives like PBDEs or SCCPs in Annex A of the Stockholm Convention. On a national level, several types of laws or regulations may be relevant for the use of CoC in electronics (UNEP 2020b). In addition to specific regulations like RoHS, overarching framework laws on chemicals or products can contain provisions that, while not specific, remain relevant for the use of CoC in electronics.

The study concluded that (UNEP 2020b):

- The chemical scope of all identified regulations is very similar; however, the provisions regarding the product scope, the specific exemptions from the provisions, and the procedures to ensure compliance vary between the regulations.
- Regulatory drivers are catalysing the removal of chemicals of concern from manufacturing processes and products, aligning with the Global Chemicals Outlook II (GCO II) (UNEP 2019g).

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[31] https://wedocs.unep.org/bitstream/handle/20.500.11822/35916/CoCBC.pdf

[32] https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/35362/CoCE.pdf

- Regulations addressing CoC in EEE have been an important driver for innovation and substitution of CoC in the sector. Therefore, regulation stands as an important tool for addressing the challenge posed by chemicals of concern in EEE and supporting the goal of minimizing harmful impacts of chemicals on human health and the environment throughout the entire lifecycle.
- The presence of chemicals of concern in EEE may constitute a barrier for recycling due to concerns about potential impacts during post-consumer usage of these materials. Regulations address that barrier and enable circularity and circular business models (see also PACE 2019).

The study made recommendation for stakeholders involved in addressing the issue of CoC in the electronics sector (UNEP 2020b):

- Accelerating and streamlining regulatory action on CoC in EEE through regional and global collaboration: Global collaboration should be explored in order to close the still significant data gaps on the presence, flow, and transboundary movement of chemicals of concern throughout the life cycle of EEE.
- Developing and implementing a coordinated and coherent regulatory approach for CoC in EEE on a national level: National regulatory approaches for CoC in EEE should be carefully coordinated across multiple regulatory domains, encompassing products, chemicals, POPs, or waste regulations. Notably, certain provisions of the Stockholm Convention can be relevant in the context of CoC in electronics. Therefore, regulators must carefully coordinate national legislation on EEE with national legislation on POPs in order to ensure a coherent set of regulations.
- Development and implementation of complementary tools: Such tools could include voluntary schemes such as labelling or voluntary sustainability standards.
- Developing regulations and policies considering circular perspectives: The continuing advances in regulations should be mindful of and support the development of concepts for circular economy. This could involve, for example, considering the potential for chemicals and materials to constitute significant barriers to recycling when making regulatory decisions. Additionally, incentives could be provided for the use of materials and technologies that facilitate circular approaches, while frameworks could ensure the communication of information on materials and potential contents of CoC along the entire value chain.
- Developing and providing specific guidance and building capacity for substituting chemicals of concern for stakeholders along the electronics value chain.

9 Selected further useful publications and resources on POPs and other CoCs in plastic

9.1 Documents from POPs Review Committee process for POPs associated with plastic

The Stockholm Convention has a mechanism for listing of POPs in Annex A (Elimination), Annex B (Restriction), or Annex C (Unintentional Production) of the convention. The POPs Review Committee (POPRC) is the subsidiary body to the convention established for reviewing chemicals proposed for listing in Annex A, B, or C. Since 2009, 22 POPs or POP groups have been newly listed in the convention, including many plastic additives. A Party of the convention may submit a proposal to the Secretariat for the inclusion of a chemical. The Party has to prepare a dossier containing chemical screening criteria, defined in the Annex D (Information Requirements and Screening Criteria) of the convention. In the next phase, the POPRC brings the application and its evaluation to the attention of all Contracting Parties and invites them to provide information concerning a risk profile, as specified in Annex E (Information Requirements for the Risk Profile). Subsequently, all Parties and observers can submit additional information in accordance with Annex F, relating to socio-economic considerations and implications of a ban on the substance. The POPRC prepares a risk management evaluation (or also called social-economic analysis) that includes an analysis of possible control measures for the chemical in accordance with Annex F and recommends whether the substance should be included in Annex A, B, and/or C of the SC.

All documents of the POPRC decision-making process (Annex D, Annex E, Annex F) are freely available for download on the BRS website[33]. Reports on decisions from the COP meetings are also available[34]. The BRS Secretariat has developed fact sheets[35] for all new POPs, which contain information on the chemical identity, POP properties, production and use information, and listing under the convention.

9.2 Major review articles on chemicals in plastic

Several review articles on chemicals in plastic are available, offering different insight into the use, presence, and release of chemicals related to plastics. They are shortly introduced here.

Furthermore, a compilation of more than 700 references related to chemical in plastic and related issues can be found in the UNEP report on Chemicals in Plastics (see Section 2.1) (UNEP 2023a), providing further avenues for specific information exploration.

9.2.1 Review on chemicals in plastics to facilitate circular economy (Aurisano *et al*. 2021)

This open access review article provides a list of more than 6,000 chemicals in plastics, which can be downloaded from the article's supplementary information as a separate Excel file. The authors give an overview of the challenges and gaps in assessing their impacts on the environment and human health along the life cycle of plastic products (Aurisano *et al*. 2021).

The review proposes five policy recommendations to enable a circular economy for chemicals in plastics and support UN Sustainable Development Goals 12.4:

1. Facilitate collaboration and involvement of all relevant stakeholders throughout the entire life cycles of chemicals and plastics with transparent supply chain management toward a common vision based on the 12 principles of circular chemistry on country, continental, and global level.
2. Harmonize regulatory and legal frameworks and enforce an overarching and global regulatory framework for plastics and related chemicals guided by systems thinking to connect the different actors of the plastics value chains. For example, necessary reforms include an extended producer responsibility for plastic products (especially those containing hazardous substances).
3. Implement funds to invest in mechanisms to strategically coordinate and support the transition of industries toward a circular economy in both upstream and downstream capacities and seeking synergies within the sound management of chemicals and waste beyond the 2020 SAICM process[36].
4. Invest in research into new technologies supporting industries in the efficient production of virgin and recycled plastics suitable for a circular economy model.

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[33] http://chm.pops.int/TheConvention/POPsReviewCommittee/ReportsandDecisions/tabid/3309/Default.aspx

[34] http://chm.pops.int/TheConvention/ConferenceoftheParties/ReportsandDecisions/tabid/208/Default.aspx

[35] http://chm.pops.int/TheConvention/ThePOPs/TheNewPOPs/tabid/2511/Default.aspx

[36] https://www.saicm.org/Beyond2020/IntersessionalProcess/tabid/5500/language/en-US/Default.aspx

5. Educate and support citizens, companies, and investors on the transition toward a circular economy for plastics and related chemical substances.

9.2.2 Review on monomers, additives, and processing aids in plastics (Wiesinger *et al*. 2021)

This open access article investigated plastic monomers, additives, and processing aids on the global market based on a review of 63 industrial, scientific, and regulatory data sources. In total, the authors identify more than 10,000 relevant substances and categorize them based on substance types, use patterns, and hazard classifications wherever possible. Over 2,400 substances are identified as substances of potential concern as they meet one or more of the persistence, bioaccumulation, and toxicity criteria in the EU (Wiesinger *et al*. 2021). Many of these substances are hardly studied according to SciFinder (266 substances), are not adequately regulated in many parts of the world (1,327 substances) or are even approved for use in food-contact plastics in some jurisdictions (901 substances). The review informs that substantial information gaps exist in the public domain, particularly on substance properties and use patterns. It concludes that for the transition to a sustainable circular plastic economy that avoids the use of hazardous chemicals, concerted efforts by all stakeholders are needed, starting by increasing information accessibility (Wiesinger *et al*. 2021).

Supporting information in form of an Excel file with a database on all substances and a PDF file presenting details on methods, additional results, and additional discussion on chemicals on the global market is also provided.

9.2.3 Review on chemicals in food contact materials including plastic (Groh *et al*. 2021)

The article describes the compilation of a database of intentionally used food contact chemicals (FCCdb). The FCCdb records 12,285 chemicals from 67 global regulatory and industry lists.

The authoritative hazard data prioritized 608 FCCdb chemicals for substitution. Predictive hazard data highlighted 1411 additional chemicals of potential concern. Over 25% of FCCdb chemicals lack hazard data in the public sources consulted (Groh *et al*. 2021).

The FCCdb is freely downloadable and searchable as a Microsoft Excel file.[37] The database has been released under a Creative Commons Attribution-Non-Commercial 4.0 license. This allows it to be freely shared and adapted for non-commercial purposes as long as appropriate credit is given. The list of 608 identified priority FCCs can be downloaded from the scientific article's supplementary information as a separate Microsoft Excel file.

9.2.4 Review on additives in plastic in recycling and disposal (Hahladakis *et al*. 2018)

This open access review article describes waste management and pollution challenges, emphasising on the various chemical additives in plastics. The additives can potentially migrate and undesirably lead to human exposure via *e.g.*, food contact materials, such as packaging. They can also be released from plastics during various recycling and recovery processes and from the products produced from recyclates. Thus, sound management along the entire life cycle has to be performed in such a way as to ensure that emission of substances of high concern and contamination of recycled products is avoided, ensuring environmental and human health protection at all times.

9.2.5 Review on chemical in plastic and marine pollution (Gallo *et al*. 2018)

This open access article describes the fate and gaps in the impact of polymers with their chemical additives (*e.g.*, POPs and other endocrine disrupting chemicals (EDCs)) in the marine environment

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[37] https://www.foodpackagingforum.org/fccdb.

from marine litter plastics. Without immediate strong preventive measures, the environmental impacts and the economic costs are set only to become worse, even in the short term. Continued increases in plastic production and consumption, combined with wasteful uses, inefficient waste collection infrastructures, and insufficient waste management facilities, especially in developing countries, mean that even achieving established objectives for reductions in marine litter remains a huge challenge. It is unlikely to be achieved without a fundamental rethinking of plastic consumption practices. The authors have identified several possible future activities to address the issue by the Basel and Stockholm Conventions Regional Centres in coordination with existing platforms, or by any other UN Environment institutions, governments, and NGOs (Gallo *et al*. 2018). The peer reviewed paper has been developed based on the INF documents of the authors "Report on the activities of the Basel and Stockholm conventions regional centres. Challenges and measures to tackle marine litter plastics and microplastics and their POPs and EDC components" (UNEP/POPS/COP.8/INF/26/Rev.1; UNEP 2017b)

9.3 Webinars on POPs and other CoCs in plastic related to UNEP

9.3.1 Webinar series on introducing to POPs in plastic and their monitoring (IPCP)

Scientific knowledge and analytical capacity for chemicals in plastic need to be strengthened to support effective decision-making at the national and regional levels and to address priority issues such as plastics/pellets and the health and environmental risks of POPs additives. Within a GEF-funded POPs Global Monitoring Plan (GMP) project, initial capacity building and monitoring of POPs in plastics, particularly in recycled plastic pellets, has been conducted in 2023. This includes a series of webinar organised by the IPCP. These webinars were recorded and are available on YouTube and the IPCP website:

https://www.ipcp.ch/activities/ipcp-webinar-series-pops-in-plastic-and-monitoring-approaches

Part I of this webinar series provides an overview on relevant POP groups (and other CoCs) in plastics and some insights into related human exposure and environmental pollution, including biota. This is provided as a two-day webinar:

Day 1: https://www.youtube.com/watch?v=fc6BzT8rU_Y&t=3s

Day 2: https://www.youtube.com/watch?v=u5Ht6vg8Y04&t=1s

Part II introduces to screening and sampling strategies for plastic categories potentially containing POPs, such as plastics in electronics and vehicles or recycled pellets:

Day 3: https://www.youtube.com/watch?v=WOHifcF71Xo

Part III introduces to extraction and clean-up methods of plastic samples for POP analysis, as well as the instrumental analysis of the major POP groups. This is provided as a two-day webinar:

Day 4: https://www.youtube.com/watch?v=o341GAxt2nY&t=26s

Day 5: https://www.youtube.com/watch?v=hcjIe6QfUE0&t=19s

9.3.2 Webinar introducing chemicals in plastic and their monitoring (SAICM Secretariat)

These webinars informing to SAICM[38] and for preparation of INC3[39] provided insight into the current status of preparing and developing an international legally binding instrument on plastic pollution, along with the key findings from UNEPs Technical Report "Chemicals in Plastic – A Technical Report" (see Section 2.1).

The webinars also aimed to show the intricate ties between chemical composition, recyclability, and environmental implications of plastics, aiming to foster an in-depth understanding of this issue that can help guide future policy decisions. Specifically, the SAICM related webinar[38] addressed the recycling challenges associated with plastic and hazardous chemicals related to UNEP's ISLAND GEF project. The assessment concluded:

- Chemicals are accumulating in (and within) plastic products entering Small Islands Developing States (SIDS).
- Safe management and disposal of existing hazardous products, including plastics that are hazardous because of the chemicals they contain is needed
- Products need to be safely managing through their life cycle, encompassing chemicals in plastics. Failing to do so renders these plastics ineligible for safe recycling. However, only a few SIDS possess recycling infrastructure, and recyclable waste often requires shipping to recycling markets. Unfortunately, shipping cost is too high and frequently plastic is sent to landfills/dumpsites.
- A growing tide of plastic waste, much of which contains hazardous chemicals, presents a significant challenge.
- The ISLAND project is looking for solutions, including the developing a partnership with shippers to address this issue.

10 Conclusion

The listing of a range of plastic additives as POPs in the Stockholm Convention (Dechlorane Plus, HBCD, HBB, PBDEs, SCCPs, and UV-328), as well as the listing of other plastic-related chemicals such as PFOS, PFOA, and PFHxS, and related compounds present in side-chain fluoropolymers as POPs in the convention, has led to major plastics use sectors containing POPs in products and waste, necessitating addressing through the Stockholm and Basel Convention. This notably includes plastic fractions from EEE/WEEE, the transport sector, the construction sector, and certain synthetic textile applications. Consequently, the assessment and management of products and waste containing these POPs are now a closely linked to the management of these major plastic waste fractions.

Since the Stockholm Convention covers the production, use, and end-of-life of POPs and products containing them, it also encompasses the entire life cycle of the listed plastic additives and related plastic products, particularly for additives that are still produced and used with exemptions; the entire life cycle need to be covered by the Convention's implementation. Within the framework of the Stockholm and Basel Conventions, guidance documents and guidelines have been developed to support the life cycle management of these POPs plastic additives and other plastic-related POPs. Simultaneously, these can facilitate the global management of POPs-containing plastic fractions and

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[38] https://thegreenforum.org/event/chemicals-plastics-deep-dive-composition-recyclability-and-policy-implications

https://www.youtube.com/watch?v=XZk6aCX8JkQ&t=19s

[39] https://www.youtube.com/watch?v=6xYZ13R5Jj0&t=500s

have been shortly introduced in this document. The categories of guidance documents facilitating the life cycle management of the POPs plastic additives include:

- Guidance documents on alternatives to POPs plastic additives
- Inventory guidance documents of the POPs plastic additives, including affected plastic products and waste
- Guidance documents on BAT/BEP for the production, use in production, and recycling of POPs plastic additives
- Basel Convention guidelines covering the end-of-life management (also included in Stockholm Convention PBDE BAT/BEP guidance due to recycling exemption).

For POPs additives with exemptions, for which alternatives were not available in several countries, the search for alternatives and information on these alternatives has high priority to reduce and eliminate production and not increase the amount of plastic containing POPs, which would negatively impact plastic recycling in the years and decades to come. Therefore, guidance documents on alternatives to the listed plastic additives decaBDE, SCCPs, and HBCD have been developed that, in addition to chemical alternatives, also include alternative materials other than plastics to substitute plastic use with materials that do not require flame retardant. Additionally, a general guidance on considerations related to alternatives and substitutes for listed POPs and candidate chemicals has been published. This includes information on identification of alternatives, the assessment of risks related to alternatives such as POPs properties, and the social and economic assessment of alternatives including cost analysis and benefit assessments, as well as a compilation of alternative assessment tools for chemical alternatives and an introduction to assessment approaches.

For all POPs listed until 2022[40], inventory guidance documents have been developed in the frame of the Stockholm Convention. While their primary aim is to facilitate inventory and management of individual POPs, they can also globally ease the inventory of major plastic fractions impacted by POPs (EEE/WEEE, transport sector, and buildings and construction). To support this sectoral approach, a cross-sectoral inventory guidance for POPs and other chemicals of concern listed in multilateral environmental agreements has recently been published for these three major plastic use sectors for UNEP (Weber 2023a). This can provide a basis for the management of plastic containing POPs in these major use sectors. To facilitate the identification of products, waste, and stockpiles containing POPs, a monitoring guidance has been developed for POPs in products and recycling, including a step-by-step methodology for detecting and analysing POPs in products (UNEP 2021a). Since most of POPs present in products are plastic additives or other POPs related to plastic, the POPs monitoring guidance is highly relevant for monitoring POPs in plastics and identifying impacted products and recycling flows. Another set of guidance documents developed in the frame of the Stockholm Convention are the BAT/BEP guidance documents. Since some of these BAT/BEP guidance documents are for POPs plastic additives (PBDEs, HBCD) or have plastic related uses (PFOS and PFOA), these BAT/BEP guidance documents can support the control of releasing POPs related to plastic production, plating of plastics, and plastic recycling. Notably, the BAT/BEP guidance for PBDEs contains descriptions of technologies for separating plastics containing PBDEs from uncontaminated plastic, enabling safe recycling of plastics from sources like WEEE and ELVs, with specific separation methods applicable to other plastics containing BFRs.

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[40] For the POP plastic additives Dechlorane Plus and UV-328 only recently listed 05/2023, no guidance documents have been developed yet.

Furthermore the BAT/BEP guidance on unintentional POPs is relevant for reducing emissions of dioxins, other unintentional POPs, and toxic releases from open burning and landfill fires, primarily fuelled by plastics. The implementation of the guidance can reduce toxic releases from plastic end-of-life management, especially in low-income countries.

The Basel Convention is responsible for the environmentally sound management and disposal of waste containing POPs, including POPs-containing plastic waste. By setting low POPs content limits the convention defines the framework for POPs-contaminated plastics, and technical guidelines for individual POPs give direction for the ESM of POPs-containing wastes, including plastic wastes. These individual guidelines include the low POP content limit providing the basis for defining plastic fractions as POPs wastes and give guidance on their ESM and disposal. A gap in the guidelines is the lack of detailed description of separating plastics containing POPs; however, this is described for PBDEs in the BAT/BEP guideline of the Stockholm Convention.

After the listing of certain plastic fraction in the Basel Convention Annexes, a general “Technical guidelines on the environmentally sound management of plastic wastes” has been developed, considering POPs in plastic, as well as other substances of very high concern (SVHCs) listed by ECHA that have been or are used as plastic additives and the 128 plastic-related substances that are currently internationally regulated by existing multilateral environment agreements (MEAs) (BRS Secretariat 2023). These substances have the potential to render plastic wastes hazardous, difficult to recycle, or unsuitable for recycling. (UNEP 2023b; UNEP and BRS 2023). The guideline give guidance for the handling, separation, collection, packaging, compaction, transportation, and storage of plastic waste, as well as for the environmentally sound disposal of plastic. This could become the knowledge base for ESM of plastic, including considerations on internationally regulated chemicals of concern.

For the process of developing an international legally binding instrument on plastic pollution, comprehensive documents on chemicals in plastic have been developed by UNEP (“*Chemicals in plastic – A Technical Report”*) and the BRS Secretariat (“*Global governance of plastics and associated chemicals*”), included as INF documents at INC2 (within UNEP/PP/INC.2/INF/5). Through these documents, an overview of the current knowledge on chemicals in plastic, along with the status of the international governance framework and solution options, has been established. This provides a basis for addressing major chemical groups of concern in plastics by substitution.

During the INC2 session in June 2023, a working document titled “*Potential options for elements towards an international legally binding instrument, based on a comprehensive approach that addresses the full life cycle of plastics as called for by United Nations Environment Assembly resolution 5/14*” (UNEP/PP/INC.2/4; UNEP 2023e) proposed potential options for control measures and voluntary approaches. These include bans, phase-outs, and/or reductions in the production, consumption, and use of chemicals or chemical groups. These measures are to be determined based on identified criteria for chemicals of concern (UNEP 2023e). Another INF document (“*Additional information linked to potential options for elements towards an international legally binding instrument*” - UNEP/PP/INC.2/INF/4; UNEP 2023f) offers potential criteria for identifying polymers and CoCs, considering harmfulness to the environment and/or human health, hindrance of recyclability or circularity, risk of slow or non-degradability in the environment, and substances with ozone-depleting or global warming potential. The Zero draft text of the international legally binding instrument on plastic pollution (UNEP 2023d) published ahead of INC3 includes different options on how to include chemicals of concern in the plastic treaty.

In addition to countries and governments, other stakeholders, including the scientific community (represented by e.g. the Scientists' Coalition for an Effective Plastics Treaty) and civil society organisations (such as the International Pollutant Elimination Network), have submitted documents supporting the inclusion of CoCs in the plastic treaty. Furthermore, the industry is currently developing a list of additives used in plastic. Therefore, major stakeholders have an interest in addressing the challenges posed by POPs and other CoCs in plastic. Depending on the ultimate framework of the international treaty, these challenges might find resolution within its provisions.

The challenges associated with POPs in plastic are already addressed under the Stockholm and Basel Conventions, with guidelines, guidance documents, and projects designed to enhance the current baseline situation concerning plastic waste containing POPs. Within these initiatives, efforts have been directed to restrict, eliminate, and substitute plastics containing POPs with safer alternatives, all within the framework of the Stockholm Convention. The established approach, including the development of guidance documents for managing POPs in plastics across their lifecycle, along with relevant implementation activities, could possibly be extended within the context of a plastic treaty to include other CoCs, considering the lessons learned by the implementation of the Basel, Rotterdam, and Stockholm Conventions.

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Assessment of state of knowledge and gaps on sampling and analysis of POPs and POPs candidates in plastic pellets in major use sectors:

Part B: State of knowledge and gaps on sampling and analysis of POPs and POP candidates in major plastic use categories and related recycled pellets, including practical guidance to monitor POPs in plastics for a better control

31 May 2023

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Abbreviations and Acronyms

ABS	Acrylonitrile butadiene styrene
ASR	Automotive shredder residues
BFR	Brominated flame retardant
c-DecaBDE	Commercial Decabromodiphenyl ether
c-OctaBDE	Commercial Octabromodiphenyl ether
c-PentaBDE	Commercial Pentabromodiphenyl ether
CAS	Chemical Abstracts Service
CFCs	Chlorofluorocarbons
CPs	Chlorinated paraffins
C&D waste	Construction & demolition waste
DDT	Dichlorodiphenyltrichloroethane
decaBDE	Decabromodiphenyl ether; BDE-209
DEHP	Bis(2-ethylhexyl) phthalate
DIBP	Diisobutyl phthalate
DP	Dechlorane Plus
ECHA	European Chemical Agency
EEE	Electrical and electronic equipment
ELV	End-of-life vehicles
EPS	Expanded polystyrene
ESM	Environmentally sound management
FR	Flame retardant
GMP	Global Monitoring Plan
HBB	Hexabromobiphenyl
HBCD(D)	Hexabromocyclododecane
HD	High density
heptaBDE	Heptabromodiphenyl ether
hexaBDE	Hexabromodiphenyl ether
HIPS	High impact polystyrene
IPCP	International Panel on Chemical Pollution
LD	Low Density
LLDPE	Linear Low Density Polyethylene
MCCPs	Medium-chain chlorinated paraffins
MD	Medium density
MoE	Ministry of Environment
Mt	Megatonne; 1,000,000 tonne
NIAS	Non-intentionally added substances
NIP	National Implementation Plan
PA	Polyamide
PAHs	Polycyclic aromatic hydrocarbons
PBDDs	Polybrominated dibenzo-p-dioxins
PBDEs	Polybrominated diphenyl ethers
PBDFs	Polybrominated dibenzofurans
PC	Polycarbonate
PCBs	Polychlorinated biphenyls
PCDDs	Polychlorinated dibenzo-p-dioxins

PCDFs	Polychlorinated dibenzofurans
PCNs	Polychlorinated naphthalenes
PE	Polyethylene
PeCB	Pentachlorobenzene
PFASs	Per- and polyfluoroalkyl substances
PFCAs	Perfluorocarboxylic acids
PFHxS	Perfluorohexane sulfonic acid; Perfluorohexane sulfonate
PFOA	Perfluorooctanoic acid; Perfluorooctanoate
PFOS	Perfluorooctane sulfonic acid; Perfluorooctane sulfonate
PIR	Polyisocyanurate
PMMA	Polymethyl methacrylate
POPRC	POPs Review Committee
POPs	Persistent Organic Pollutants
PP	Polypropylene
ppm	Parts per million (mg/kg)
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
RoHS	Restriction of Hazardous Substances
SAN	Styrene acrylonitrile
SC	Stockholm Convention
SCCPs	Short-chain chlorinated paraffins
SCP	Sustainable Consumption and Production
SD	Sustainable Development
SFPs	Side-chain fluorinated polymers
t	Tonnes; metric tons
tetraBDE	Tetrabromodiphenyl ether
TOP	Total Oxidizable Precursor
UNEP	United Nations Environmental Programme
USEPA	United States Environmental Protection Agency
UVA	UV absorber
UV-328	2-(2H-Benzotriazol-2-yl)-4,6-di-tert-pentylphenol
WEEE	Waste electrical and electronic equipment
XPS	Extruded polystyrene
XRF	X-ray fluorescence

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1 Introduction to POPs in plastic and their monitoring

1.1 Background on POPs in plastic and major use sectors

A wide range of persistent organic pollutants (POPs) listed under the Stockholm Convention has been used or is used as plastic additives or is otherwise related to plastics (Abbasi *et al.* 2019; Chen *et al.* 2022; Weber 2022; for an overview see IPCP webinar Part I[1]). This includes various flame retardants (e.g., c-PentaBDE, c-OctaBDE, decaBDE, HBCD, Dechlorane Plus), primarily used in sectors with flammability standards, such as electrical and electronic equipment (EEE), the transport sector, the construction sector, and textiles (Table 1; Shaw *et al.* 2010; Charbonnet *et al.* 2020). These sectors represent major plastic uses (Figure 2; Figure 3).

The recently listed UV absorber (UVA) UV-328 (2-(2H-Benzotriazol-2-yl)-4,6-bis(2-methylbutan-2-yl)phenol) has also been used in the above-mentioned plastic-use sectors (Table 1) and in plastic packaging, including food packaging (Chang *et al.*, 2013; Zhang *et al.*, 2016; Rani *et al.*, 2017), which is the largest plastic-use sector (Figure 2; Figure 3). Furthermore, UV-328 has been detected as a plastic additive in agricultural plastics (Li *et al.* 2023a; Yao *et al.* 2023), another relevant plastic-use sector (Figure 3). Additionally, short-chain chlorinated paraffins (SCCPs) and the POP candidate medium-chain chlorinated paraffins (MCCPs)[2] appear to be present to some extent in the packaging sector, including some food packaging (Dong *et al.* 2020; Wang *et al.* 2022), and likely also in some agricultural plastic, particularly in PVC.

Therefore, several POPs are present to some extent in all major plastic-use sectors and require control in their use and recycling. It needs to be stressed that only a portion of the plastics in these uses contain POPs, and the majority of them do not, making them potentially recyclable from a POPs-perspective. However, plastics containing POPs are normally not labelled regarding their POP content. Therefore, monitoring of plastics in these sectors is necessary to detect POP contamination and determine their presence. It also involves verifying compliance with regulatory limits, such as the low POP content limits of the Basel Convention, thereby classifying if waste is a POP waste. Additionally, it is essential to monitor recycled plastics in these major POP-use sectors to ensure compliance with unintentional trace POP limits in products, as defined, e.g., in Annex I of the European POP directive (European Commission 2019). These POPs limits can be applied, for example, in the assessment of recyclates.

It is crucial to emphasize that plastics have the potential to act as sources of POPs and other chemicals of concern in the environment, releasing these substances at various stages throughout their life cycle on land (Weber *et al.* 2011; Brandsma *et al.* 2019; Oloruntoba *et al.* 2019, 2021; Li *et al.* 2023a; **Figure 1**) and in the oceans/water (Gallo *et al.* 2018). Consequently, monitoring and controlling POPs in plastics is of vital importance to achieve the goals of the Stockholm Convention and prevent environmental contamination by POPs.

Moreover, it is important to highlight that, in addition to POPs, other chemicals of concern can be relevant for the contamination of plastics and recyclates. However, their regulation is mostly regional or specific to certain countries (Aurisano *et al.* 2021a; Weber 2022), with the exemption of mercury substances and ODS, which are also regulated by Multilateral Environmental Agreements (MEAs).

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[1] IPCP webinar on monitoring POPs in Plastic Part I-B with presentations on individual POPs groups in plastic. https://www.youtube.com/watch?v=u5Ht6vg8Y04&t=9s

[2] MCCPs meet the Annex D criteria and is recommended for listing as a POP by the POPRC (UNEP 2023f)

Overall, out of the 3200 chemicals of potential concern, only 128 are regulated by chemical MEAs (BRS Secretariat 2023).

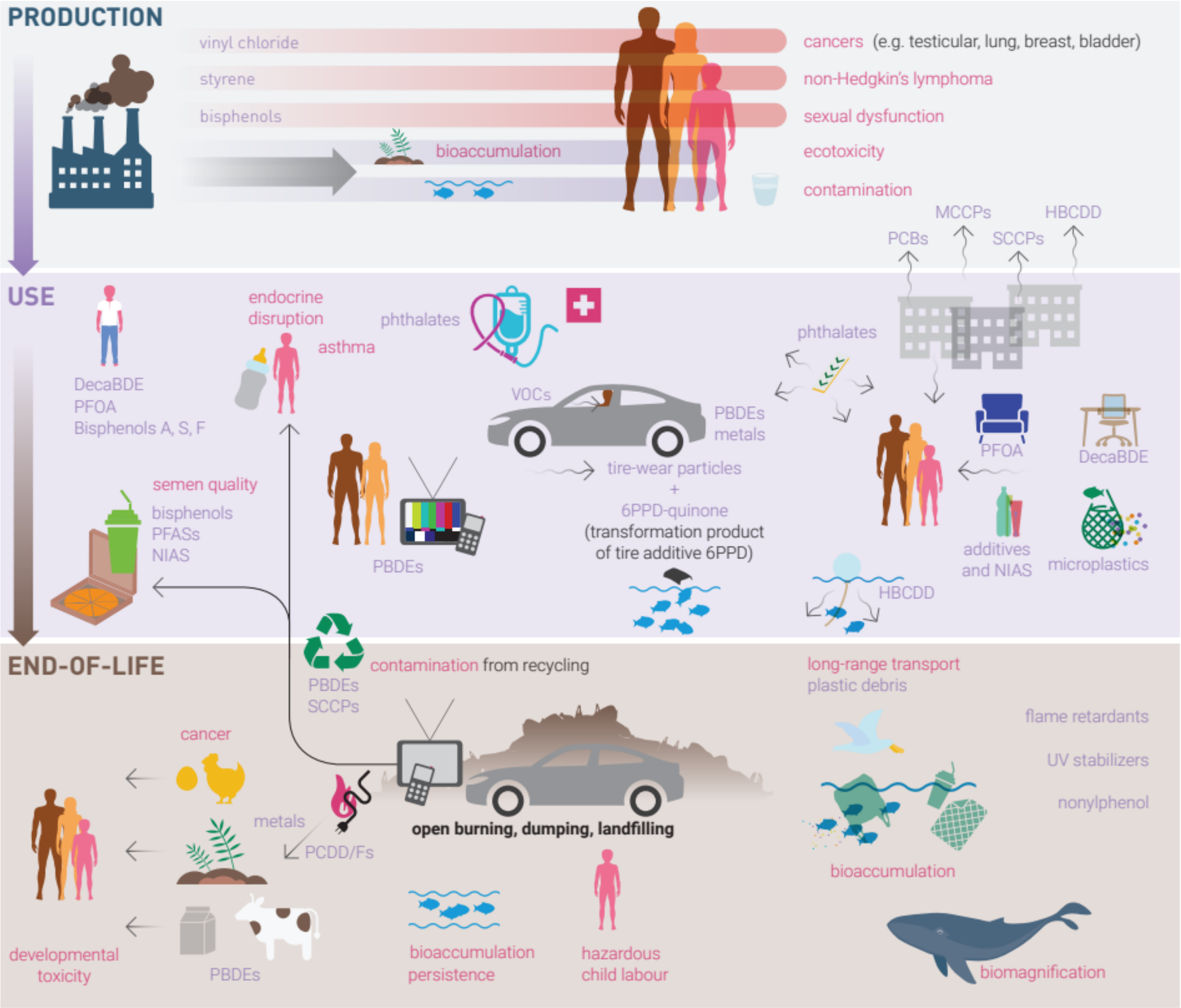

Figure 1: Major life cycle stages of plastic products where POPs and other chemicals of concern are released and contaminate the environment, biota and related food chains and humans (UNEP and BRS Secretariat 2023)

1.2 Objective

For some POPs a range of studies on their presence in the individual use sectors such as EEE/WEEE or the transport sector has been conducted. However, for other POPs, especially recently listed POPs (e.g. Dechlorane Plus and UV-328), there is hardly any available data on products, waste, or recycling.

The objective of this report is to give an overview on POPs used in plastic in the major use sectors as a basis for conducting well-informed monitoring of POPs in products in use, waste, and recycling phases. The document aims to inform on best practice monitoring studies and sampling approaches to investigate the presence of POPs in plastics in products, waste, and recycling. When standardized sampling methodologies are available, they are mentioned; otherwise, the need of robust methodologies is emphasized.

Additionally, knowledge gaps for different major use sectors of POPs in plastic are mentioned, where further or enhanced monitoring would be needed to better understand and control POPs in plastics.

This document provides experiences and approaches for monitoring plastic in EEE/WEEE in Chapter 2, monitoring plastic in the transport sector in Chapter 3, monitoring plastic in the construction sector in Chapter 4, and monitoring plastic in other use sectors in Chapter 0.

Table 1: POPs and POP candidates used as plastic additive or other plastic related use in three major use sectors (Abbasi *et al.* 2019; Weber 2022)

POP (main production and use period)[a]	**Building & Construction Sector**	**Electrical and electronic equipment**	**Transport Sector**	**Textiles**
c-PentaBDE (1970-2004)	Former use	Minor former use	Major former use	Former use
c-OctaBDE (1970-2004)	Minor former use	Major former use	Minor former use	Former use
decaBDE (since 1970s)	Major use	Major use	Major use	Major use
HBCD (1980 to 2021)	Major former use	Minor former use	Minor former use	Former use
HBB (1970 to 1976)	Not relevant	Former use	Former use	Not relevant
SCCP (Since 1930s)	Major use	Minor use	Minor use	Minor use
MCCP[2] (Since 1930s)	Major use	Use	Use	Minor use
PFOS (1960 to 2012)[b]	Former use	Former use	Former use	Former use
PFOA (since 1960s)	Use	Minor use in product	Use	Use
PFHxS (1960 to 2021)	Former use	Former use	Former use	
PCB (1940 to 1980)	Major former use	Major former use[c]	Former use[c]	Minor former use
PCN (1930 to 1970s)	Minor former use	Minor former use	Minor former use	
Lindane (1950 to 2000)[d]	Former use[d]	Minor use[d]	Not relevant	Minor former use
Mirex (1950 to 2000)	Former use	Former use	Former use	
Dechlorane Plus (DP)	Use	Major use	Major use	Use
UV-328	Major use	Major use	Major use	Use

[a] Main period for production and use in these sectors;

[b] Major production/use stopped 2002 by 3M; in the first list of exemptions the use in coatings of carpets, textile and paper was included which stopped since largely alternatives have been used (UNEP 2012).

[c] Considering also PCB containing capacitors which during shredding get crushed and contaminate shredder waste of electronics or vehicles including plastics.

[d] The use of lindane in plastics in e.g. cables was a minor use (Ulman 1972; Vijgen et al. 2022).

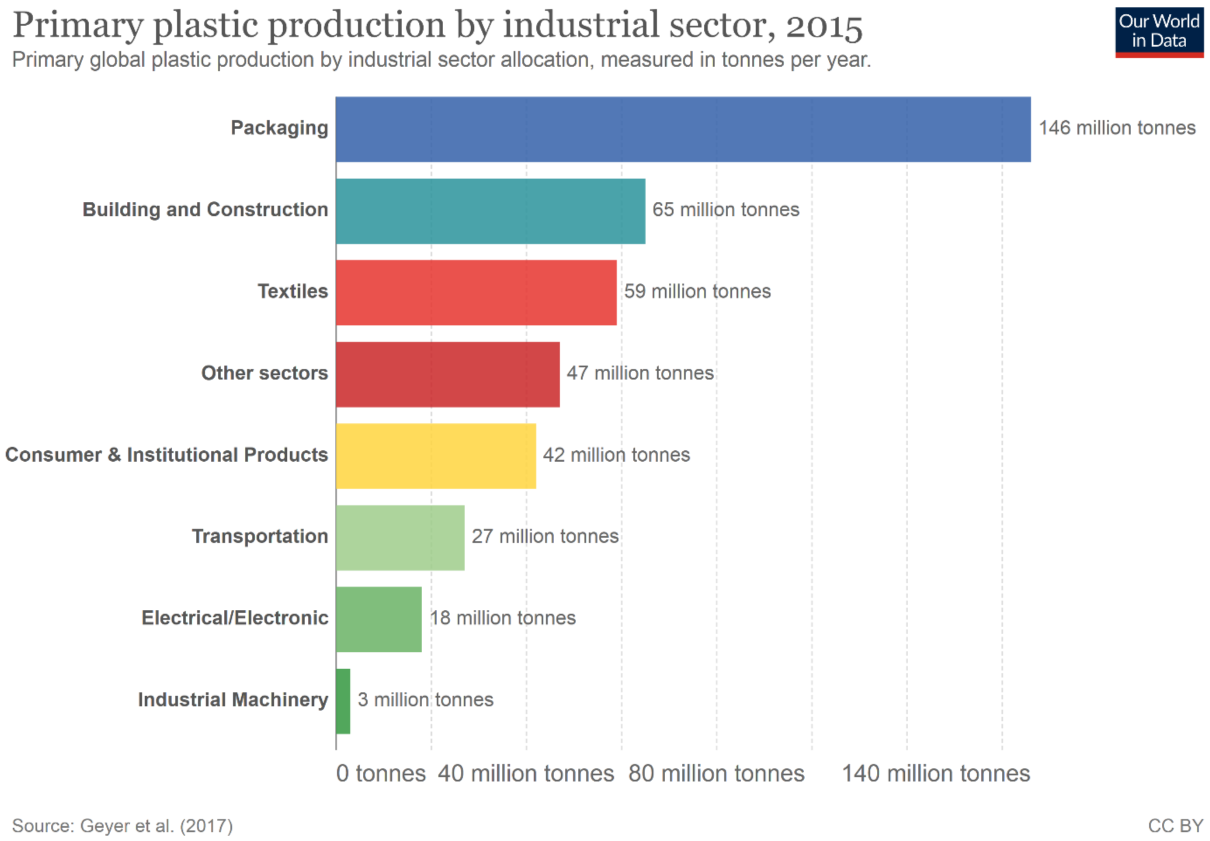

Figure 2: Global primary plastic production in the main use sectors 2015 (World in Data based on Geyer *et al.* 2017)

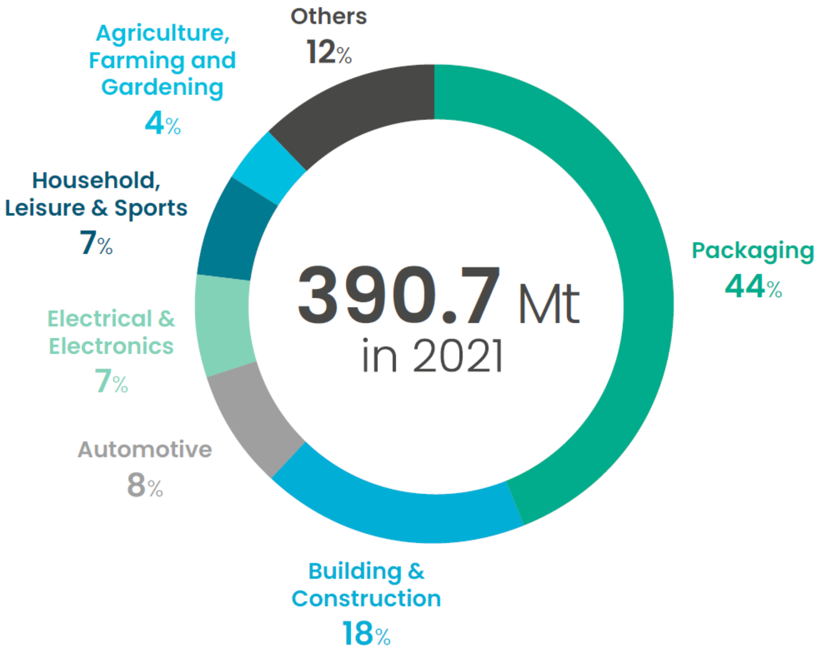

Figure 3: Global plastic production and share of the major plastic use sectors in 2021 (Sources: Conversio Market & Strategy GmbH; Plastics Europe 2022a)

1.3 Assessment in the life cycle of products and plastic

The objective of analyzing POPs in plastics throughout their life cycle are important to:

- Identify sources and pathways through which POPs can be released;
- Understand migration of additives from plastics directly to humans, release indoor or leaching to the environment.
- Assess human exposure by comparing levels with the guidelines set forth by the Basel Convention;
- Guide waste management practices by evaluating their suitability for recycling, or if they should be treated as special waste;
- Determine levels in recycled plastics for risk/exposure assessment and compliance with regulations.

The assessment of POPs in plastic can be carried out according to the life cycle: in the production of plastic products, assessment of new products in the market or in imports, in products/sectors in current use, and in end of life, including recycling (see, e.g., Stockholm Convention inventory guidance for SCCPs (UNEP 2019) or PBDEs (UNEP 2021a)). The release from the use phase is relevant for all regions while the release from the end of life phase is particularly relevant in low and low income countries with frequent open burning and dumping of waste and associated releases (Figure 1; Babayemi *et al.* 2015, 2019; UNEP and BRS Secretariat 2023).

For POPs currently produced and used as plastic additives, the assessment of the primary plastic producers can be relevant. For example, monitoring of SCCPs and MCCPs[2] around a PVC production plant in China showed similar contamination levels compared to chlorinated paraffins (CP) production sites (Li *et al.* 2023b).

In the current report, monitoring studies and strategies, as well as knowledge gaps, are described for the major polymer use sectors containing POPs as plastic additives and other plastic-related POPs (see Table 1). Robust monitoring data and approximate usage breakdowns within major plastic use sectors have been published for certain POPs like PBDEs (see Table 2; Abbasi *et al.* 2019). For a few POPs also a particular regional use is known such as that 90% of c-PentaBDE has been used in the USA with associated high levels in human milk in the USA and neighbouring countries compared to other regions (UNEP 2013; Charbonnet *et al.* 2020). For HBCD it is known that ~90% has been used in EPS/XPS in insulation in construction and less than 10% in textiles with minor uses in plastics in electronics and vehicles (UNEP 2021b). However, for other POPs, similar information concerning their major use sectors or specific use in regions is currently lacking.

Table 2. Percentage of commercial PBDEs in major uses and average lifespan of product type (Abassi *et al.* 2019 with additions)

Use area	**c-PentaBDE**	**c-OctaBDE**	**c-DecaBDE**	**Lifespan*[years]**
Electronics	10%	40%	30%	7 – 20*
Foam & carpet	50%	15%	25%	10
Construction	20%	25%	20%	30 – 50
Transportation	15%	15%	15%	15 – 35*
Textile	5%	5%	15%	10

*the longer lifespan for vehicles or electronics is prevalent in developing countries

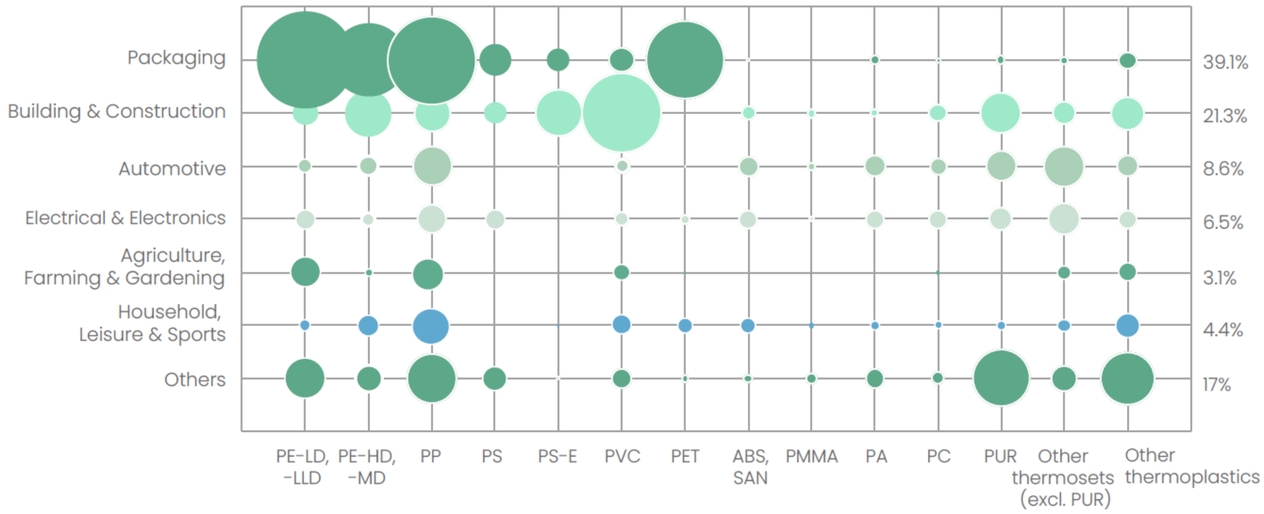

Figure 4: Plastic type and application based on the demand of European plastics converters (Source: Conversio Market & Strategy GmbH; Plastics Europe 2022a)

1.4 Step by step approach on monitoring POPs in plastic

To determine the occurrence and quantities of POPs in different products containing plastic, including consumer products, the Stockholm Convention recommends a "5-Step Approach" for monitoring POPs in products and recycling (UNEP 2021c). Elements of this 5-step approach can be selected as appropriate for monitoring campaigns in plastic use sectors. An introduction into the 5-step approach is available in the webinars from the International Panel on Chemical Pollution (IPCP) in the frame of the UNEP GMP project[3]. Additionally, an overview on practical monitoring POPs in plastic is given in another lecture in this IPCP webinar series[4.]

1.4.1 Step 1: Survey of products and recycling streams containing POPs

Before collecting samples, a survey should be conducted to determine which products possibly contain or have been contaminated with POPs. Furthermore, recyclates potentially contaminated by POPs may contaminate new products and should be assessed for the presence of POPs. Sample candidates can be identified from the list provided in Annex 1 of the UNEP guidance on monitoring POPs in products for individual POPs (UNEP 2021c; see also IPCP webinar[3]). If access is readily available, the team conducting the study may collect samples. Relevant stakeholders might be contacted for support, input, and samples. These stakeholders might include industries producing or using the chemicals or products, as well as competent authorities overseeing industries, consumer market, or customs (UNEP 2021c).

1.4.2 Step 2: Sample collection

1.4.2.1 Standard sampling procedures and protocol

Robust sampling procedures should be established and agreed upon before starting a sampling campaign. Sampling should comply with national legislation, where it exists, or with international

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[3] IPCP webinar on monitoring POPs in Plastic Part 2; Presentation "UNEP Guidance POP monitoring Part I" Weber R from 0:04:19 on (https://www.youtube.com/watch?v=WOHifcF71Xo&t=3s) & IPCP webinar on monitoring POPs in Plastic Part 3 (Weber R) from 1:59:45 on (https://www.youtube.com/watch?v=hcjIe6QfUE0&t=21s)

[4] IPCP webinar on monitoring POPs in Plastic Part 2; Presentation "Sampling of POPs in plastic" Weber R from 0:24:43 on (https://www.youtube.com/watch?v=WOHifcF71Xo&t=3s)

regulations and standards. In cases where standard procedures do not exist, all steps of the sampling procedure should be documented, including storage and shipment to a laboratory capable and possibly accredited for measuring the POPs of interest or for performing an adequate analysis of the respective sample and selected POPs.

The sampling documentation should include (UNEP 2021c):

- The type of sample;
- The location and date of sampling;
- Any relevant information about the sample (e.g., year of manufacture, country of manufacture, polymer type if relevant);
- A picture of each sample;
- If the products consist of multiple components, specify which component was sampled.

1.4.2.2 Representative sampling from products, mixed waste, or recyclates containing POPs

In a circular economy, waste becomes resource and different methods are established to produce recyclates. POPs are not evenly distributed in individual equipment; rather only a (small) share of equipment contain POPs as additives (see Section 2.3.1.1 and 2.3.1.2) and, in an equipment, often only a few plastic parts might be flame retarded (see Section 2.3.1.2). Therefore, plastic shredder also contains normally only a (small) share of POP-containing plastic particles, but these particles can contain up to 25% POP additive, enough that a plastic fraction might exceed regulatory limits. Therefore, proper sampling of POPs in waste (e.g., plastics, other polymers, rubber, or textiles) takes into account the following interrelated considerations (Vencovsky *et al.* 2021; Box 1):

- The distribution of the concentrations of POPs in waste;
- The statistical background of the determination of the size of a representative sample;
- The chemical characterization of particles and samples by field and laboratory methods.

Box 1: Sampling volume of shreds/particles from waste or recycling depending of POPs frequency in shreds/particles (UNEP 2021c)

In mixed plastic shredder waste, such as from e-waste or end-of-life vehicles, the distribution of concentrations of additives in plastic shredder particles is skewed by large values in often only a few individual plastic particles and is not Gaussian (normal) distributed. The 99th – 99.9th centile fractions of particles ranked by increasing concentration are typically much more concentrated than in classical normal distributions. The median (the concentration of the 50th centile of particles ranked by increasing concentration) is often 10-20 times smaller than the mean concentration, while they are equal in a normal distribution. These populations are best described by considering all of the following concentrations: the median, mean, and the last centiles. The confidence interval of the mean (typically two or three times the standard deviation) does not enclose the 95th or 99th centile of the population as is the case with a normal distribution, because the standard deviation is more than double or triple the mean. The concentrations of POP-BFRs decrease over time along with related modification of distribution of POP-containing plastic particles, due to the progressing substitution of regulated substances with others.

The high centiles, which account for a large part of the POP content in waste, must be present in a representative sample and any sub-samples to reliably determine the mean content of the relevant POPs. The sample, which is a smaller portion of a batch, must therefore contain enough particles to include the rare particles with the same frequency as they are present in the whole batch. The size of a representative sample is expressed as the number of particles ‘n’. It has been demonstrated that a representative sample from a batch must contain 100 particles of interest (the critical particles of the last centiles) to have a coefficient of variation of repeated measurements of 10%, and a 95% confidence interval of repeated measurements of 20%. As ‘p’ is the frequency of rare particles, it follows that the number of these particles in a representative sample is n*p = 100, and that n = (100/p) parts or shreds. This formula is very useful in practice: once p is known or estimated, the number of particles that a representative sample must contain can be determined. Two types of rare particles can be defined: 1) ‘rare particles with regard to concentration’ can be defined as particles with a concentration greater than any given concentration of interest; 2) ‘rare particles with regard to size’ can be defined as particles with a size range less frequently present in the particle size distribution. The resulting size of a representative sample will be large if the batch contains only a few concentrated particles but can be smaller if the fraction of particles with a concentration greater than a concentration limit is higher and known.

When p is known (typically in more homogeneous waste), n is calculated as 100/p. For instance, if p > 0.1 (as in the case of the highly brominated plastic fraction of separately collected fluorescent lamps), n = 100/0.1 = 1,000. If a single post-shredder particle weighs two grams, a representative sample would weigh 2 kg.

When p is not known (as in mixed waste), it can be assigned a value of 0.001 (CEN TR 15310-1), or it can be estimated for specific POPs by calculating the ratio of their concentration limits (CLs) that must not be exceeded for regulatory or quality compliance and their functional concentrations (FCs) in products: p = CL/FC38,39. This is simply the fraction of POP-containing particles that must not be exceeded in order for the whole batch not to exceed the CL. For PBDEs with a hypothetical CL of 200 mg/kg, p = 200 mg/kg / 180,000 mg/kg ≈ 0.001. This value is probably reached for decaBDE in the low-density sorted fraction of shredded end-of-life vehicles and large household electrical appliances. If p ≈ 0.001, n ≈ 100/0.001 ≈ 100 000, and if one particle weighs 10 grams, a representative sample would weigh ≈ 1 tonne. For a CL of 100 mg/kg for HBCDD in expanded polystyrene EPS and extruded polystyrene XPS, p = 100 mg/kg / 40 000 mg/kg = 0.0025, and a representative sample of mixed packaging waste with unknown frequency of parts/shreds with HBCDD should have n = 100/0.0025 = 40 000 parts/shreds. This number can be reduced to some extent if the batch of non-mixed waste is homogeneous, such as uniform external, floor, or roof insulation of individual parts of a building. For a SCCPs CL of 420 mg/kg, in unknown mixed waste, p = 420 mg/kg / 30,000 mg/kg = 0.014, and n = 100/0.014 ≈ 7,000; in homogeneous waste from one known product (e.g. old underground conveyor belts), the sample size can be significantly reduced.

One or two steps of size reduction, mixing, and subsampling are necessary to produce a laboratory sample of one to several dozen kg containing for instance 100,000 particles. In the laboratory, other similar operations of size reduction (< 0.5 mm), mixing and subsampling are necessary to produce the test portion of approximately 2 grams (containing approximately 100,000 spherical particles with size < 0.3 mm) that will be extracted and quantified.

1.4.3 Step 3: Pre-screening of samples during sampling or in the laboratory and selection

Products can be screened with different techniques for the presence of fluorine, bromine, or chlorine during sampling in the field or in the laboratory which gives an indication of possible POP content and can reduce instrumental analysis (UNEP 2021c). The tests in the laboratory are usually more sensitive compared to those using portable equipment in the field. A commonly used technology for this purpose is X-ray fluorescence (XRF) spectroscopy, which allows for the screening of halogens or other elements a preselection of samples (Gallen *et al.* 2014; Kajiwara *et al.* 2014; Sindiku *et al.* 2015; UNEP 2021c).

Additionally, some screening methods in the laboratory have been developed for determining the presence of target chemicals in a sample, including the DART method described for PFOS and other PFASs and the pyrolysis GC/MS method for screening PBDEs/BFRs or SCCP/MCCPs[2] (UNEP 2021c).

It is important to ensure that the detection limit of the screening method used is more sensitive than the limit set by the legislation for that chemical.

Additional complexity stems from the fact that the available field screening methods measure the total elemental concentration (e.g., bromine, chlorine, or fluorine) rather than individual substances, and that the sorting methods for plastic are based on solid or atomic density measurements. This is particularly pertinent to regulated POP-BFRs in plastic which have been progressively substituted with other brominated and dense substances in new products for some time, thus plastic waste now contains both POP-BFRs and a larger share of non-regulated BFRs. Therefore, there is not necessarily a direct relationship between bromine levels and the concentration of regulated POP-BFRs (Hennebert 2021; Kajiwara *et al.* 2023). The same principle applies to fluorine and listed POPs PFASs.

Step 4 involves quantification through instrumental analysis, followed by Step 5 which includes documentation. These procedures are detailed in the Stockholm Convention guidance on monitoring POPs in products and recycling (UNEP 2021c).

1.5 Background and steps of plastic waste management and recycling

For assessing POPs in plastic products and recycling, it is useful to understand the fundamentals of plastic recycling. Plastics are partly recycled from major plastic use sectors which contain POPs, such as electrical and electronic equipment (EEE) and related waste (WEEE), the transport sector, and buildings and construction sector. These are the major sectors where flame retardants listed as POPs were and partly are still used. In these three sectors, plastics face similar challenges related to the presence of multiple types of polymer resins, hazardous legacy additives, and different fractions for collection and sorting. Some plastics in these waste streams contain regulated hazardous additives, POPs or other chemicals of concern, which are an obstacle in recycling. Table 3 lists the most abundant polymer types in these three waste streams and their most prominent waste management related issues including problematic additives (UNEP and BRS Secretariat 2023).

Table 3: Overview of major mixed plastic waste streams, plastic types and major waste related management issues including hazardous additives (UNEP and BRS Secretariat 2023)

Waste stream	Polymer	Major waste management related issues
WEEE	PP	Often filled with talcum, increasing density and hindering separation from ABS and PS. Blends with PE coexist in recycled PP fractions.
	ABS	ABS from specific applications may contain BFRs, some of which are listed as POPs (PBDE, HBCDD, HBB) or may define waste as hazardous (TBBPA > 0.25%).
	PS / HIPS	PS / HIPS from specific applications may contain BFRs, some of which are listed as POPs today (PBDE, HBCDD).
	PC/ABS	Often separated with a heavy fraction from bulk ABS, PS, and PS fractions by density separation. Needs effective separation from other polymers, as contaminations higher than 1.5 % may deteriorate qualities. Market segment of recycled PC/ABS requests high quality standards.
	PVC	May contain REACH listed phthalates, POPs (SCCPs); traces of PVC in other target fractions deteriorate qualities, including thermal recovery.
ELV	PP	Often filled with talcum or glass fibers, increasing density and hindering separation from ABS and PS. Blends with PE coexist in recycled PP fractions.
	ABS	Difficult to separate from PP(T), often used with metal plating.
	PA	Often used together with glass or carbon fibers. Not a standard collection stream.
	PVC	May contain REACH listed phthalates and Stockholm Convention listed SCCPs. Traces of PVC in other target fractions deteriorate qualities.

	PU	Not a standard collection stream. Not recyclable by remelting, requires chemical recycling.
	PET fibers	Not a standard collection stream. Used as composite with other fibers and coatings.
	PC	Not a standard collection stream. Used in multicomponent parts like headlights, with or without metal plating.
Construction	PE / PE-X	Not a standard collection stream. PE and PE-X are not separated, PE-X cannot be re-melted.
	PVC-soft	Used in flooring and cable; may contain REACH listed phthalates and Stockholm Convention listed SCCPs; traces of PVC in other fractions deteriorate qualities.
	EPS	Contains HBCDD; low density hampers collection and incineration.
	PVC-hard	Used in window frames and pipes. May contain lead and cadmium stabilizers.
	PU	Not a standard collection stream. May contain BFRs; not recyclable by remelting, requires chemical recycling.

Of the 7 billion tonnes of plastic waste generated globally in the past, less than 10% has been recycled (Geyer 2020) and the largest share of plastic wastes ended up in landfills and dumpsites (Market & Strategy GmbH Conversio 2019; UNEP and BRS Secretariat 2023). For the recycling of plastic, the plastic in products like WEEE or ELV is normally shredded and separated in different plastic types since only relatively clean plastic fractions of the same plastic type can be recycled into new products. It is important to distinguish between thermoplastics (PET, PA, PUR, PE, PP, PS, ABS) and thermosets (e.g., PUR, epoxy resin, melamine resin). While thermoplastics can be re-melted and are applicable to primary or secondary material recycling processes (Grigore 2017), thermosets are not or have limited suitability for mechanical recycling (UNEP and BRS Secretariat 2023). Plastics can be recycled by various methods, depending on the type of plastic and the recycling facility, including mechanical recycling, chemical, and thermal options (Schwarz *et al.* 2021). Mechanical recycling involves processing plastics waste (particularly thermoplastics) into secondary raw materials or products without significantly changing the material's chemical structure. If POPs are present in the waste plastic and if they are not separated, then they are transferred to the recyclates and new products.

The common steps for mechanical recycling include collection, sorting and separation, size reduction, washing, and extrusion (**Figure 5**). In the literature there are different terms for the individual steps. Nevertheless, a simplified scheme of the plastics recycling process is represented below and in the next subchapters, its process steps will be discussed in more detail.

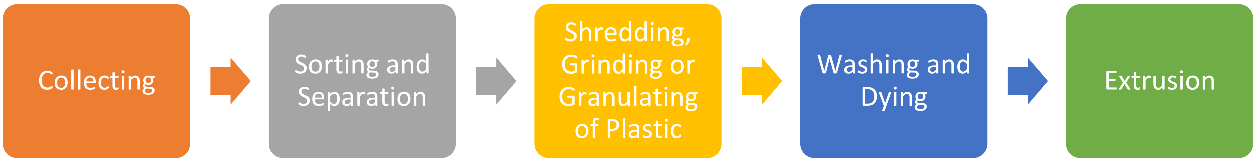

Figure 5: Simplified diagram of the common process steps of mechanical recycling

1.5.1 Collection

Collection as the first stage in the plastic waste recycling process, has emerged as an important challenge. Effective collection from separate and mixed waste streams positively impacts their quality and suitability for downstream pre-treatment, sorting, and recovery operations. A harmonized waste management collection process is pivotal for effective waste collection. Currently, over 50% of all post-consumer plastic waste is collected via different mixed waste collection schemes for households as well as industrial, commercial, and agricultural sectors (Plastic Europe 2022). Generally, local authorities, either directly or through waste management contractors, are responsible for collection. The waste is then transported to recovery facilities or recycling centres for sorting (see Section 1.5.2). Effective plastic collection is crucial for smooth operation of the recycling system. The more recyclable plastic collected, the greater the availability of material for reprocessing and utilization in the production of new products (Plastics Europe 2022). In some cases, plastics may be sorted from non-plastics before being collected, or they may be separated from a mixed waste stream after collection.

1.5.2 Sorting and separation

The second stage is to separate plastic from non-plastics materials and, whenever possible and practical, sort them into single plastic types (UNEP 2023a). Separating the plastic components into single plastic material streams requires considerable expertise, unless the plastic components are clearly marked with the plastic type (e.g., PE, PP, see more in UNEP 2023a).

A wide range of technologies is currently used for waste pre-treatment and sorting, ranging from manual dismantling and picking to automated processes such as shredding, sieving, air or liquid density separation, magnetic separation, and highly sophisticated spectrophotometric sorting technologies such as UV/VIS (ultraviolet/visible), NIR (near infrared), or laser/optical sorting. More recently, digital watermark, robotic, and bar-coding technologies[5] have been introduced (UNEP 2023a). At the end of the separation process, ESM of the separated waste streams is critical to minimize environmental impact. In this step POPs containing plastic can be separated with different technologies (UNEP 2021d). Certain plastic fractions within complex waste streams are not suitable or easily sorted, or may not be available in sufficient amounts to make mechanical recycling a viable solution, from both an economic and environmental perspective (UNEP 2023a).

1.5.3 Size reduction: shredding, grinding, or granulating of plastic (resizing)

Most plastic products require size reduction for cost-effective transportation or further processing. Size reduction is a necessary process for plastic waste recycling, providing a controlled particle size range for the downstream sorting process and enabling liberation of different material types from complex waste components (e.g., HDPE screw-caps from PET beverage bottles; brass screw inserts from electronics casings) (UNEP 2023a).

For size reduction into small flakes, technologies like shredding, grinding, crushing, cutting, or granulating technologies can be used. The chosen method depends on the input size of the waste stream, the size and thickness of the items, and the toughness of the plastic type as well as the plastic waste format (e.g., solid mouldings, flexible films, woven textiles etc) (UNEP 2023a)

The most frequently used technology for plastic materials is shredders, which reduce the products to a particular size. Shredders are also used for shredding WEEE or ELVs. (UNEP 2023a). Flakes/shreds pass through a series of separation processes (see also Section 1.5.2) based on their physical properties (e.g., density, colour, composition). POPs containing plastic which impact the density can be separated in the density separation.

1.5.4 Washing and drying of plastic

The aim of washing is to remove adhesives, residual waste left in containers, food waste, and labels. It is important that these contaminants are removed, and the plastic is as clean as possible, thereby

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[5] https://legacy.plasticseurope.org/en/focus-areas/circular-economy/zero-plastics-landfill/waste-collection-pre-treatment-and-sorting

improving the quality of the recyclates before they proceed to the next stage. During the washing process, the plastic may undergo various washing methods (manual or machine cleaning, wet or dry friction methods) depending on the contamination and processors. Drying is used to remove surface moisture after wet washing (UNEP 2023a).

The washing and drying step can occur before or after the size reduction process depending on the type of plastic waste. For example, in the PET bottle recycling process, the washing step occurs after the size reduction process, whereas for EPS fish boxes, the washing process takes place before the size reduction process. Sometimes, there may also be a pre-washing step, for instance, for LDPE films used in agriculture and industry (UNEP 2023a).

1.5.5 Extrusion and pelletizing

The plastic flakes are melted to enable the formation of solid raw materials or shaped and profiled products. At this stage, in some processes, plastic flakes could be sorted again and controlled before being sent for extrusion (Plastic Europe 2022).

There are several processes available to produce pellets from recycled plastics. Plastic extrusion is the most commonly used method for the final stages of plastic recycling. Extrusion is used to melt plastic flakes in an electrically heated screw-barrel with a homogenous polymer compound and consistent material properties (UNEP 2023a). Plastics flakes are finally converted into homogenous pellets ready for use in the manufacturing of new products. Blending, mixing, vapour venting and melt-filtration can be applied to create a homogenous and uniform polymer material. Additionally, other additives can be added to the in feed mix to create a specific plastic compound grade (UNEP 2023a).

The molten output flow leaving the extruder is normally shaped into the form of filament strands by a multi-port die-head, and then cutting or ‘chipping’ is applied to create small (circa 2 to 3 mm) solid plastic pellets (UNEP 2023a). Alternatively, thermal extrusion equipment can be fitted with direct shape-forming die heads to make continuous shaped profiles (e.g., PVC window frames) or wide sheets to create rolls of thin plastic suitable for onward shape forming.

In many countries, this thermal re-processing stage marks the ‘end-of-waste’ point and the creation of recycled plastic ‘product’ – (often called ‘recyclate’ or secondary raw material).

Plastic flakes are sometimes directly melted to produce new plastic products without pelletizing step.

2 Monitoring and controlling POPs in EEE and related waste (WEEE) plastic

2.1 Introduction to plastics and POPs in electrical and electronic equipment (EEE) and related pollution

2.1.1 Plastic in EEE and WEEE

In 2019, 53.6 million tonnes of waste electrical and electronic equipment (WEEE; e-waste) were generated containing more than 10 million tonnes of plastic which need to be managed in an environmentally sound manner (Forti *et al.* 2020; UNEP 2021a,d). Plastics are present in virtually all EEE. They are commonly used in casings, frames, covers, and small parts of these devices. Various types of plastic are used (Figure 4, page 17), including ABS (acrylonitrile butadiene styrene), PS (polystyrene), and PP (polypropylene), which are common in the manufacturing of computer or televisions, for example. Additionally, many other types are used depending on the characteristics needed, as well as the plastic compounds.

The major amount of plastic is found in the following main EEE categories (see Table 4): Large household appliances (such as freezers, refrigerators, air conditioners, washing machines, dishwashers, clothes dryers, and cookers); small household appliances, which are portable or semi-portable machines designed to perform household task (for example, microwave ovens, toasters, humidifiers, and coffeemakers). Another major category is Information and Communication Technology (ICT) equipment, which includes computers and computer screens, copy/fax machines, scanners, and printers. Lastly, a final relevant category is consumer equipment, including TVs (both CRTs and flat screens), radios, video cameras, and cameras.

Table 4: EEE categories and amount of plastic in the respective categories in EU (UNEP 2021a)

WEEE Category/Product Category		Plastic share [in % by weight]	Annual plastic flow [in t/year]
1	Large household appliances without cooling appliances	19%	500,500
1	Cooling and freezing appliances	28%	473,100
2	Small household appliances	37%	369,400
3	ICT equipment without screens	42%	317,600
3	Computer screens (CRT and flat)	20%	156,100
4	Consumer equipment w/o screens	24%	180,900
4	TV screens (CRT and flat)	20%	200,100
5	Lighting equipment – Lamps	3%	7,300
6	Electrical and electronic tools	11%	37,800
7	Toys, leisure and sports equipment	73%	7,600
8	Medical devices	3%	400
9	Monitoring and control instruments	60%	11,900
10	Automatic dispensers	20%	3,500
	Total amount	**Average 20%**	**2,266,100**

2.1.2 POPs in plastics in EEE and WEEE

Plastic fractions from WEEE are the largest and most relevant products and material streams contaminated with PBDEs. Considering the need to move towards a more circular economy for electronics (UNEP 2021e), end-of-life management and recycling require considerable improvements, including the recycling of WEEE plastic. For the recycling and recovery of plastic and other materials from WEEE, it needs to be considered that a share of the WEEE plastic contains POPs that are still being produced and used (see Table 1; Table 5) and also some legacy POPs whose production has ceased but are present in EEE that is in use (see Table 1: Table 5). Table 5 provides an overview of POPs in EEE, their major or minor use, and the period of use. While this is known, the detailed presence and use of POPs in different EEE/WEEE categories and different EEE parts are less known and have only been investigated in some regions or countries (Wäger *et al.* 2010; Sindiku *et al.* 2015; Hennebert and Filella 2018). Furthermore, the amount of POPs in plastic waste changes over time depending on the time of production/use of a certain POP (see Figure 6) and the service life of a certain product category (Table 2).

Also, the use of different POPs has been specific to different plastic types, such as the predominant use of c-PentaBDE in PUR foam, c-OctaBDE in ABS, HBCD in polystyrenes (EPS, XPS, and HIPS), or SCCP/MCCPs[2] in PVC and PUR spray foams (UNEP 2021a,b,c; Chen *et al.* 2021, 2022).

Table 5: POPs used in plastic in electrical and electronic equipment and period of use (Weber 2022)

POP	Application in EEE	Use period*
c-DecaBDE	Flame retardant with use in many plastic types in casings of EEE, cables, and other plastic parts in EEE	Current and former uses. Continued use is allowed for certain casings of electronics
c-OctaBDE (hexaBDE and heptaBDE)	Flame retardant with former use mainly in cathode ray tube casings in TV and computers, office equipment	Former use (1970 to 2004)
c-PentaBDE (tetraBDE/ pentaBDE)	Flame retardant in PVC cables, printed circuit boards, and PUR foam	Former use (1970 to 2004)
HBCD	Minor flame retardant used in HIPS in CRT casings and other HIPS plastic parts	Former use (1970 to 2013)
SCCP/MCCP[2]	Plasticizers and FR in cables and other PVC and rubber parts	Current and former uses. SCCP is exempted for use in PVC
PCBs and PCNs	Cables (PVC and others); (and capacitors);	Former use (PCBs 1950 to 1980s; PCNs 1930s to 1960s)
PFOA	Medical devices; nonintentional in fluoropolymers	Current and former uses
PFOS	Medical devices	Mainly before 2002
Dechlorane Plus	Flame retardant use for wire and printed circuit board housing, other plastics, and rubber parts	Former and current uses
UV-328	UV absorber in liquid crystal displays	Since 1970s

*EEE and plastics in EEE have a wide service life span of a few years (e.g. mobile phones) to some EEE with service life of more than 30 years

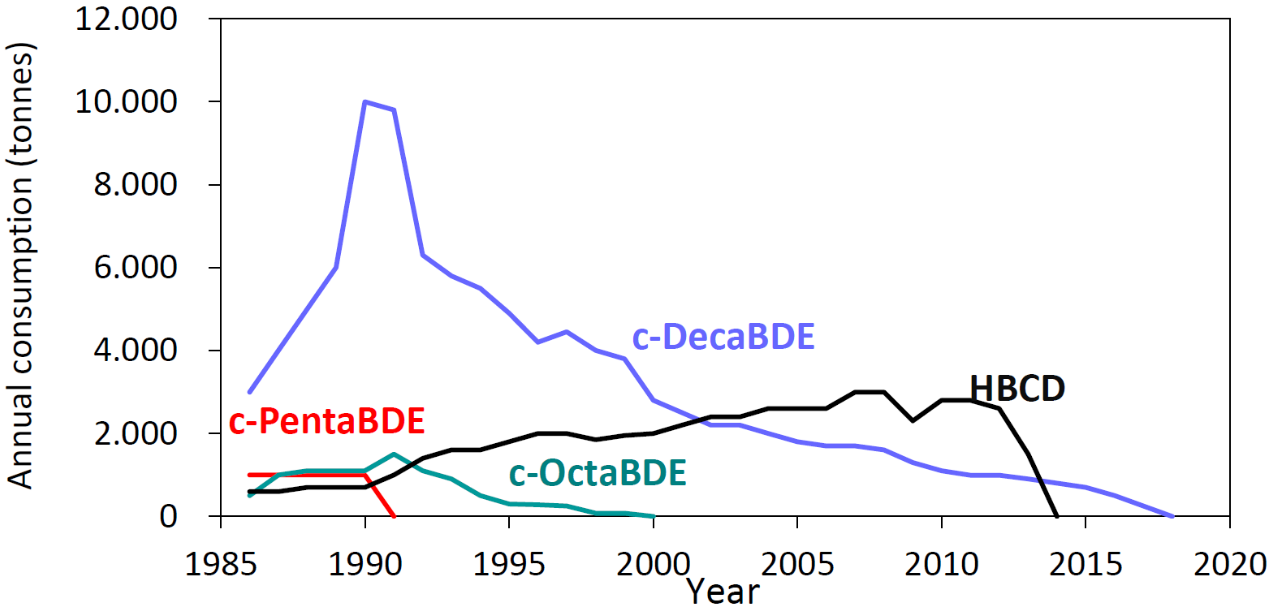

Figure 6: Time trend of the use of brominated POPs in production in Japan (Kajiwara 2020)

2.1.3 POPs contamination from plastics of EEE and WEEE

POPs are released along the life cycle of EEE/WEEE with related indoor contamination and pollution of the environment in particular if WEEE is not managed in an environmentally sound manner in end-of-life including open burning and disposal on dumpsites (Shaw et al. 2010; Weber et al. 2010).

While the quality and value of plastics in EEE may be high, recycling rates are low due to the complexity of the plastic mixtures in EEE, lack of infrastructure and knowledge, and the presence of legacy additives such as POPs in WEEE plastic (e.g. PBDEs) (UNEP 2021d). With the transition towards a more circular economy, it is expected that recycling of plastic from WEEE will increase. This is also happening in low-income countries, as documented in contemporary activities in countries where plastic pellets have been sampled (see Section 6.2.2 and e.g., the sampling report from Nigeria in, Annex 2). Detailed studies on WEEE plastic recycling documented that e. g. in the informal plastic recycling sector of India POPs are normally not separated in WEEE plastic recycling (Haarman and Gasser 2016). Also in the asssessment of this study in some South American countries, Nigeria, or Vietnam (Annexes in Section 8.1, 8.2 and 8.5) showed that POPs containing plastic are not considered for separation and management. This can also be seen in the monitoring of products like toys and food contact materials containing PBDEs (Chen *et al.* 2009; Puype *et al.* 2015; Kuang *et al.* 2018, Kajiwara *et al.* 2022) as well as a range of plastic pellets monitored within the UNEP GMP project (UNEP 2023d).

Used EEE and e-waste are partially exported from high-income countries to low- and middle-income countries, where frequently only the metals are recovered. The e-waste plastic is often treated by open burning to recover metals, releasing considerable amounts of POP additives and unintentional POPs including PCDD/PCDFs that contaminate the environment and the food chain (ILO 2012; Lebbie *et al.* 2021; Petrlik *et al.* 2022; **Figure 1**). Another large share of WEEE plastic end in landfills and dumpsites where they are a source of landfill/dumpsite fires with associated POP releases (Gullett et al. 2010; Babayemi *et al.* 2015, 2019, Pozo *et al.* 2023) and are also released in leachates and by evaporation contaminating the surrounding environment including food (Weber *et al.* 2010; Oloruntoba *et al.* 2019, 2021). Meanwhile, the largest share of WEEE in low- and middle-income countries also comes from domestic EEE, which has increased in the last decade in low- and middle-income countries and also needs environmentally sound management (ESM) (Forti *et al.* 2020).

Therefore the end-of-life management of POPs containing WEEE plastics in low- and middle income countries need significant improvement (UNEP and BRS Secretariat 2023; Petrlik et al. 2022).

2.2 Monitoring POPs in EEE on the market

POPs can be monitored in new EEE available in the market or in imports. A few systematic surveys have been conducted to examine brominated flame retardants (Bantelmann *et al.* 2010; Gallen *et al.* 2014). The use of flame retardants in EEE depends on flammability standards (Shaw *et al.* 2010; Charbonnet *et al.* 2020) and the type of electronic devices (Table 6). It is worth noting that flammability standards differ in different regions and can also change over time (Charbonnet *et al.* 2020). Besides, different EEE have different requirements for the flammability of their plastic components. EEE that generate heat often require more stringent flame retardation measures, while cooling and freezing appliances typically use fewer or no flame retardants in their plastic. This variation has been confirmed through assessments of plastic fraction and PBDE content in different categories of EEE. Notably, the highest levels of PBDEs were found in TV and computer cathode ray tubes (CRT) casings and flat screen TVs, while cooling/freezing appliances and washing machines exhibited low levels of PBDEs (Table 6).

It is important to highlight that similar studies are missing for other POP plastic additives such as Dechlorane Plus, UV-328, or SCCPs. These studies are necessary to comprehensively understand the presence of these chemicals in EEE.

Table 6: Listed PBDE content (hexa/heptaBDE and decaBDE) in total (mixed) polymer fractions of different WEEE in Europe (UNEP 2021a[6])

Category/Article		∑hexa/heptaBDE in plastic fractions [kg/tonne]* ($C_{hexa/heptaBDE;Polymer}$)			decaBDE in plastic fractions [kg/tonne] ($C_{decaBDE;Polymer}$)		
		Minimum	Maximum	**Mean**	Minimum	Maximum	**Mean**
1	Cooling/freezing appliances; washing machines			**<0.05**			**<0.05**
1	Heating appliances			**<0.05**			**0.8**
2	Small household appliances				<0.1	0.5	**0.17**
3	ICT equipm. w/o monitors	0.027	0.22	**0.12**	0.5	1.4	**0.8**
3	CRT monitor casings	0.08	5.7	**1.37**	0.5	7.8	**3.2**
4	Consumer equipment w/o monitors (1 composite sample)	-	-	**0.08**	0.7	0.9	**0.8**
4	TV CRT monitor casings	0.03	1.9	**0.47**	0.8	7.8	**4.4**
4	Flat screens TVs (LCD)	0.008	0.010	**0.009**	1.2	4.3	**2.75**

* RoHS limit for PBDEs is 1000 mg/kg or 1 kg/t. The Basel Convention provisional low POPs limit for PBDEs is currently 1000 mg/kg (1 kg/t) or 500 mg/kg (500 g/t) or 50 mg/kg (50 g/t)

2.2.1 Case study market survey Switzerland: Monitoring BFRs in polymers of electronics on the Swiss market

In the year 2000, the Swiss relevant authorities conducted a monitoring of brominated flame retardants in consumer products, which included electrical devices, building materials, and lighting equipment (Bantelmann *et al.* 2010). The aim of the survey was to evaluate the compliance of commercial products with the provisions of Swiss restrictions on BFRs: In Switzerland, the placing on the market and use of c-PentaBDE, c-OctaBDE, and PBBs as individual substances, as well as in preparations with contents of each of these BFRs equal to or exceeding 0.1% by mass, is prohibited. Placing on the market – but not the use – of products that contain these substances in concentrations equal to or exceeding 0.1% by mass is also banned.

Specific features of this best practice case study on PBDEs and other RoHS relevant substances in WEEE plastic are as follows:

- The study is a comprehensive market survey that follows a three-step approach to monitor brominated flame retardants in contemporary products (Bantelmann *et al.* 2010):
  - Screening of bromine/BFRs in products.
  - Analysis of the samples with bromine presence for prohibited PBDEs and PBB and commonly used flame retardants.
  - Scanning of samples with bromine presence where the target BFRs could not be detected, in search of unknown “novel” brominated flame retardants used as alternatives to the prohibited BFRs (Zennegg 2011)

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[6] Based on measurements in Europe Wäger *et al.* (2010); Hennebert and Filella (2018).

- The study gives insight into the BFRs used in electronic products imported to the European market. The study showed that the PBDE content in products sampled 2009/2010 on the Swiss (and likely European) market was already low.
    - Only 2 out of approximately 2000 samples contained c-OctaBDE above the 0.1% RoHS threshold.
    - 17 samples contained decaBDE above the RoHS threshold of 0.1%
- The study further gives an overview on other critical RoHS relevant pollutants, which is relevant today for many other regions with legislation similar to RoHS.

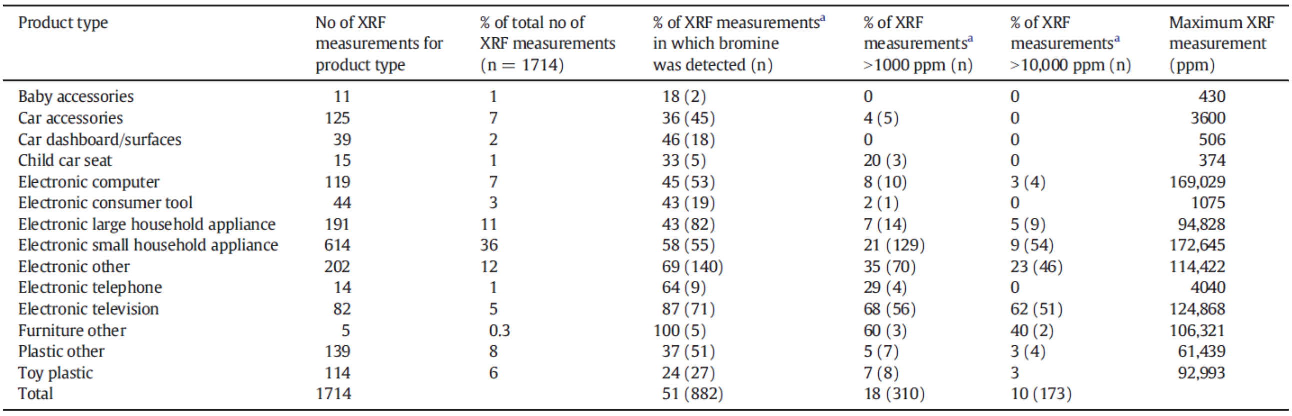
The results of the third screening level of unknown BFRs in the samples by the Swiss Federal Laboratories for Materials Science and Technology EMPA revealed that some of these samples contained, for example, hexabromobenzene (HBBz) or pentabromobenzene (PeBBz) (Zennegg 2011).

2.2.2 Case study market survey Australia: Monitoring BFRs in polymers of EEE and other consumer products

A three-tiered testing strategy comparing results from non-destructive testing (X-ray fluorescence (XRF)) (n = 1714, including more than 1200 EEE), a surface wipe test (n=137), and destructive chemical analysis (n = 48) was undertaken to systematically identify BFRs in a wide range of consumer products (Gallen *et al.* 2014).

XRF rapidly identified bromine in 92% of products, which were later confirmed to contain BFRs. Surface wipes tests of the products accurately identified c-OctaBDE congeners, decaBDE, and tetrabromobisphenol A (TBBPA) when confirmed by destructive chemical analysis (>75% accuracy). A promising relationship was observed between the amounts of BFRs detected in surface wipe tests and subsequently extracted plastics, allowing not only the identification of the types of BFRs present but also the estimation of their concentrations (Gallen *et al.* 2014). The study revealed that over 50% of the samples contained brominated flame retardants, but approximately 80% of these bromine-positive samples had bromine concentrations below 1%. Consequently, it was concluded that BFRs were not intentionally added but rather stemmed from the recycling of BFR containing plastic. Most products containing intentional added BFR (Bromine >1%) were EEE (Table 7).

Table 7: Summary of XRF bromine-screening of consumer products in Australia according to product type (Gallen *et al.* 2014)



Product type	No of XRF measurements for product type	% of total no of XRF measurements (n = 1714)	% of XRF measurements[a] in which bromine was detected (n)	% of XRF measurements[a] >1000 ppm (n)	% of XRF measurements[a] >10,000 ppm (n)	Maximum XRF measurement (ppm)
Baby accessories	11	1	18 (2)	0	0	430
Car accessories	125	7	36 (45)	4 (5)	0	3600
Car dashboard/surfaces	39	2	46 (18)	0	0	506
Child car seat	15	1	33 (5)	20 (3)	0	374
Electronic computer	119	7	45 (53)	8 (10)	3 (4)	169,029
Electronic consumer tool	44	3	43 (19)	2 (1)	0	1075
Electronic large household appliance	191	11	43 (82)	7 (14)	5 (9)	94,828
Electronic small household appliance	614	36	58 (55)	21 (129)	9 (54)	172,645
Electronic other	202	12	69 (140)	35 (70)	23 (46)	114,422
Electronic telephone	14	1	64 (9)	29 (4)	0	4040
Electronic television	82	5	87 (71)	68 (56)	62 (51)	124,868
Furniture other	5	0.3	100 (5)	60 (3)	40 (2)	106,321
Plastic other	139	8	37 (51)	5 (7)	3 (4)	61,439
Toy plastic	114	6	24 (27)	7 (8)	3	92,993
Total	1714		51 (882)	18 (310)	10 (173)	

[a] Total number of XRF measurements for product type.

2.3 Monitoring of POPs in plastic in WEEE and related control

In this section, the approach to monitoring individual WEEE, including case studies, is introduced in Section 2.3.1 and the monitoring of shredded WEEE plastic, also with case studies, is presented in Section 2.3.2.

Monitoring of POPs in e-waste plastic and e-waste recycling is needed to understand the presence of POPs in different WEEE categories and in different plastic parts in equipment. This knowledge is essential for establishing control and elimination strategies for POPs in e-waste recycling. While monitoring of plastic fractions from different WEEE categories provided valuable information about major PBDE-impacted WEEE plastics more than 10 years ago (Table 6; Wäger *et al.* 2010; Section 2.3.2), the screening of individual WEEE and plastic parts in WEEE on POPs content has only been investigated more recently (e.g. Sindiku *et al.* 2015, see also Section 2.3.1.2; Keeley-Lopez *et al.* 2020, see also Section 2.3.1.1).

2.3.1 Sampling and analysis of plastic from individual EEE/WEEE

For some purposes, monitoring individual electronic appliances is useful to get a detailed understanding of the use of POPs plastic additives in different EEE categories. This includes:

- The period during which individual POPs were used.
- The regional distribution of the use of POPs.
- Whether certain POPs use is associated with specific product types or particular companies.

If such a study is conducted, the following information should be recorded for each sample, if available:

- Producer and model name.
- Country of origin.
- Production year.
- Plastic parts which contained POPs (see, e.g., Keeley-Lopez *et al.* 2020).

This monitoring is particularly relevant for equipment with high use of flame retardants, such as TVs, computers, or heating appliances. Additionally, other important EEE categories with low average PBDE/BFR content (e.g., refrigerators, freezers, air conditioners) should be screened for flame retarded parts. Documentation of the share of bromine-positive samples and the percentage of bromine-positive samples containing restricted BFRs (PBDEs, HBCD, HBB) should be carried out.

The use of c-OctaBDE and c-PentaBDE stopped before 2005. The major use of c-DecaBDE was from the 1980s to 2008 (for Japan, see Figure 6) when decaBDE was finally restricted under the EU RoHS Directive. DecaBDE has been restricted in 2017 under the Stockholm Convention, but some use of decaBDE in EEE continues until now due to the exemptions granted by Stockholm Convention (UNEP 2021a). In addition, production of Dechlorane Plus and UV-328 continues, including some use in EEE.

2.3.1.1 Monitoring of PBDEs in individual plastic parts in individual EEE in the UK/Wales

POPs flame retardants, like PBDEs or Dechlorane Plus, are exclusively used in specific plastic parts in EEE that need to meet certain flammability standards. There is only one best practice study that screened individual plastic components in a wide range of WEEE for bromine and analysed them for PBDEs in bromine-positive samples (Keeley-Lopez *et al.* 2020). The study analysed items from four WEEE categories (large household appliances (LHA), small household appliances (SMW), cooling appliances, and displays) to determine if they contained PBDEs or other substances of concern and at what level.

A comprehensive sampling programme was conducted at nine WEEE processing facilities in England and Wales, and over 2,000 WEEE items were screened using X-ray fluorescence (XRF) to measure bromine concentration and preselect samples for subsequent chemical analysis (Keeley-Lopez *et al.* 2020). XRF screening provided detailed information about individual plastic parts and the proportion of plastic containing BFRs in different WEEE, with further confirmation analysis for PBDEs (Keeley-Lopez *et al.* 2020):

- Printed circuit boards: Partly contained PBDEs above the EU POP Regulation maximum concentration limit (MCL) of 1000 mg/kg for waste material. This limit corresponds to the highest provisional low POP content set by the Basel Convention (UNEP 2023b).
- Cables: PBDEs were found at levels exceeding the MCL in some internal and external cables of various WEEE items.
- CRT displays: PBDEs were found at levels above the Basel Convention low POP content in some CRT plastic casings (see detailed study in 2.3.1.2 below)
- Flat panel displays: PBDEs were found at levels above Basel Convention low POP content in the plastic casings of some flat panel displays.
- Fridges and refrigerators: Only some small plastic components surrounding the fridge compressor exceeded the Basel Convention low POP content for PBDEs. While all large plastic parts, such as casings, doors, and interior plastics, did not contain PBDEs/BFRs.
- Washing machines, tumble driers, and dishwashers: Only some small plastic components surrounding the compressor were found to exceed the Basel Convention low POP content. While the large plastic parts of the casings did not contain PBDEs.

Similar studies might be replicated in other countries/regions and include the analysis of other POPs, in particular, recently listed POPs, such as Dechlorane Plus, SCCPs/MCCPs[2], and UV-328.

2.3.1.2 Practical case study on monitoring of CRT casings of TVs and computers in Nigeria

A study was conducted in Nigeria, with the aim of assessing the period of use of PBDEs in cathode ray tubes (CRT) plastic casings. This study was initiated through collaboration between the BRS Secretariat, the Basel Convention Regional Center, and the Fraunhofer Institute in Germany (Sindiku *et al.* 2015). These casings, originating from TVs and computers, are considered to have the highest average content of PBDEs among EEE/WEEE (see Table 6 and *PBDEs Inventory Guidance* (UNEP 2021a)). The recycling of the plastic of CRTs is of economic interest due to the plastic types used and the size of these components. Consequently, this WEEE category has a particular relevance for the recycling of WEEE plastic and the control of PBDEs.

A total of 382 individual CRT casing from computers and TVs were sampled at WEEE storage sites in Nigeria (Sindiku *et al.* 2015). The labels on the TVs and computer monitor plastic housings were examined to gather information about the manufacturer, brand, model, serial number, year, and place of production. Mainly for TV samples, the year of production was found printed inside the plastic casings. This information was recorded, and parts of about 250 cm^2 size were cut from each sample for subsequent screening using XRF in the laboratory, as well as for additional instrumental analysis (Figure 7). These fragments were then transferred to a workshop where 40 mm x 40 mm squares were cut for laboratory XRF analysis (Figure 8). These cut squares were packaged in labelled polyethylene envelopes (Figure 8) for further analysis and stored in a dark place. In cases where handheld XRF device is available, samples could be screened in the field or at the recycling facilities, with simple cutting procedures.

The production years of the sampled WEEE ranged from 1987 to 2006 for computers and from 1981 to 2004 for TVs. This timeframe is considered most relevant for the use of c-OctaBDE, as its production ceased in 2004. Additionally, the major use of c-DecaBDE occurred during this period (UNEP 2021a; Figure 6). However, the use of c-DecaBDE in electronics sharply declined before 2008 due to restrictions imposed by the EU RoHS Directive and similar legislation in some other countries. Nevertheless, c-DecaBDE might be still used today since the Stockholm Convention included an exemption for its use in electronic devices requiring flame retardancy (UNEP 2021a). Therefore, EEE/WEEE produced from 2008 to 2020 should also be included in monitoring, although PBDE usage in these products is likely less frequent, making them a lower priority in PBDE monitoring studies.

The 382 CRT casings included 224 computers and 158 TV sets. The numbers of samples categorized by their region of origin (production or assembly) are shown in Table 8. This distribution broadly reflected the origin of TVs and computers in the e-wastes in Nigeria during that period.

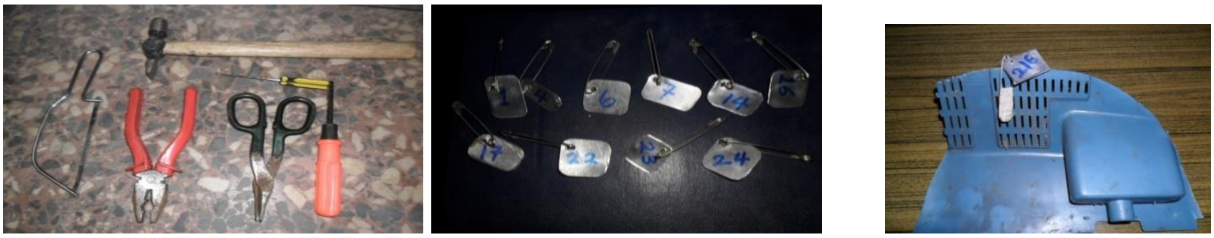


Figure 7: Sampling tools for cutting WEEE plastic, labelled tags and CRT plastic casing with tag

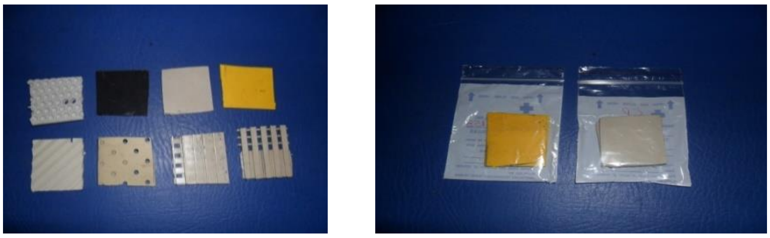


Figure 8: Cut squares for XRF analysis and packaged CRT plastic samples[7]

Table 8: Number of samples from each region of production/assembly

Region	Computer	TVs	Total
Europe	50	100	150
Asia	100	58	158
America	74	0	74
Total	**224**	**158**	**382**

These samples underwent XRF screening with the purpose of semi-quantifying bromine, chlorine, and inorganic compounds listed in the RoHS directive (detailed result can be found in the supporting information of Sindiku *et al.* 2015). It was found that a high proportion of CRT casings (61%)

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[7] Samples were analysed in laboratory with benchtop XRF using this sample size. If a handheld XRF with measurements in the field are conducted, then simple pieces from crushing of the equipment can be used/taken for laboratory analysis or screening can directly be conducted in the field.

contained over 10,000 mg/kg of bromine from BFRs, and this proportion was higher in computer CRTs (Figure 9).

Subsequently, bromine-positive samples were selected for GC/ECD and GC/MS analysis. In the context of monitoring in Nigeria, it was discovered that decaBDE was the major flame retardant used in TV sets, while tetrabromobisphenol A (TBBPA) was predominant in computer CRT casings:

Out of a total of 158 TVs, 30 were flame retarded with c-DecaBDE, with concentrations ranging from 2.5% to 23.7% by weight.

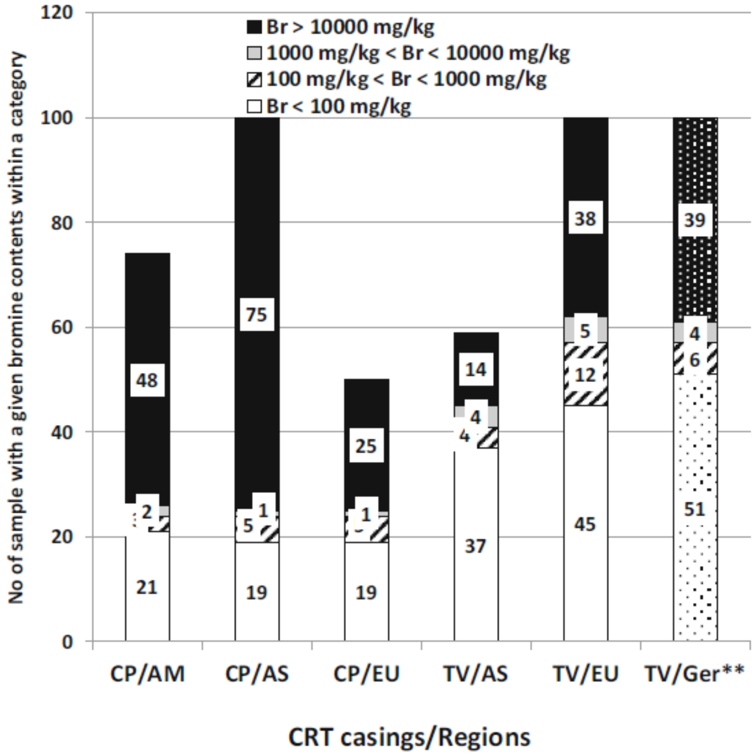
Another 18 TVs had c-DecaBDE concentrations ranging from 0.1% to 1.6% by weight, likely due to the recycling of plastic containing c-DecaBDE.

Among the 158 TVs analysed, three were flame retarded with c-OctaBDE, with concentrations varying from 5.9% to 29.0% by weight.

Two further TVs contained 0.7% and 0.1% c-OctaBDE by weight, introduced by recycling of plastics containing c-OctaBDE. It is worth noting that the five samples with c-OctaBDE were produced before 1990.

Regarding computer CRTs, only 3 out of 224 analysed were flame retarded with c-DecaBDE, with concentrations ranging from 4.6% to 5.4%. 12 additional computer CRTs had c-DecaBDE concentrations from 0.2% to 0.5% by weight, attributed to recycling. Only one out of the 224 computer CRTs was flame retarded with c-OctaBDE, at a concentration of 5.1%. Two further computer CRTs casings contained 0.87% and 0.95% c-OctaBDE by weight, also attributed to recycling.

The average PBDE content (sum of c-OctaBDE and c-DecaBDE) in Nigerian-stockpiled CRT casings (from the 1980s to 2006) was 1.1% by weight for TVs and 0.13% by weight for computer CRTs, both above the highest Basel Convention low POP content limit of 0.1% (1000 mg/kg).



AM America, AS Asia and EU Europe) sampled in Nigeria. **Compared to TV CRT casings sampled at a German e-waste recycling facility (TV/GER sampled in 2009

Figure 9: Distribution of bromine content within a category in casings of CRT TVs (TV) and computer monitors (CP) from different world regions (from Sindiku *et al.* 2015)

2.3.2 Sampling methodology for monitoring POPs in shredded WEEE plastic

In the WEEE recycling process, e-waste is frequently shredded and the metallic fraction is separated, leaving a residual fraction mainly consisting of plastic, including some impurities like heavy metals. Even when WEEE is manually dismantled, the plastic must eventually be shredded for cost-effective shipping and further processing. Therefore, the major samples from WEEE plastic recycling to be monitored for POPs is shredded WEEE plastic. The POP contamination in such mixed plastic fractions decides if the plastic shred can be used in recycling or needs separation of POP containing plastics.

The sampling of a representative laboratory sample can be highly complex and depending on the particle size and the frequency of pollutants in them (USEPA 2003). The correct sampling of POPs-containing plastics (or other polymers like PUR foam) needs to consider the interrelated following issues (Vencovsky *et al.* 2021):

- The distribution of POP concentrations in waste products and waste fractions.
- Statistical issues related to determining the size of a representative sample.
- The chemical characterization of particles and samples by field and laboratory methods.

In the case of mixed plastic waste, the distribution of concentrations of PBDEs (or other POP additives) is often asymmetric due to plastic particles with high concentration, which can reach up to 20%. These distributions do not follow a Gaussian (normal) pattern, influencing the determination of sample size and volume (see Box 1 in Section 1.4.2.2).

The Swiss Federal Laboratories for Materials Science and Technology, EMPA, developed a standardized methodology for sampling WEEE plastic with the aim of conducting a survey of PBDEs and other RoHS regulated substances in WEEE plastic (Wäger *et al.* 2010). This methodology can be applied for general assessment of POPs in WEEE plastic and has been used in the Swiss national survey of POPs in WEEE plastic (Taverna *et al.* 2017). The study by Wäger *et al.* (2010) includes a sampling methodology and protocol, which are described here with some modification to comply with the standard TS50625-3-1:2016-04 (CENELEC 2016). This sampling strategy and protocol are applicable when shredding plants for processing of WEEE or shredding of WEEE plastic are available.

2.3.2.1 Input quantity

The starting point for a representative sampling procedure is a quantity of approx. 20 t input WEEE into the recycling process, encompassing all mixed WEEE categories and WEEE categories. This equates to around 3 to 7 tonnes of plastic, which is typically sufficient for obtaining a representative sample in most cases. In the case of sampling individual product types, the ideal target is also within the range of 3 to 7 t of plastics. However, in many cases, achieving this ideal quantity may not be feasible. Hence, samples should be drawn from as much input material as can be achieved within an acceptable timeframe and effort.

2.3.2.2 Fraction to be sampled

The output of a WEEE recycling process often contains various fractions, depending on the characteristics of the recycling process. It is suggested to sample the fraction that is most likely to be directed towards a plastics recycling process. This can be done based on criteria such as the quantity of plastic present or the quality of the fraction (e.g., plastic grain size, impurities content). The criteria applied should be documented in the sampling protocol.

If a product type is processed manually (e.g., manual dismantling of plastic housings of TV or computer monitors), the dismantled plastics of all the input material should be collected and then shredded down to a grain size of 20–50 mm or smaller. Samples are then taken from the shredded plastic fraction. The sampled fraction must be thoroughly described in the sampling protocol.

2.3.2.3 Sampling location (container/heap or directly from shredding)

A) Sampling from a container

If it is not possible to take samples directly from the output flow, samples can be taken from the corresponding collecting container with a shovel or a sampling container. At each individual sampling time (sampling interval, see chapter 2.3.2.5), the material that has fallen into the container is collected, taking into account the required sample size (sample size, see Section 2.3.2.4). The applied procedure must be described in the sampling protocol.

B) Sampling from a falling stream

When sampling is performed from a falling stream (e.g., at the outlet of a continuous mechanical treatment/shredding process), the sample is collected directly from the output flow of the plastic fraction across the entire cross-sectional profile of the flow.

The following 3 special cases can be distinguished:

- If the width and depth of the stream are small, place a sampling container into the stream using unidirectional action. It is recommended to position the sampling container at a 90° angle to the falling output flow. Hold the sampling container in place for the specified period to gather the desired volume of material.
- If the width of stream is large and depth is small, insert the container at one end of the stream and, at a uniform rate designed to collect the required amount of material, move the container through the width of the stream to the opposite end.
- If both the width and depth of the stream are large, follow the method as described above but repeat procedure at 90° angle to the initial sampling direction.

The applied procedure should be described in the sampling protocol.

2.3.2.4 Required number and size of sample

Number of samples

From the ideally 3 to 7 t of plastics, 20 single samples are taken. Then, ten of these single samples are mixed to create a composite sample (see Figure 10 and Table 9). If necessary, the resulting two composite samples are reduced to the size of laboratory samples (for details on the preparation and reduction of composite sample see chapter 2.3.2.6).

Size of samples

The sample size depends on the grain size of the sampled fraction and is defined according to Table 9. The sizes of the single, composite, and the laboratory samples must be documented in the sampling protocol.

Table 9: Minimum size of single, composite, and laboratory samples based on TS 50625-3- 1:2015 (CENELEC 2016)

Max. grain size (95% of plastic particles) [mm]	Min. single sample [litre]	Min. volume of mixed sample [litre]	Amount of Lab.-sample [litre]
> 2 to < 20	3	30	4
> 20 to < 50	5	50	12
> 50 to < 120	10	100	25

2.3.2.5 Sampling period and interval

Sampling period

The 20 t of input material should be processed as a batch. The sampling period corresponds to the processing time of approximately 20 t of input material. This period varies depending on the recycling process (facility size, processing speed, etc.).

Sampling interval

To define the sampling interval, the required processing time of the input material is divided by 10. The first sample is taken after the first tenth of the sampling period and so on.

The sampling time should be documented in the sampling protocol.

2.3.2.6 Methods for mixed sample preparation and reduction by conical heap method

A) Mixed sample preparation

The aim of the mixing procedure is to get a homogeneous sample without contamination and material losses. To do this:

- Identify an area sheltered from the effects of wind and rain, preferably flat and large enough to allow easy access around the whole sample when spread on the surface.
- Place a clean protective floor covering, preferably a clean plastic sheet, on the ground to prevent contamination of the sample by the floor surface. Ensure that all tools used for mixed sample preparation have been cleaned to reduce the risk of cross-contamination.
- Apply the conical heap method as follows: Mix ten of the single samples to create a mixed sample using the conical heap method (Figure 10). A conical heap is formed by successively depositing the material (single samples) on the peak of the cone. The deposited material should flow down on all sides of the cone to ensure effective mixing of different particle sizes.
- The volume of the tool used for coning should be half the volume of the single samples (approx. 5% of the heap), and this action should therefore be repeated at least 20 times to transfer the full amount of material to the new cone. The formation of a conical heap should be repeated three times to guarantee thorough mixing of the material.
- The mixed sample preparation must be documented in the sampling protocol.

B) Mixed sample reduction

If the (two) mixed samples are each larger than the required laboratory sample size (see Table 9), they have to be reduced using the coning and quartering method (Figure 10 and Figure 11). Otherwise, the laboratory sample corresponds to the mixed sample.

After applying the conical heap method (see above), flatten the last (third) cone by repeatedly and horizontally inserting the shovel onto the peak of the cone to form a flat heap with uniform thickness and diameter.

Quarter the flat heap along the two diagonals intersecting at right angles using a shovel inserted vertically into the material (Figure 10). Discard one pair of opposite quarters and place the remainder into a stockpile. If necessary, repeat the process of mixing and quartering until the volume of the remaining sub-sample is equal to the desired size.

The method and laboratory sample size must be documented in the sampling protocol.

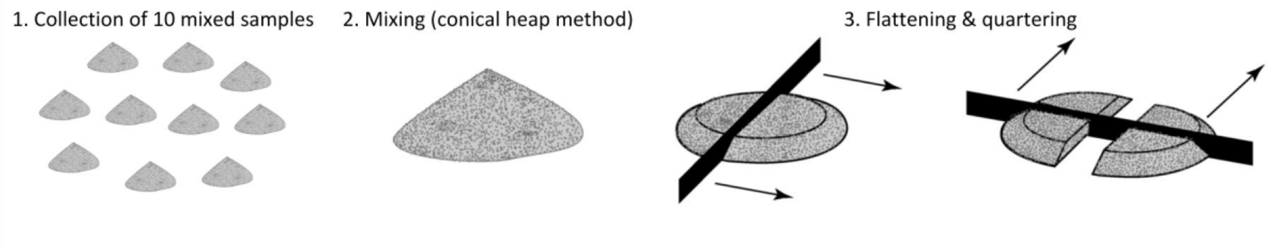


Figure 10: Conical heap method for mixing shredded plastic and quartering to reduce sample size (adapted from USEPA 2003)

Figure 11: Flat heap of WEEE plastic separated in quarters by two diagonals for reducing sample volume

2.3.2.7 *Packaging and sending of mixed sample*

The plastic samples should be packaged into sturdy and clean plastic bags or sealable boxes. Each bag/box should bear a clear label with information compiled in Box 2:

Box 2: Example of label of laboratory sample.

Company/Recycler: (e.g., Company X Recycling)
Name of fraction: (e.g., Fine-grained plastic of LCD TV)

Sampling volume: (e.g., 8 liters)
Name of laboratory sample: (e.g., FG-L1)
Date of WEEE sample preparation: (e.g., Day. Month. Year).

2.3.2.8 Record of sampling procedure and photographical documentation

The sampling procedure must be thoroughly documented in a sampling protocol.

In addition, it is recommended to complement the sampling process with photographic documentation that includes the following:

- The input material from which the samples were taken.
- The resulting output fractions, including the plastics fraction from which the samples were taken.
- The sampling location.
- The execution of the sampling.
- The mixed sample preparation process.
- The reduction to the laboratory sample size (if necessary).
- The packaging and storage of the mixed samples.

2.3.3 Results of the Swiss national monitoring study of POPs in WEEE plastic

In a Swiss national monitoring study on hazardous chemicals in WEEE shredder, POPs flame retardants and a wide spectrum of other flame retardants were measured (Taverna *et al.* 2017).

The study was based on the sampling methodology described in Section 2.3.2.

The most frequently found halogenated flame retardants were tetrabromobisphenol A (TBBPA), decabromodiphenyl ether (DecaBDE), decabromodiphenylethane (DBDPE), 1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE), and octabromodiphenyl ether (OctaBDE). These five substances were present at levels >100 mg/kg. Additionally, Dechlorane Plus was detected at an average concentration of 33 mg/kg.

Table 10: Concentrations of POPs and other flame retardants in Swiss WEEE** sampled 2011 (Taverna *et al.* 2017)

Substance in WEEE	**Mean value and uncertainty [mg/kg total WEEE]*** **
PentaBDE	2.4 ± 0.69
OctaBDE	120 ± 33
DecaBDE (BDE 209)	390 ± 45
HBCD	14 ± 4.1
TBBPA	630 ± 85
Decabromobiphenyl (DecaBB)	4.5 ± 2.7
2,4,6-Tribromophenol*	18 ± 1.4
1,2-Dibrom-4-(1,2dibromethyl) cyclohexan (DBE-DBCH)*	19 ± 1.0
2,3,4,5,6-Pentabromtoluol (PBT)*	3.7 ± 0.2
2,3,4,5,6-Pentabromethylbenzol (PBEB)*	3.7 ± 0.2
Hexabromobenzene (HBB)	2.9 ± 1.7

Mirex*	3.7 ± 0.2
2-Ethylhexyl-2,3,4,5-tetrabrombenzoat (EH-TBB)*	3.7 ± 0.2
1,2-Bis(2,4,6-tribromphenoxy)ethanBTBPE	150 ± 14
Bis(2-ethylhexyl)tetrabrom-phthalat (BEH-TEBP)*	3.7 ± 0.2
Dechlorane Plus DDC-CO	33 ± 11
Decabromdiphenylethan (DBDPE)	340 ± 200
2,4,6-Tris(2,4,6-tribromphenoxy)-1,3,5-triazin	14 ± 4.8

* Frequently below the limit of quantification **Without large household appliances ***The values are calculated to total WEEE and was ~three times higher in the approx. 30% plastic fraction.

2.3.4 Recommendations of POPs monitoring in plastic waste from WEEE

2.3.4.1 Recommendation for further monitoring of plastic parts in individual EEE categories

To date, no studies have been published on e.g. individual flat screen TVs, air conditioners and a rane of other WEEE. Furthermore, there is a lack of information on the new POPs Dechlorane Plus[8] (DP) and UV-328 in EEE. DP is found in the plastic of EEE/WEEE, such as cables, printed circuit boards, housings, other plastics, and rubber parts (UNEP 2021f). The use of Dechlorane Plus appears to be considerably lower compared to decaBDE, as indicated by a monitoring of WEEE plastic in Switzerland (Taverna *et al.* 2017; see below Section 2.3.3), which might result in a very low detection frequency.

On the other hand, UV-328 is used in EEE as UV absorber in liquid crystal displays in medical and in-vitro diagnostic devices and in liquid crystal displays in instruments for analysis, measurements, control, monitoring, testing, production, and inspection. These EEE could be considered for a screening study of UV-328.

2.3.4.2 Recommendations of POPs monitoring in plastic waste shreds from WEEE

Only a few robust national studies of POPs in plastic shredder from WEEE are available and all from high-income countries (Schlummer *et al.* 2007; Wäger *et al.* 2010; Taverna *et al.* 2017; Hennebert and Filella 2018; Bill *et al.* 2022). Such national studies of POPs and other chemicals of concern in plastic shredder from WEEE would be interesting for other countries in particular low- and middle-income countries. Low- and middle income countries which start WEEE plastic recycling might have a higher share of older WEEE with a higher average concentration of legacy POPs additives in the WEEE plastic as e.g. is reported in WEEE plastic in Nigeria (Sindiku *et al.* 2015).

Such monitoring should consider robust sampling protocols (e.g. Section 2.3.2) and sampling standards (for example TS 50625-3-1:2015 (CENELEC 2016)).

All POPs present in WEEE plastic and possibly other chemicals of concern present in WEEE plastic (Taverna et al. 2017; Weber 2022) could be considered for such a monitoring. This likely need to include an evaluation on the practical feasibility to conduct such studies in low- and middle income

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[8] Dechlorane Plus is used as non-plasticizing flame retardant in thermoplastic (e.g. polypropylene, polyester, ABS, natural rubber, polybutylene terephthalate (PBT)) and thermosets (e.g. epoxy and polyester resins, polyurethane foam, polyurethane rubber, silicon rubber).

countries. Since low-income countries often lack analytical capacity, such monitoring can possibly with cooperation of interested collaboration partner or commercial laboratories.

By understanding the presence of POPs in different WEEE categories (Wäger et al. 2010; Hennebert and Fillia 2018; Bill et al. 2022) risk fractions can be eliminated or better sorted. This can promote a more circular economy with reduced POPs amount in recycled plastic contributing to the implementation of the Stockholm Convention.

Information on monitoring of POPs in products including plastic have been compiled in a Stockholm Convention guidance (UNEP 2021g) and a webinar series developed and recorded in the frame of the UNEP GMP project[9].

3 Monitoring and controlling POPs in the transport sector and related plastic waste

3.1 Introduction to plastics and POPs in the transport sector and related pollution

3.1.1 Plastics in the transport sector

The transport sector plays a crucial role in the flow of materials, encompassing cars, industrial vehicles, trains, ships, and airplanes. Currently, there are 1.45 billion vehicles worldwide, of which 1.1 billion are passenger cars. These passenger cars alone contain approximately 200 million tonnes of plastics. With an average lifetime of approx. 15 years, it can be estimated that approx. 14 million tonnes of plastic waste are generated each year exclusively from end-of-life passenger vehicles.

The plastics present in vehicles are very diverse and include thermoplastics and thermosets, such as foams, rubbers, and synthetic textiles, which are increasingly used in the manufacturing of modern cars. Plastics and other polymers in commercial vehicles comprise about 50% of all interior components, including safety subsystems, doors, and seat assemblies. Aiming to reduce weight, the average content of plastic/polymers in cars has increased over the last 50 years. While cars produced in the 1970s contained 50 kg plastic/polymers, this figure rose to 160 kg in 2008, and for some years now, the average cars contain more than 200 kg plastic/polymers, including approx. 25 kg of synthetic textiles (Szeteiova 2010; American Chemistry Council 2016).

Various types of plastic are used in the transport sector in different proportions (Box 3; and Figure 4 page 17), of which PP, PUR, HD/MDPE, PA (polyamide), PC, and ABS/SAN (styrene acrylonitrile resin) are the most commonly used.

Box 3: Plastic and polymers used in vehicles and main uses (Szeteiova 2010)

PP – polypropylene is extremely chemically resistant and almost impervious to water. Black PP has the best UV resistance and is increasingly used also in the construction industry. Application: automotive bumpers, chemical tanks, cable insulation, battery boxes, bottles, petrol cans, indoor and outdoor carpets, carpet fibres.

PUR – polyurethane polymers are widely used in high-resilience flexible foam seating and head/armrest, rigid foam insulation panels, microcellular foam seals and gaskets, automotive suspension bushings, electrical potting compounds, hard plastic parts (e.g. electronic instruments), or cushions.

PVC – polyvinyl chloride has good resistance to chemicals and solvents. Its vinyl content gives it good tensile strength and it can be plasticized. Coloured or clear PVC material is available. Application:

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[9] IPCP Webinar Series: POPs in plastic and monitoring approaches https://www.ipcp.ch/activities/ipcp-webinar-series-pops-in-plastic-and-monitoring-approaches

automobile instruments panels, sheathing of electrical cables, pipes, doors, waterproof clothing, and chemical tanks.

ABS – acrylonitrile-butadiene-styrene is a durable thermoplastic, resistant to weather and some chemicals, popular for vacuum-formed components. It is a rigid plastic with rubber-like characteristics, which gives it good impact resistance. Application: car dashboards and covers.

PA – polyamide is known as nylon 6.6 or nylon 6. Both nylons have high resistance to abrasion, low friction characteristics, and good chemical resistance. However, they easily absorb water, causing components to expand in wet or humid conditions, limiting their use in applications where dimensional stability is required. Application: gears, bushes, cams, bearings, and weatherproof coatings.

PBT – polybutylene terephthalate has good chemical resistance and electrical properties, and it is a hard and tough material with low water absorption. It also has very good resistance to dynamic stress and thermal and dimensional stability. It is easy to manufacture due to its fast crystallization and cooling. Application: Fog lamp housings and bezels, sunroof front parts, locking system housings, door handles, and bumpers.

PC – polycarbonate has good weather and UV resistance, with transparency levels almost as good as acrylic. Applications: security screens, aircraft panels, bumpers, spectacle lenses, and headlamp lenses.

PE – polyethylene has good chemical resistance. Two PE-types are used, low-density polyethylene (LDPE) and high-density polyethylene (HDPE) in a range of densities. Application: glass reinforced for car bodies, electrical insulation, and packaging where strength and aesthetics are important.

PET – polyethylene terephthalate has similar conditions as PBT, including good thermal stability, good electrical properties, very low water absorption, and excellent surface properties. Application: wiper arm and their gear housings, headlamp retainers, engine covers, and connector housings.

PMMA – Polymethyl Methacrylate (acrylic) is more transparent than glass, has reasonable tensile strength (shatterproof grades are available), and good UV and weather resistance. It also offers high optical quality and surface finish with a wide range of colour. Application: windows, displays, and screens.

POM – polyoxymethylene (also known as polyacetal or polyformaldehyde) has high stiffness, rigidity, and excellent yield, which remain stable in low temperatures. It has very good chemical and fuel resistance. Application: interior and exterior trims, fuel systems, and small gears.

PS – polystyrene is very popular, easy to manufacture, but has poor resistance to UV light. Application: equipment housings, buttons, car fittings, and display bases.

ASA – acrylonitrile styrene acrylate material has great toughness and rigidity, good chemical resistance and thermal stability, outstanding resistance to weather, aging, and yellowing. Application: housings, profiles, interior parts, and outdoor applications.

3.1.2 POPs in plastics in the transport sector

A wide range of POPs are present in the transport sector such as brominated flame retardants (PBDEs, HBCD), SCCPs/MCCPs[2], Dechlorane Plus, UV-328, and PFOA/PFOS related compounds (Table 11). Furthermore, several POPs have received exemptions for the continued production or use in vehicles, such as decaBDE (Table 12), Dechlorane Plus (Table 13), and UV-328 (Table 14). These exemptions also specify in what plastic parts the respective POPs might be present.

PBDEs are the most extensively studied POPs in vehicles, as transport was a major use (Abassi *et al.* 2019) and has exemptions for decaBDE use in vehicles under the Stockholm Convention (Table 12; UNEP 2021a). Their major use was/is in back-coated textiles, such as rear decks, upholstery, headliners, automobile seats, headrests, sun visors, trim panels, and carpets (see case study Section 3.3.1.2) (Kajiwara *et al.* 2014). Furthermore, depending on the flammability standard, also PUR foam can be flame-retarded in cars, especially in those manufactured in the US, where 90% of c-PentaBDE was used, mainly in seats, headrests, or armrests until 2004 (Abbasi *et al.* 2019; Table 2), as confirmed by monitoring studies in Japan and the Netherlands (Leslie *et al.* 2013; Kajiwara *et al.* 2014).

Furthermore, a range of small plastic parts in the powertrain, such as cables and electrical connectors, can contain decaBDE (Table 12).

Currently, there is no data available on which producers have used PBDEs in which model. Therefore, only XRF screening and in currently used vehicles (or end-of-life vehicles) and subsequent instrumental analysis could clarify the presence or absence of PBDEs/BFRs in the respective vehicles.

HBCD has been used until approx. 2013 in low volumes in vehicles and has only been detected in a few floor coverings so far (Kajiwara *et al.* 2014; Section 3.3.1.2). In addition, HBCD-containing polystyrene foam has been used in refrigeration trucks/vans and is likely still present in such vehicles today.

HBB is of minor relevance overall, with only approx. 5,400 t produced in the United States from 1970 to 1976 (UNEP 2021a). Therefore, only cars and other vehicles produced in those years in the US might contain treated PUR foam and possibly other plastic/polymers, and a few of such HBB-containing cars might still be in use or available for sale as vintage cars.

Table 11: POPs used in the transport sector and related use period

POP	**Application in transport sector**	**Use period***
DecaBDE	Use in private and public transportation; in maritime, aviation and land transport, as well as astronautics	Current and former uses. Continued use is allowed for a range of plastic parts
c-PentaBDE (tetra/pentaBDE)	Flame retardants in PUR foam (seat, head rest) and textiles in vehicles from US	Former use in vehicles (1970 to 2004)
HBCD	EPS/XPS insulation in refrigerator trucks. Minor use in transport textiles (seating, floor coverings)	Former use (1970 to 2013)
HBB	Vehicles in the United States	1970 to 1976
SCCPs/MCCPs[2]	Plasticizer and FR in cables and other PVC and rubber parts in vehicles	Current and former uses. Use of SCCP is exempted in PVC
PFOA	Side chain fluoropolymers in textiles and carpets; impurity in fluoropolymers	Current and former uses
PFOS	Side chain fluoropolymers in textiles and carpets	Former uses (main use before 2002)
Dechlorane Plus	Use as flame retardant in plastic in the automotive and aviation sector	Continued use
UV-328	Liquid crystal panels and meters; paint; resin used for interior and exterior parts	Continued use

*Vehicles and plastics in vehicles have a long service life in low- and middle-income countries, often 30 years and longer;

Table 12: Specific exemptions under the SC for decaBDE parts for use in vehicles

Specific exemption	**Application**
(a) Parts for use in legacy vehicles, defined as vehicles that have ceased mass production, and with such parts falling into one or more of the following categories:	(i) Powertrain and under-hood applications such as battery mass wires, battery interconnection wires, mobile air-conditioning (MAC) pipes, powertrains, exhaust manifold bushings, under-hood insulation, wiring and harness under hood (engine wiring, etc.), speed sensors, hoses, fan modules and knock sensors; (ii) Fuel system applications such as fuel hoses, fuel tanks and fuel tanks under body; (iii) Pyrotechnical devices and applications affected by pyrotechnical devices such as air bag ignition cables, seat covers/fabrics (only if airbag relevant) and airbags (front and side); (iv) Suspension and interior applications such as trim components, acoustic material and seat belts.
(b) Parts in vehicles specified in paragraphs	(i) Reinforced plastics (instrument panels and interior trim)

(a) (i)–(iv) above and those falling into one or more of the following categories:	(ii) Under the hood or dash (terminal/fuse blocks, higher-amperage wires and cable jacketing (spark plug wires)); (iii) Electric and electronic equipment (battery cases and battery trays, engine control electrical connectors, components of radio disks, navigation satellite systems, global positioning systems and computer systems); (iv) **Fabric such as rear decks, upholstery, headliners, automobile seats, head rests, sun visors, trim panels, carpets**.

Table 13: Specific exemptions under the SC for Dechlorane Plus in vehicles

Specific exemption	Exempted application
Replacement parts for, and repair of, articles where Dechlorane Plus was originally used in the manufacture of those articles and may be available, limited to the following applications, until the end of the service life of the articles or 2044, whichever comes earlier:	Motor vehicles (covering all land-based vehicles, such as cars, motorcycles, agricultural and construction vehicles, and industrial trucks; applications include cables, wire harnesses, connectors, and insulation tapes);
	Aerospace (such as aircraft engine fan case rub strip products and voidfilling and edge-sealing products, aircraft engine manufacturing repairs, electrical items, structural panels, and aircraft cabin interiors);
	Space (such as satellites, probes and other exploration equipment, manned cabins and laboratories, heat-insulating materials for rocket motors, and ground support equipment);
	Defence (such as naval vessels, missiles, launch platforms, ordnance, communication equipment, radar and lidar systems, and support equipment)
	Stationary industrial machines (such as tower cranes, concrete plants, and hydraulic crushers; applications include cables, wire harnesses, connectors, and insulation tapes) for use in agriculture, forestry and construction;
	marine, garden, forestry, and outdoor power equipment; and

Table 14: Specific exemptions under the SC for UV-328 in vehicles

Specific exemption	Exempted application
Replacement parts for articles where UV-328 was originally used in the manufacture of those articles until the end of the service life of the articles or 2044, whichever comes earlier	Motor vehicles (covering all land-based vehicles, such as cars, motorcycles, agricultural and construction vehicles, and industrial trucks);
	Stationary industrial machines (such as tower cranes, concrete plants, and hydraulic crushers) for use in agriculture, forestry, and construction;

3.1.3 POPs contamination from plastics of vehicles

POPs are released along the life cycle of vehicles with related contamination in the vehicle (Abdallah and Harrad 2009; Harrad and Abdallah 2010; Kajiwara et al. 2014) and pollution of the environment in particular if vehicles are not managed in an environmentally sound manner in end-of-life including open burning and disposal on dumpsites (Shaw et al. 2010; Weber et al. 2010). The release and contamination of POPs from ELV management is less investigated compared to WEEE although the total plastics from ELV is in the same order of magnitude or even slightly higher (see Section 2.1.1 and 3.1.1). However first studies on the informal recycling of end-of-life vehicles (ELVs) document that it can result in environmental contamination with oil, PCBs, PBDEs (Nwachukwu et al. 2012; Takahashi et al. 2017) and likely also other POPs present in vehicles (Table 11). If open burning of cables and other plastics is practiced, additional unintentional POPs and brominated dibenzo-p-dioxins and dibenzofurans (PBDD/PBDFs) are formed and released (Gullett et al. 2007; Weber and Kuch 2003; Petrlik et al. 2022).

3.2 Monitoring POPs in new vehicles, vehicles in current use, and vehicle parts

Overall, there is a lack of monitoring data of POPs in the transportation sector. Only a few studies have conducted screening of a limited amount of POPs, in particular PBDEs (e.g., Leslie *et al.* 2013; Kajiwara *et al.* 2014; Redin *et al.* 2017; Liu *et al.* 2019). For newly listed POPs like Dechlorane Plus and POPs PFASs initial are available for automotive shredder in Norwegian Environment Agency 2021). Given the listed exemptions in the Stockholm Convention for Dechlorane Plus (Table 13) and UV-328 (Table 14), more monitoring in used and new vehicles is needed.

3.2.1 Monitoring of POPs in new and in-use vehicles

POPs can be monitored in new vehicles on the market or in imports. However, sample collection is typically destructive and, therefore, challenging in new vehicles. One non-destructive option to screen POPs in products is the use of wipe tests developed for no destructive screening by research groups in Australian and the Netherlands (Gallen *et al.* 2014). For this simple wipe test, respective samples are treated with a pre-cleaned filter paper folded into quarters and wetted with isopropanol, then wiped firmly in concentric circles towards the middle of the area. Rinsing this filter paper allows for the determination of BFRs present, even in a semi-quantitative manner (Gallen *et al.* 2014). In the test, c-OctaBDE congeners, decaBDE, and tetrabromobisphenol A (TBBPA) were detected with relatively high accuracy (>75%) when confirmed by destructive chemical analysis. There is a promising relationship between the amounts of BFRs detected in surface wipes and subsequent extracted plastics, allowing for predictions not only of the types of BFRs present but also estimates of concentrations in a semi-quantitative manner (Gallen *et al.* 2014). Such wipe tests can likely also screen for other POPs additives. XRF is another non-destructive screening option, although it can only determine bromine or chlorine content (UNEP 2021c).

3.2.2 Rubber materials used in transport

In studies conducted in China, rubber tracks were found to contain high CP concentrations. One study found a mean SCCP and MCCP[2] concentration of 3,639 and 41,368 mg/kg, respectively, in rubber track products (Xu *et al.* 2019). Another study measured 338 mg/kg SCCPs and 3,095 mg/kg MCCPs[2] in rubber tracks (Wang *et al.* 2018).

Conversely, in a study carried out in the Netherlands, car tires contained SCCPs/MCCPs[2] but at lower levels and not as plastic additives (Brandsma *et al.* 2019).

3.2.3 Monitoring of spare parts

Monitoring of POPs in spare parts is another approach to monitor POPs in vehicles. Exemptions for vehicle (spare) parts for decaBDE (Table 12), Dechlorane Plus (Table 13), and UV-328 (Table 14) have been granted and the listed parts can be screened with a priority.

Gallen et al. (2014) screened 125 car accessories using XRF screening and wipe tests described in Section 2.2.2, but did not find any part with bromine concentration above 1% (Gallen et al. 2014; Table 7). Nevertheless, the study primarily focused on brominated compounds and specific product categories. To achieve a comprehensive understanding of the global prevalence of POPs in vehicle spare parts, it is imperative to conduct investigations into other POPs across various regions worldwide.

3.3 Monitoring and sampling of plastic and polymers in end-of-life vehicles (ELVs)

3.3.1 Sampling and analysis of plastic/polymers from individual ELVs

3.3.1.1 Background on monitoring individual vehicles

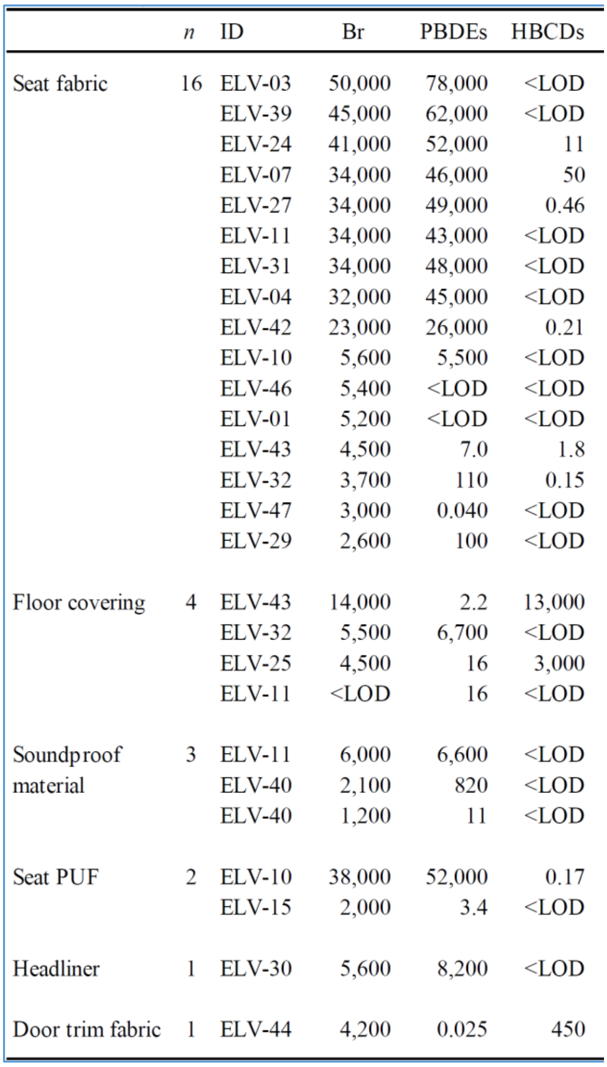
Monitoring of individual vehicles and compiling those studies is useful to get a detailed overview of the use of PBDE mixtures (or other additives), including:

- The age distribution of the use of e.g. PBDEs, SCCPs, MCCPs, Dechlorane Plus, UV-328.
- The regional distribution of the use of PBDEs SCCPs, MCCPs, Dechlorane Plus, UV-328.
- Whether specific POPs use is associated with certain companies or product.

When conducting such a study, the following information is recorded in the sampling process, if available:

- Producer and model name
- Country of origin (since several large producers were/are producing in different regions/countries with different flammability standards and, therefore, flame retardant use)
- Production year.

Table 15: PBDE/HBCD in bromine positive components of 45 vehicles/515 components (Kajiwara *et al.* 2014)



	n	ID	Br	PBDEs	HBCDs
Seat fabric	16	ELV-03	50,000	78,000	<LOD
		ELV-39	45,000	62,000	<LOD
		ELV-24	41,000	52,000	11
		ELV-07	34,000	46,000	50
		ELV-27	34,000	49,000	0.46
		ELV-11	34,000	43,000	<LOD
		ELV-31	34,000	48,000	<LOD
		ELV-04	32,000	45,000	<LOD
		ELV-42	23,000	26,000	0.21
		ELV-10	5,600	5,500	<LOD
		ELV-46	5,400	<LOD	<LOD
		ELV-01	5,200	<LOD	<LOD
		ELV-43	4,500	7.0	1.8
		ELV-32	3,700	110	0.15
		ELV-47	3,000	0.040	<LOD
		ELV-29	2,600	100	<LOD
Floor covering	4	ELV-43	14,000	2.2	13,000
		ELV-32	5,500	6,700	<LOD
		ELV-25	4,500	16	3,000
		ELV-11	<LOD	16	<LOD
Soundproof material	3	ELV-11	6,000	6,600	<LOD
		ELV-40	2,100	820	<LOD
		ELV-40	1,200	11	<LOD
Seat PUF	2	ELV-10	38,000	52,000	0.17
		ELV-15	2,000	3.4	<LOD
Headliner	1	ELV-30	5,600	8,200	<LOD
Door trim fabric	1	ELV-44	4,200	0.025	450

3.3.1.2 POP-BFR screening in plastic and other polymers in vehicles in Japan

To date, only one study has screened PBDEs and HBCD in vehicles in detailed. It examined 515 materials/components in 45 vehicles produced between 1993 and 2012 using XRF (Kajiwara et al. 2014; Liu et al. 2019). The XRF survey showed that 32 out of 515 materials/components investigated (6.2% of the total) contained ≥0.1% of bromine. The sampled components with bromine content above 0.1% were further analysed for PBDEs and HBDD in the laboratory.

Major components that contained PBDEs (or other FRs) ≥0.1% by weight included seat fabric, floor covering, and soundproof materials (Table 14). The predominant PBDE detected was decaBDE, mainly in seat fabric. Furthermore, PUR foam in seats and headliner from a US car contained c-PentaBDE. 90% of c-PentaBDE was used in the USA (likely affecting all of North America). Due to the high toxicity/health cost (Attina et al. 2016) and bioaccumulation potential of the PBDE congeners in c-PentaBDE, vehicles containing c-PentaBDE and related PUR foam should be a priority for screening and management.

HBCD were found only in two floor coverings (Table 14), indicating lower relevance.

Plastic parts of car seats, floor mats, and dashboards did not contain BFRs above 1000 mg/kg in all 45 vehicles (Kajiwara et al. 2014). It needs to be stressed that 60 samples contained bromine levels between ≥0.01% and ≤0.1%, and around 50% of samples had bromine levels between ≥0.005% and ≤0.01%, suggesting contamination from recycling or secondary sources (Kajiwara et al. 2014).

The study focus did not include powertrain, under-hood applications, and fuel system applications, which might also contain PBDEs (see Table 12).

The use of PBDEs and HBCD might be different in other regions, as seen for c-PentaBDE in US cars (see also the monitoring study from The Netherlands (Leslie et al. 2013) in Section 3.3.1.3).

When screening PUR foam in seats, the impact of back-coated seat fabric on the surface of the PUR foam should be considered, and screening should be conducted in the bulk of the PUR foam. In addition, certain hazardous phosphorus flame retardants (PFRs), such as the carcinogenic tris(1,3-dichloro-2-propyl) phosphate (TDCPP) (California EPA 2011), substituted PBDEs in PUR foam, especially in countries with specific flammability standards that have led to the use of FRs in PUR foams (Charbonnet et al. 2020).

3.3.1.3 National monitoring of PBDEs in the waste stream, including vehicles, in the Netherlands

The Dutch authorities investigated how waste materials that possibly contain PBDEs are sorted, separated, disposed of, recycled, landfilled, incinerated and/or exported in the Netherlands. The relevant background information was collected through interviews with key actors in the waste sector, as well as from reports and scientific literature. For ELVs and WEEE, national organizations coordinated the sampling and processing activities (Leslie *et al.* 2013). In general, PBDEs were found in very few single car parts. Seats of American cars were identified as PBDE hot spot within ELVs, with concentrations of up to 25,000 μg/g in the PUR foam of a Pontiac car seat (mostly c-PentaBDE congeners) (Leslie *et al.* 2013).

3.3.1.4 Dismantling of cars for recycling and recovery of plastic and polymers

Car dismantling/depollution refers to the selective removal of parts, either for use as spare parts or to recover valuable materials that otherwise could be lost to automotive shredder residue (ASR) where separation of individual polymers is challenging and plastics get also partly cross-contaminated by car fluids (motor fuel, hydraulic oil, coolant, CFCs, etc.). It is also carried out to remove potential pollutants, such as mercury-containing switches, car batteries, and car fluids.

Studies have compiled information on the recycling of certain plastic parts containing valuable plastics, such as bumpers, radiator grilles, lamps, and instrument panel (Zhang and Chen 2014). As can be seen from the monitoring in studies in Australia (Gallen et al. 2014), Japan (Kajiwara et al. 2014) and Netherlands (Leslie et al. 2013), most plastic and polymer parts in vehicles do not contain PBDEs or HBCD, nor do they contain bromine or BFRs above 1,000 mg/kg. Therefore, most plastic or polymers in cars do not contain POP-BFRs as additives above 0.1% and, from this perspective, could be recycled.

However, the newly listed POP, UV-328, has a major use in plastic parts of vehicles, in particular in exterior plastic parts. Therefore, it is important to include UV-328 in the monitoring and assessment of plastic parts. The use of UV-328 has received exemptions for further use which could be used as list for priority monitoring (Table 14).

3.3.2 Sampling and analysis of plastic and polymers from shredder fractions of ELVs

As for the WEEE plastic (see Section 2.3.2), a robust assessment and monitoring of the average POP content in ELVs can be conducted by monitoring POPs considering national monitoring of ASR and other screenings (Liu *et al.* 2019; Kajiwara 2020). In high-income countries, shredding is the main end-of-life treatment method for vehicles. After shredding, the shredded material is separated into heavy and light shredder fractions. The light shredder fraction (representing 15 to 25% of the shredding) contains plastic, polymers, textiles, and rubber, including the main share of POP plastic additives. These light shredder fractions can be sampled and analysed for the individual POPs present in vehicles (Table 11) that are relevant for further management options. Furthermore, the shredder fractions can be screened for bromine, indicating PBDEs and other BFRs, and could be further monitored (Danish EPA 2014).

3.3.2.1 Monitoring of PBDEs in ASR in Japan

The Ministry of Environment of Japan and the Japan Automobile Manufacturers Association (JAMA) conducted several monitoring campaigns measuring PBDEs in automotive shredder residues. DecaBDE was the major PBDE detected, with decaBDE concentrations ranging from 200 to 618 mg/kg for cars produced before 2000 and from 39 to 190 mg/kg decaBDE for cars produced after 2000 (Table 16). This translates to an average concentration of 40 to 124 g of decaBDE per Japanese car produced before 2000 and 8 to 38 g of decaBDE per Japanese car produced after 2000 (Table 16). Lower brominated tetraBDE to heptaBDE congeners were below detection limits in all measurements (Table 16). This decrease in concentration in automotive shredder residues aligns with the decreasing consumption of decaBDE in Japan since 1992 (Figure 6). Additionally, the finding that tetraBDE to heptaBDE were not detected in the car shredder residues can be explained by the stop of use of c-PentaBDE in Japan in 1991 and the reduced use of c-OctaBDE in the 1980s, followed by further decline in the early 1990s (Figure 6).

Table 16: PBDE content in automotive shredder residues (PBDE content in component, automotive shedder residues, and related amount per vehicle)

	DecaBDE (mg/kg)	**∑PBDEs 2009 (tetra-heptaBDEs) (mg/kg)**	**POP-PBDE in average car*(g)**	**Reference**
XRF, chemical analysis (48 cars produced from 1989 – 2001 and ASR; Japan)	200 – 618 in ASR before 1996, 39 – 190 after 2000	N.D. – 28 (component samples)	40 – 124 before 1996 7.8 – 38 after 2000	JECC (2012)
Car shredder residues (cars produced before 1996; Japan)	406	N.D.	81.2	JAMA (2016), Japanese MoE (2011);
Car shredder residues (cars older than 1999; Japan)	335	N.D.	67	JAMA (2016), Japanese MoE (2011)
Car shredder residues (cars younger than 2000; Japan)	120	N.D.	24	JAMA (2016), Japanese MoE (2011)

* Calculated based on approx. 200 kg of light shredder residues per vehicle.

3.3.2.2 Monitoring of POPs in ASR in Norway

In a recent monitoring of POPs in European automotive shredder (Norwegian Environment Agency 2021), some additional POPs have been measured in addition to those already mentioned. The concentration of SCCPs in European ASR was 16 mg/kg, equivalent to an average of approximately

4.8 g SCCP per car[10], indicating low levels. On the other hand, the concentration of MCCPs[2] in European ASR ranged from 130 to 210 mg/kg, corresponding to around 50 g MCCPs[2] per car (between 39 and 63 g per vehicle).[10]

Regarding Dechlorane Plus, one shredder sample measured 12 mg/kg, whereas the majority of samples detected levels below 1 mg/kg (Norwegian Environment Agency 2021). This indicates that the average concentration of Dechlorane Plus in ELVs in Europe is likely below 3 g per vehicle[10].

Furthermore, in the first monitoring of extractable[11] PFOA in ASR in Europe, levels ranged from 0.048 to 0.067 mg/kg[12] (Norwegian Environment Agency 2021), equivalent to an average of ~15 mg per car[10]. In contrast, levels of extractable[11] PFOS were lower, ranging from 0.006 to 0.020 mg/kg[12], corresponding to ~3 mg per car[10]. Levels of extractable[11] PFHxS were the lowest, between 0.0006 and 0.0008 mg/kg13 (Norwegian Environment Agency 2021), corresponding to ~0.2 mg per car[12]. The total amount of PFOA, PFOS, PFHxS and related compounds is likely considerably higher due to the presence of non-extracted related compounds in side-chain fluorinated polymers. However, there is currently available method to appropriately quantify these total related compounds (UNEP 2021c), in particular covalently bound PFASs in side-chain fluorinated polymers, which are likely either not extracted or only extracted in small amounts.[11]

It is important to note that there are also other studies which have additional data on PBDEs in European shredder waste (see compilation in PBDE inventory guidance UNEP 2021a).

3.3.3 Sampling and analysis of POPs in car tires and related recyclates

Rubber from car tires is frequently recycled to produce rubber granulates. Recycled rubber is used in playgrounds and sports fields. In the Netherlands, an assessment of car tires and their recycled products, such as rubber granulates and playground tiles, was conducted to measure the concentrations of SCCPs, MCCPs[2], and LCCPs (Brandsma *et al.* 2019). Total CP (C_{10}–C_{30}) concentrations ranged from 1.5 to 67 mg/kg in car tires, 13 to 67 mg/kg in rubber granulates, and 16 to 74 mg/kg in playground tiles. The similar concentration ranges in car tires and recycled products suggested that chlorinated paraffins (CPs) were not introduced during shredder or moulding processes but were already present in car tires. Moreover, the authors suggested that the low CP content (maximum of 67 mg/kg) detected in car tires could indicate contamination during the manufacturing process rather than intentional CP application. Nevertheless, they estimated that tire wear particle (TWP) releases could be responsible for an annual input of 2 to 89 t of CPs into the environment in the European Union.

3.4 Recommendation for further monitoring of POPs in vehicles

3.4.1 Development of a standardized methodology for taking representative samples

While standardized methodologies for taking representative samples of plastic in WEEE have been developed (Wäger *et al.* 2010; CENELEC 2016), a similar standardized sampling procedure is currently lacking for end-of-life vehicles. Therefore, it would be useful to develop a standardized

[10] Considering an average ASR amount of 300 kg per car (20% ASR of a mid-size vehicle of 1500 kg).

[11] The shredder residues were extracted with methanol.

[12] These levels were detected after applying TOP-Assay of the extract (Norwegian Environmental Agency 2021).

[13] At the detected concentration, PFHxS might be considered an unintentional co-pollutant of PFOS.

methodology, possibly led by organizations like CENELEC or ISO to generate robust data of POPs and other chemicals of concern in ELVs. This would enable the development of robust impact factors for reliable inventories and data for a risk assessment for end-of-life management scenarios for vehicles and evaluation of the risk for environmental pollution and human exposure.

Until then, a sampling approach similar to the method developed for WEEE plastic could be applied:

For e.g. cars a representative sample number and representative method to take a shredder sample is needed. This could include the shredding of at least a total of 100 cars to obtain a representative sample (Ökopol 2020). Such shredding would result in more than 30 t of light shredder residues. The selection of cars could include an average mix of vehicles or only specific cars, such as those produced before 2004 (when the largest share of PBDEs was used) to generate impact factors as basis for inventory development (see PBDE inventory guidance UNEP 2021a). Monitoring cars from a specific region or producer could also be considered.

As an initial approach, from this shredder waste 10 single samples of 10 kg could be taken of total 100 kg. Since the grain size from car shredder samples is too large for taking a representative sub-sample using the heap method and considering the POP distribution in particles (see Box 1 in Section 1.4.2.2), these samples would need to be further shredded to an appropriate grain size (see Table 17) before representative subsamples could be taken. The resulting mixed samples can then be reduced to the size of laboratory samples using methods described in chapter 2.3.2.6 for WEEE plastic. The sample size depends on the grain size of the sampled fraction and should be adjusted as indicated in Table 17 and document the sizes of single, mixed, and laboratory samples in a sampling protocol.

Table 17: Minimum size of single, composite and laboratory samples as developed for WEEE plastic according TS 50625-3- 1:2015 (CENELEC 2016)*

Max. grain size (95% of plastic particles) [mm]	Min. single sample [litre]	Min. volume of mixed sample [litre]	Amount of Lab.-sample [litre]
> 2 to < 20	3	30	4
> 20 to < 50	5	50	12
> 50 to < 120	10	100	25

*Please note that a standard procedure of shredder from ELVs has not been established

3.4.2 Recommendation of more POPs data in ASR from different regions with a wide POP spectrum

Currently, only a few robust data for PBDE in ASR are available, mainly from Japan and Europe (UNEP 2021a; e.g. Table 16). Only some preliminary data on other POPs in ASR, such as Dechlorane Plus and PFOS/PFOA, have been generated in a European study (Norwegian Environment Agency 2021; Section 3.3.2.2), which cannot be considered representative. Therefore, there is a need for more POP monitoring data in ASR from different regions, covering relevant POPs.

3.4.3 Recommendation of more screening for plastic part categories and POPs

Up to now, only a few screening studies of PBDEs and HBCD in individual components of vehicles have been published (Leslie *et al.* 2013; Kajiwara *et al.* 2014; Redin *et al.* ; Liu *et al.* 2019; Section 3.3.1.2). More studies covering more regions and a wider range of plastics and POPs are needed for a better understanding of the presence and frequency of POPs in vehicles. In such screenings also other chemicals of concern in plastic (UNEP and BRS Secretariat 2023) or other pollutants related to international treaties (Weber 2022) could be included in the monitoring.

3.4.4 Recommendation for POP monitoring in plastics in trains, planes, and ships

While it is known that, e.g., PBDEs have been frequently used in materials in public transport like trains and airplanes, with related exposure (Allen *et al.* 2013; Strid *et al.* 2014), there is no robust monitoring study on POPs in plastics (including textiles) used in trains, airplanes, or cruise ships. Such studies are needed to assess exposure and to plan end-of-life management and recycling of plastics in these vehicles.

4 Plastics in buildings and construction and related control

4.1 Introduction to plastics and POPs in buildings and construction and related pollution

4.1.1 Plastics in buildings and other constructions

The construction sector is the second largest consumer of plastics, accounting for approximately 18% of the global plastic production. In 2015, this sector consumed 65 Mt of plastic, a figure that increased to 70 Mt in 2021 (see Figure 2 and Figure 3). The major plastic types used are PVC, PUR, HDPE/MDPE, PP, and PS, including EPS/XPS (Figure 4).

The major plastic products used in buildings and construction include:

- Insulation materials (mainly EPS/XPS, PUR, PIR, PP).
- Pipes for electrical conduits, rainwater and sewage pipes, and plumbing (PP, PVC).
- Insulation on cables, insulation tapes (PVC, Nylon, PP, PE).
- Flooring tiles and rolls (PVC, PP, PE, linoleum).
- Roofing (e.g., PC, unplasticized PVC, fiber-reinforced plastic).
- Windows and doors, along with their frames, and greenhouses (PE, PVC, PC).
- Domes/sky lights (PC, PMMA)
- Storage tanks (HDPE, PP).

4.1.2 POPs in plastics in buildings and other construction

Buildings and construction are a major area of plastic use containing additives listed as POPs (Table 18; UNEP 2021f; Weber 2022). Due to fire risk associated with plastics and flammability regulations (Charbonnet *et al.* 2020), flame retardants are often applied to plastics used in buildings. Major brominated flame retardants used include HBCD in insulation foams (Li *et al.* 2016; UNEP 2021a) and PBDEs in insulation foams and a wide range of other plastic materials. Table 18 provides an overview of the POPs used in plastics in buildings and construction, indicating whether they are used majorly or minimally and the time periods of use.

SCCPs and MCCPs[2], frequently produced as SCCP/MCCP mixtures, are high-volume POPs currently produced at approximately 1 million tonnes per year (Guida *et al.* 2020; Chen *et al.* 2021). They are mainly used (about 70%) as plasticizer in PVC (Chen *et al.* 2021; Chen *et al.* 2022), which is exempted in the Stockholm Convention (Table 19). Approximately 60 to 70% of PVC is used in the construction sector (Figure 4; Guida *et al.* 2020; Chen *et al.* 2021; Plastics Europe 2022a). Furthermore, SCCPs and MCCPs[2] are major flame retardants in polyurethane (PUR) spray foam (Brandsma *et al.* 2021; Chen *et al.* 2021).

Another use of POPs in construction is in paints and coatings, where POPs (SCCPs/MCCPs[2], PCBs, HBCD, and PFASs) are or were frequently used as plasticizers or flame retardants.

Due to their long service life, plastic containing POPs that have been used in construction over the past 60 years are still in use (Li *et al.* 2016; Weber *et al.* 2018; Chen *et al.* 2022). For example, PCBs used in high volumes in sealants and paints from the 1950s to approximately 1975 are still in use to more than 50% (Weber *et al.* 2018). Out of the total 703,000 t of HBCD produced from 1960s to 2021, approximately 650,000 t have been added to 45 MT[14] of EPS/XPS insulation in buildings present as stock in buildings around the globe and will need to be managed in the coming decades to century (Li *et al.* 2016; Chen *et al.* 2022).

The inventory of POPs and other chemicals of concern in buildings and construction is relevant information for the ESM of Construction and Demolition (C&D) waste (Weber 2022). Due to the lack of labelling of POPs in plastic used in construction, monitoring is needed for establishing robust inventories and for the ESM of plastic in C&D waste.

Table 18: POPs used in the building and construction sector and use period

POP	**Application in building and construction**	**Use period***
DecaBDE	PUR and XPS insulation, cladding panels, PE/PP films, cables and electrical ducts, and fittings or piping insulation	Current and former uses. New use is allowed in polyurethane (PUR) foam for building insulation
c-PentaBDE (tetraBDE, pentaBDE)	Flame retardants in PUR foam, PVC in cables, wires, floor mats, and industrial sheets	Former use (1970 to 2004)
HBCD	Major flame retardant in EPS/XPS; interior textiles (e.g. roller blinds)	Former use (1970 to 2021)
SCCPs and MCCPs[2]	In PVC in cables, flooring, and roofing; PUR spray foam, adhesives, rubber, sealants, paints, and coatings	Current and former uses. SCCP is exempted for use in PVC, paints, and adhesives
PCBs	Sealants, paints, plasters, adhesives, floor finishes, cables, and anticorrosion coatings	Former use (1950 to ca. 1975)
PCNs	Paints and coatings, cables, and wood treatment	Former use (1940 to 1980)
PFOA	Paints, lacquers and sealants, carpets, and floor covering; foam in fixed fire extinguishing systems	Current and former uses
PFOS	Carpets and floor covering, paints and varnishes, and coatings; foam in fixed fire extinguishing systems	Former uses (mainly before 2002). Firefighting foam use continues
PFHxS	Carpet and floor covering, paints, coatings, plaster, drywall, facade materials, textile, plastic insulation	Former use (until 2021)
Dechlorane Plus	FR in polymers in roofing materials and other building materials, non-woven PVC wallpaper, latex paint, laminated floorboards, fiber board, sealants, line pipes, sound absorbing foam, and EPS	Since 1960 until now (last manufacturer in China plans to produce until 2026). DP is available for sale from several vendors
UV-328	UV-absorber in polymeric materials, fillers, paints, lacquers, varnishes, adhesives, and wood coatings	From 1970 until now

Table 19: Specific exemptions for short-chain chlorinated paraffins

Chemical	**Activity**	**Specific exemption**
Short-chain chlorinated paraffins (Alkanes, C_{10-13}, chloro)$^+$: straight-chain chlorinated hydrocarbons with chain lengths ranging from C_{10} to C_{13} and a content of chlorine greater than 48%, by weight.	Production	As allowed for the Parties listed in the Register
	Use	• Secondary plasticizers in flexible polyvinyl chloride, except in toys and children's products; • Tubes for outdoor decoration bulbs; • Waterproofing and fire-retardant paints;

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[14] IPCP webinar on monitoring POPs in Plastic Part 2; Weber R "Sampling of POPs in plastics in major POP use sectors" from 1:59:45 on (https://www.youtube.com/watch?v=hcjIe6QfUE0&t=21s)

For example, the substances with the following CAS numbers may contain short-chain chlorinated paraffins: CAS No. 85535-84-8; CAS No. 68920-70-7; CAS No. 71011-12-6; CAS No. 85536-22-7; CAS No. 85681-73-8; CAS No. 108171-26-2.		• Additives in the production of transmission belts in the natural and synthetic rubber industry; • Spare parts of rubber conveyor belts in the mining and forestry industries; • Leather industry, in particular fatliquoring in leather; • Lubricant additives, in particular for engines of automobiles, electric generators and wind power facilities, and for drilling in oil and gas exploration, petroleum refinery to produce diesel oil; • Adhesives; • Metal processing;

4.1.3 POPs contamination from plastics from construction and demolition

Indoor environment contributes greatly to human exposure and can be a major source of exposure to certain chemicals, including POPs and other plastic additives (Meyer *et al.* 2013; Fantke *et al.* 2016; Lucattini *et al.* 2018). In Northern Hemisphere, approximately 90% of time is spent indoor (home, workplace, and transport) (Leech *et al.* 2002). Sick Building Syndrome (SBS) and Building Related Illness (BRI) are scientifically recognised conditions, mainly related to new buildings that release high levels of chemicals from their interiors, including plastics.

POPs are released along the life cycle of plastics in buildings with related contamination in indoor air and dust documented for HBCD (Abdallah and Harrad 2009; Harrad and Abdallah 2010), SCCPs and MCCPs (Britts et al. 2020; Lu et al. 2023; McGrath et al. 2023) and for PCBs (Weber and Herold 202). For SCCPs and MCCPs it has been found that the SCCP/MCCP concentration in industrial countries is lower compared to low- and middle-income countries (Britts et al. 2020; Lu et al. 2023; McGrath et al. 2023).

The release of POPs additives from polymers can also contaminate the environment (Figure 1). This is e.g. documented for PCBs in sealants where for Germany the release from the formally 20,000 t of PCB in sealants in buildings and other construction still release 5 to 15 t of PCBs/year to the environment with associated contamination of vegetation/gras and cattle (Weber *et al.* 2018; Zimmermann *et al.* 2019). Also the use of PCB containing construction and demolition waste for landscaping has resulted in PCBs contamination of the environment and livestock (Weber et al. 2018).

4.2 Monitoring POPs in plastic used in construction on the market

Several POPs used in the construction industry are still being produced under exemptions and are currently used in large amounts in construction plastics. Moreover, due to the absence of labelling for POPs in construction materials, these substances are imported in large quantities within plastic materials including low-income countries which do not have production of POPs (Babayemi *et al.* 2022). A preliminary inventory of SCCP and MCCP imports to Nigeria estimated that 33,700 t of SCCP and 25,600 t of MCCPs[2] were imported into Nigeria in different PVC products over the last 20 years, primarily ending up in buildings and construction (Babayemi *et al.* 2022). SCCPs and MCCPs[2] were detected in household dust in Africa at high ppm levels (Brits *et al.* 2020), likely as a result of plastics in buildings, and Africa has the highest SCCP and MCCP[2] levels in the UNEP/WHO human milk study conducted in the frame of the Global Monitoring Plan (GMP) (Krätschmer *et al.* 2021).

Therefore, it is crucial to control POPs and other chemicals of concern in building materials (UNEP 2021f; Weber 2022; UNEP 2023a) and due to the absence of labelling on plastic products, systematic monitoring is required to address this issue.

4.2.1 Monitoring SCCPs and MCCPs[2] in plastic used in construction

SCCP and MCCPs[2] are used as plasticizer in PVC and PUR spray foam as major uses (Table 18). Driven by these uses, China is a major producer of CP mixtures containing SCCPs and MCCPs (Chen *et al.* 2021; Xia *et al.* 2021; Chen *et al.* 2022). The major uses of SCCPs and MCCPs in China were identified through a monitoring study of 124 product samples from Chinese markets (2018−2019), including PVC products (n = 47), rubber and other plastics (n = 17), leather materials (n = 9), metalworking fluids (n = 5), polyurethane foam adhesives (n = 6), paints and varnishes (n = 21), and textiles (n = 19). The study revealed that 208,000 t of SCCPs and 334,000 t of MCCPs were used as plasticizer in PVC produced in China in 2019 (Chen *et al.* 2021) with a high share of PVC used in construction (Plastics Europe 2022a). Additionally, in 2019, 12,600 t of SCCPs and 25,500 t of MCCP were used in PUR spray foam produced in China. In PVC flooring, MCCPs[2] predominated, with levels ranging from 3,100 to 57,900 mg/kg (mean 8,500 mg/kg), while SCCPs were detected at lower levels, ranging from 2,000 to 11,800 mg/kg (mean 6,200 mg/kg) (Chen *et al.* 2021).

Furthermore, a study in the Netherlands found that cured do-it-yourself one-component spray foams (OCFs) often contained MCCPs[2] (C_{14}-C_{17}) and long-chain chlorinated paraffins (LCCPs, C_{18}-C_{37}), with concentrations ranging from 0.2% to 50% while SCCPs were below the detection limit (Figure 12). All (10/10) new OCFs contained CP levels above 2%. MCCPs were detected in 9/10 between 1 and 50% including 6 samples where MCCPs were present as major flame retardant.

LCCPs – not listed or assessed as POP but having long range transport, bioaccumulative and toxic properties (Yuan *et al.* 2021; Chen *et al.* 2023) – were also detected in 9/10 new OCFs products but only in 2 products as major flame retardant above 20% (Figure 12) (Brandsma *et al.* 2021). In the used OCF products in buildings MCCPs were detected in 5 of 10 tested samples as major flame retardant from 8 to 22% while LCCPs were not detected (Figure 12). This indicate that in the Netherlands PUR foam manufacturers comply with the restriction of SCCPs and have started the process to substitute MCCPs by LCCPs.

Furthermore, the foams contained 0.9% to 30% w/w of tris(1-chloro-2-propyl)phosphate (TCIPP) (Brandsma *et al.* 2021) which also is of toxicity concern (IPCS 1998; Van der Veen and de Boer 2012).

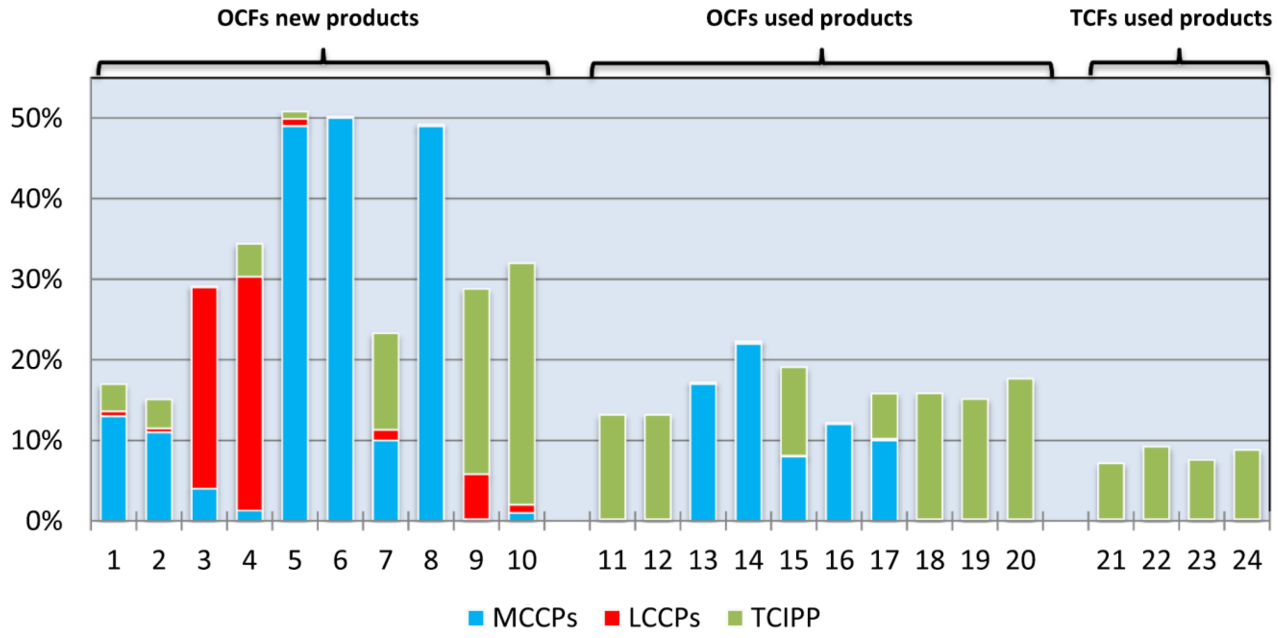

Figure 12: MCCP and LCCP and TCIPP levels (% w/w) in cured new and used one component spray PU foams (OCFs) and used two component spray PU foams (TCFs) (Brandsma *et al.* 2021)

4.2.2 POPs in adhesives used in construction

PCBs have been used in adhesives for flooring in buildings, contributing to indoor contamination (Meyer *et al.* 2013; Weber *et al.* 2018). In many "open applications", PCBs have been substituted with SCCPs (UNEP 2019). Monitoring of adhesives revealed high levels in both with mean SCCP concentration in adhesives of 3,340 mg/kg. Four-fifths of these adhesives exceeded the limit (1.5 g/kg) set in Chinese standard GB 36246-20184 and the EU POPs regulation (Xu *et al.* 2019).

4.2.3 More monitoring of POPs in new plastic products in construction needed

The case studies described above give an initial insight into the widespread use of POPs in high concentrations in plastics used for construction materials and therefore buildings. However, comprehensive studies on SCCPs and MCCPs in other regions and across various products are needed. It is worth noting that there are currently no studies available regarding the newly listed POPs, Dechlorane Plus or UV-328, in plastics used in construction. Also there is a lack of monitoring of PFAS in buildings.

4.3 Monitoring of POPs in building materials in use

Monitoring POPs and other chemicals of concern in buildings serves several purposes, including assessing exposure risk (Lucattini *et al.* 2018) and facilitating planning for remediation and deconstruction activities (Bavarian Environmental Agency 2019). Several POPs in plastics in buildings have been used in the past and new uses have stopped (e.g. for HBCD, PBDEs listed 2009, PCB, PCN) and therefore for these POPs monitoring of plastics in use and in construction and demolition waste is of interest.

4.3.1 Monitoring PCBs in plastics in buildings

It is estimated that approximately 25% of the total global PCB production (approximately 375,000 t) was used in open applications, mainly in the construction sector (UNEP 2021f; UNEP 2021h). PCBs and PCNs have been used in construction for sealants, coatings, paints, adhesives, and cables (UNEP 2019; UNEP 2021c). Overall, the use of PCBs in these applications was considerable higher than that of PCNs. PCBs were predominantly used in open applications from the 1950s to 1975, while PCNs were mainly used from 1930 to 1960 (UNEP 2021h). PCBs have been detected in industrial, public, and residential buildings, with substantial quantities still present and released into indoor air and the environment (Weber *et al.* 2018; Zimmermann *et al.* 2019).

In Switzerland, a nationwide screening of PCB in polymer sealants in buildings analysed 1348 samples of joint sealants from concrete buildings constructed between 1950 and 1980 (Kohler *et al.* 2005). Among these samples, 568 sealant samples (42%) exceeded the screening limit of 50 mg PCB/kg which is also the Basel Convention low POP content. PCB concentrations were above 10,000 mg/kg in 21% of samples, and above 100,000 mg/kg in 9.6% of samples. The study revealed that the use of PCBs in joint sealants was a common construction practice in Switzerland between 1955 and 1975, with the majority of sealants still in use, representing a significant stockpile of PCBs.

A second plastic additive use of PCBs in buildings were in chloroprene paints and chloroprene lacquers as well as in PVC copolymers used in buildings, road marking or underwater paint for concrete and brick at a concentration of 5 to 35% (BUWAL 2000).

A monitoring in Norway of 68 flaking old paint from various buildings in Bergen suggests that paint may be the most important contemporary source of PCBs in the Norwegian urban environment (Jartun et al. 2009). PCBs were found in several categories of paint from wooden and concrete buildings frow where it is introduced to the environment by natural weathering, renovation, and volatilization (Jartun et al. 2009). PCB paints present in farms were also found as source for contamination of meat, milk and eggs (Vaccher et al. 2018; Weber et al. 2018; Petrlik et al. 2022).

4.3.2 Monitoring of SCCPs and MCCPs in buildings

SCCPs and MCCPs have been used as plastic additives since more than 50 years. In the screening of PCBs in sealants in Switzerland (see Section 4.3.1), a subset of 85 sealants was additionally analysed for chlorinated paraffins, which were detected in about 33% of the samples (Kohler *et al.* 2005).

4.4 Monitoring of recycled plastic products used in construction or produced from construction materials

Plastic containing POPs in C&D waste might enter recycling cycles. After 80 years of using POPs plastic additives in construction, these plastics become part of C&D waste and are partly recycled. Furthermore, the drive towards a more circular economy for plastics will lead to higher recycling rates of plastics in all sectors, including construction. Consequently, some governments have projects to assess the recycling of plastics from construction (German Environment Agency 2021; Plastics Europe 2022b).

On the other hand, plastic is recycled to a large share into building materials, for example 45% of all recycled plastic in Europe is used in the construction sector (Plastics Europe 2022b).

4.4.1 Monitoring of SCCPs/MCCPs in PVC flooring

Initial studies have detected SCCPs and MCCPs[2] in PVC flooring, where the presence of multiple plasticizers (SCCPs/MCCPs and several phthalates) where documented in individual samples (Ramungul *et al.* 2023; UNEP *et al.* 2023e). This indicates that these flooring materials have been produced from recycled flexible PVC containing a wide range of plasticizers, including SCCPs and MCCPs (Ramungul *et al.* 2023).

4.4.2 Monitoring of HBCD in products revealing recycling of HBCD into new products

While EPS/XPS packaging normally does not require flame retardants, HBCD has been detected in some EPS packaging in the UK and Ireland (Abdallah *et al.* 2018) and in food packaging in Korea (Rani *et al.* 2014). HBCD has also been detected in EPS buoys used in fish/mussel farming, leading to associated contamination (Hong *et al.* 2013; Pan *et al.* 2023). The total HBCD levels were lower than those used for flame retardation, indicating that they most likely resulted from recycling of EPS. Since almost all HBCD in EPS/XPS has been used in construction, and EPS packaging normally did not contain HBCD, recycled EPS most likely originates from building insulation foam. Therefore, end-of-life management of EPS and XPS in packaging, including food packaging, disposable dishes, and drinking cups, should be evaluated for cross-contamination from recycling. Also, other uses of EPS/XPS might be screened for (cross) contamination.

4.5 Monitoring of construction and demolition waste (C&D Waste) and related control

Hundreds of million tonnes of plastic in buildings contain POPs as additives, which will need to be managed in the coming decades when buildings are renovated or demolished. Guidance documents have been established to manage pollutants (including POPs) when demolishing or deconstructing buildings (Bavaria Environment Agency 2019; Schweizer Bundesamt für Umwelt 2020. USEPA 2021).

4.5.1 Monitoring of PCBs, PCNs and POPs pesticides used in plastics in construction and demolition waste

Construction and demolition waste (C&D waste) from buildings built in the 1950s to 1990s can be contaminated with PCBs, PCNs or POP pesticides (Bavaria Environment Agency 2019; USEPA 2021). C&D waste is partly used for landscaping, including areas on farms (e.g. for farm tracks), which has led to PCB contamination in cattle (Weber *et al.* 2018).

PCB concentrations in C&D waste determine whether and how a PCB waste is regulated for disposal. The limits for disposing of construction waste differ between countries. The PCB limit for recycling C&D waste is 1 mg/kg in Germany and 0.5 mg/kg in Switzerland to prevent environmental contamination when C&D waste is used for landscaping. The monitoring of such wastes is however conducted by authorities or commercial laboratories and therefore there is a lack of published monitoring studies of PCBs and PCNs in C&D waste. Published studies are rather testing leachates and did not analyse total PCB content (Butera *et al.* 2014).

Monitoring of PCNs and POPs pesticides formerly used as plastic additives (Lindane and Mirex; Table 18) in waste from construction were conducted only in waste wood (Koyano *et al.* 2019) but not in plastics.

4.5.2 Monitoring PBDE and HBCD in C&D waste

Some studies have screened for PBDEs and HBCD in C&D waste. In a monitoring study in the Czech Republic, a variety of construction materials made from plastic (16 PUR foams and 5 PS foams) and wood (14 oriented strand board and 18 wood insulation) were analysed for PBDEs and HBCD (Vojta *et al.* 2017). While some PS samples were flame retarded with HBCD (0.5%), none of the analysed plastics contained PBDEs as flame retardants (all samples were below 1 mg/kg) (Vojta *et al.* 2017). Additionally, Dechlorane Plus and 11 other novel flame retardants were included in the monitoring but were detected at a maximum concentration of 40 mg/kg (Vojta *et al.* 2017) and were therefore not intentionally added in any of the products.

In a monitoring study in China, 11 C&D plastic waste samples were analysed for HBCD and PBDE (Duan *et al.* 2016). The levels detected were in the ppm and ppb range and did not contain intentionally BFR containing plastics. The sampling was done without bromine pre-screening.

Overall, the sample size in the conducted studies was relatively small and were performed without the use of bromine/chlorine pre-screening. Therefore, robust monitoring studies of POP-BFRs and other POPs present in C&D waste plastics have not been conducted to date.

4.5.3 Fast screening of HBCD in EPS/XPS waste to decide on management

For the future management of HBCD-containing EPS and XPS waste, a fast, robust, and cost-effective field method was required to distinguish between foams containing HBCD and foams containing a brominated polymeric flame retardant (PolyFR) that were free from HBCD. This assessment is necessary, for instance, when buildings with EPS/XPS are demolished or insulation is replaced, requiring waste management information. Schlummer *et al.* (2015) developed a screening method to identify expanded and extruded polystyrene foams containing HBCD and distinguish them from brominated polymeric systems. The test principle is based on the fact that PolyFR (a brominated polymeric macromolecule) is not extractable by a solvent, whereas HBCD (an additive FR) is extractable (Schlummer *et al.* 2015). Following rapid extraction of HBCD with acetone, the brominated flame retardant is identified and quantified by bromine screening using a handheld XRF instrument. A robustness test revealed a high level of accuracy and repeatability in the testing system

(Schlummer *et al.* 2015). However, due to the recent utilization of other additive BFRs in EPS/XPS, this test have become less specific for HBCD in EPS/XPS produced since 2019.

4.6 Recommendation for further monitoring of POPs in buildings and construction

4.6.1 Development of a standardized methodology for taking representative samples

POPs in buildings are not systematically monitored and there is a lack on monitoring of POPs in buildings (see Section 4.6.2) with only larger studies on PCB in sealants and paints (). Information of the presence of POPs in buildings is in particular relevant for indoor exposure and for management of POPs and other pollutants in buildings. Some countries have developed guidance documents

The Bavarian Environment Agency published a guidance on controlled deconstruction of contaminated buildings, considering the management of pollutants, including POPs (Bavarian Environment Agency 2019). The guidelines emphasize that selective/controlled dismantling today is a standard in demolition in Germany and that it is essential to assess pollutants during a pre-investigation of the building. The guidance gives an introduction to the individual pollutants, including the POPs such as PCBs, CPs, HBCD, and PCP and affected construction materials and related exploration (Bavarian Environment Agency 2019). Similarly, Switzerland published a guidance «construction and demolition waste» which outlines the legal basis for the disposal of C&D waste (Schweizer Bundesamt für Umwelt 2020). In particular, specifications for determining pollutants and the creation of a disposal concept are defined, e.g., for PCBs and CPs, and the disposal of asbestos-contaminated C&D waste is regulated. However brominated POPs are not mentioned in the guidance document yet. Furthermore, the possibilities for recycling excavated materials and mineral-based demolition waste are specified. The aim is that C&D waste can be used as secondary raw materials and be processed into high-quality recycled construction material as a basis for the sustainable management of construction waste (Schweizer Bundesamt für Umwelt 2020). Both guidance documents are in German and not in a UN language. Similar guidance documents could be developed in UN language and for other regions-

4.6.2 Recommendation of more POPs data in plastics in buildings

4.6.3 Lack of screening of POPs in plastics in construction and need for monitoring

For the nearly 2 million tonnes of PBDEs produced, it is estimated that more than 20% were used in plastics in buildings (Table 2; Abassi et al. 2019). Due to the long service life of plastics in buildings of 30 to 50 years, the largest remaining PBDE stocks is likely in buildings while for EEE/WEEE, vehicles and furniture a large share of PBDE has entered end of life (Abassi et al. 2015).

it is likely that the majority of PBDEs currently in use are found in plastics in buildings and construction. While the different uses of PBDE in buildings is known (UNEP), no monitoring data on PBDE in these plastics in use or in construction has been published. While monitoring and information for PCB in sealants and paints are available from high-income countries such as Germany, Norway, Sweden, Switzerland or USA (Kohler et al. 2005; Jartun et al. 2009; Weber and Herold 2015; USEPA 2023), no data are available from low- and middle income countries and only Tier II assessment without measurements has been conducted for PCB/PCN in open applications in South Africa (Weber and Okonkwo 2019). It is also probable that the largest share of stocks of SCCPs and MCCPs is likely in buildings considering the major use of SCCPs/MCCPs in PVC (Chen *et al.* 2021) and the major use of PVC in buildings (Plastics Europe 2022a). While some studies on POPs in plastic waste have been conducted (Duan *et al.* 2016), systematic studies on POPs in C&D plastic waste are lacking. These studies should include several hundred or even thousands of plastic samples representing different uses and types of plastics, and analyse the major POPs used. This is essential, for example, to understand former use of technical PBDE mixtures in construction, including major use, frequency, and time of use. Since hardly any monitoring data for the newly listed POPs, UV-328 and Dechlorane Plus, in buildings and C&D waste are available, these newly listed POPs should be included in such screening as appropriate.

PCBs and PCNs have been substituted by SCCPs/MCCPs in major polymer uses in construction (sealants, paints/coatings, and adhesives) and SCCPs/MCCPs are used in construction in high volume today (see Section 4.2.1) (UNEP 2021h; Weber 2022). Therefore, it is recommended to assess and jointly monitor PCBs, PCNs and SCCPs/MCCPs in suspected building materials in use.

5 Monitoring of other plastic use sectors potentially containing POPs

5.1 Monitoring of other major polymer use sectors

For several plastic-related POPs, the three above mentioned sectors (EEE, transport, building & construction) were the major users of industrial POPs used as additives in plastic. However, several POPs have also been used in the textile sector. Furthermore, the newly listed POPs UV-328 and SCCPs and the POP candidate MCCPs have been detected in plastic packaging and agricultural plastics. Therefore, this chapter compiles information on the monitoring of POPs in synthetic textiles, plastic packaging, and agricultural plastics.

5.2 Monitoring POPs in Textiles

5.2.1 Background

Textiles are another important sector in the use of plastics, with a consumption of 59 million tonnes of plastics in 2015 dominated by polyester (Figure 2; Geyer *et al.* 2017). Textiles are considered a priority sector for chemicals in plastic due to direct human exposure and the release of chemicals into the indoor environment (UNEP and BRS Secretariat 2023). This is partly because the amount of additives used in textiles can vary from 5 to 15% of the weight of a garment (Safer Made 2018).

A wide range of POPs have been and are used in textiles (Table 1). A considerable share of brominated POPs has been used as flame retardants in the textile sector (c-PentaBDE, c-OctaBDE, decaBDE, and HBCD) (Table 2). Additionally, chlorinated flame retardants (SCCPs, MCCPs**Error! Bookmark not defined.**, or Dechlorane Plus) have been or are still used to some extent in textile production. The use of flame retardants depends on the flammability standards for textiles in different uses (Charbonnet *et al.* 2020).

The textile sector is a major user of PFAS (Lassen *et al.* 2015). Textile manufacturers utilize the oil- and water-resistant properties of PFAS to produce stain- and rain-repellent materials (Hill *et al.* 2017; Schellenberger *et al.* 2019). PFAS are also used to treat leather and household textiles such as carpets and tablecloths (Kotthoff *et al.* 2015; Glüge *et al.* 2020). Synthetic carpets, particularly those made of nylon, have been a major use of fluorinated POPs like PFOS, PFOA, and related compounds (UNEP 2023c; IPCP webinars[15]). The use of PFOA and PFOA-related compounds in textiles is exempted and likely continues in some regions.

5.2.2 POPs monitoring in chemical formulation used in textile production

One promising approach to monitor and control the contamination of textiles by POPs is the monitoring and control of chemical mixtures used in textile production. Initial studies have been conducted and are shortly mentioned.

5.2.2.1 Screening of PFAS in textile finishing

Textile finishing agents (TFAs) were screened for fluorinated POPs and other PFASs (Mumtaz *et al.* 2019). Quantification results demonstrated a significant presence of PFOS (0.37 mg/L) in TFAs manufactured using electrochemical fluorination technology. The products obtained through short-

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[15] Prof. Ian Cousins "Introduction to fluorinated POPs (PFOS, PFOA, PFHxS and other PFAS) related to polymers & plastics". IPCP webinar Part 1. 25 April from 2:38:56 on https://www.youtube.com/watch?v=u5Ht6vg8Y04&t=2s ;

Dr. Roland Weber "Monitoring of PFAS in products & recycling including screening methods for fluorine in plastics and side-chain fluoropolymer coatings" IPCP webinar Part 2. 19 May from 3:10:08 on https://www.youtube.com/watch?v=WOHifcF71Xo&t=3s

chain PFAS-based telomerization were dominated by perfluorooctanoic acid (mean concentration: 0.29 mg/L). Moreover, the total oxidisable precursor assay indicated high levels of indirectly quantified precursors, including side-chain fluorinated polymers partly containing long alkyl chains (C7–C9) (Mumtaz *et al.* 2019).

5.2.2.2 Screening of PFAS in dirt repellents and impregnations

Synthetic textiles and carpets can also become contaminated with PFAS by the application of impregnation sprays. PFAS were found in 7 out of 16 waterproof impregnation sprays, with 3 sprays containing PFOA-related compounds (Sero *et al.* 2022). In an earlier study in 2010, impregnation sprays contained long-chain fluorotelomers (Fiedler *et al.* 2010), which can degrade to PFOA or long-chain perfluorocarboxylic acids (PFCAs), which have been evaluated as POP candidates by the POP Review Committee and are proposed for listing in the Stockholm Convention at the next Conference of Parties (UNEP 2023f).

5.2.2.3 Screening of unintentional POPs in chemicals used in textile production

The textile industry uses a range of organochlorine chemicals that may contain unintentional POPs (UNEP 2013) and can cross-contaminate synthetic fibres. Chlorobenzenes and chlorotoluenes are found in textile applications in the apparel and footwear supply chains (ZDHC 2018a,b). Chlorobenzenes and chlorotoluenes may be used as carriers during the dyeing process of synthetic fibres, especially for polyester and polyester blends (ZDHC 2018a). Furthermore, chlorophenols are used in textile production (ZDHC 2018b). Chlorobenzenes and chlorophenols contain unintentional POPs such as PCDD/PCDFs or PCBs at different levels (UNEP 2013). A wide range of other dyes and pigments used in the textile industry contains unintentional POPs that can be transferred to the textile, and PCDD/PCDF levels can even increase during textile production (Križanec and Majcen Le Marechal 2006).

Chloranil is another chemical used in dyes in the textile industry. High levels of unintentionally POPs, including PCDDs/PCDFs, PCBs, PeCB, and HCB, were detected in chloranil samples from Chinese producers up to 522 µg TEQ/kg PCDDs/PCDFs (Liu *et al.* 2012). This is 105 times above the low POPs threshold of the Basel Convention for wastes (5 µg TEQ/kg) (UNEP 2023b). The estimated total PCDD/PCDF content of chloranil from China alone was 1044 g TEQ for 2012 (Liu *et al.* 2012), which was about 10% of China’s total PCDD/PCDF inventory and 1% of global dioxin inventory (Wang *et al.* 2016). Considering that these compounds were directly present in treated consumer products like textiles this is a high human risk for textile workers and consumers as well as a source for environmental contamination.

5.2.2.4 Recommendation of extension of monitoring of POPs present in textile production

Up to now, only one published study has assessed fluorinated POPs in textile finishing. Since partly side-chain fluorinated polymers (SFPs) are used in textile finishing, the monitoring of PFOA and PFOA-related compounds and other PFASs is complex and requires monitoring strategies like total fluorine screening and TOP-Assay[18,19] or other degradation of the covalent bonds in SFPs (see Sections 5.2.2.1 and 5.2.3.1).

Monitoring of POPs, including unintentional POPs, in chemicals used for textile production should be expanded to encompass more POPs and various textile finishes and other chemicals of concern used in textile production and textiles (UNEP and BRS Secretariat 2023). This would enable a more comprehensive assessment of the presence and risks associated with chemical exposure in textiles production and use and would broaden the understanding of the presence and potential impact of

POPs in textile products. This could fill the knowledge gaps and would enable a more comprehensive assessment of the risks associated with chemical exposure in textile production and use and would broaden the understanding of the presence and potential impact of POPs in textile products.

5.2.3 POPs monitoring in textiles

Several studies on POP monitoring in textiles have been published[16] for various groups of POPs. However, this can only be considered as a beginning of a more robust monitoring and documentation.

5.2.3.1 Monitoring fluorinated POPs in textiles

A wide range of studies have monitored PFOS and PFOA in different textile applications, such as outdoor wear and in accessories for outdoor sports (e.g., waterproof shoes, jackets, back-packs, tents) (Santen and Kallee 2014; Kottoff *et al.* 2015; van der Veen *et al.* 2020 and 2022; Strakova *et al.* 2022). In a recent study of IPEN, 84% (21/25 samples) of outdoor clothing and sportswear products from China and Russia contained PFASs (Strakova *et al.* 2022). The main PFAS detected was 8:2 FTOH, which is a PFOA precursor. Considering the detected levels, the study concludes that PFAS are present in side-chain fluorinated polymers (SFPs) often used to make outdoor clothing water- or dirt-repellent (Strakova *et al.* 2022).

During outdoor use, PFASs can be released from textiles into the environment. In a study, the effects of aging, washing, and tumble drying on the concentration of extractable PFASs in the durable water-repellent coating of perfluorohexane-based short-chain SFPs (FC-6 chemistry) and of perfluorooctane-based long-chain SFPs (FC-8 chemistry) were assessed (van der Veen *et al.*2022). For this purpose, polyamide (PA) and polyester (PES) fabrics were coated with FC-6- and FC-8-based SFPs. The results show that aging of the coated fabrics leads to an increase in concentration and the formation of perfluoroalkyl acids (PFAAs), including PFOA for FC-8 chemistry but not for the FC-6 chemistry (van der Veen *et al.* 2020). The results demonstrate that weathering can influence PFASs used in durable water-repellent coating of outdoor clothing, affecting both the PFAS profile and measured concentrations.

In another study, thirteen commercial textile samples were exposed to elevated ultraviolet (UV) radiation, humidity, and temperature in an aging device for 300 hours, simulating the lifespan of outdoor clothing (van der Veen *et al.* 2020). Before and after this process, textile samples were extracted and analysed for ionic PFASs, such as perfluoroalkyl acids (PFAAs) and perfluorooctane sulfonamide (FOSA), as well as volatile PFASs, including fluorotelomer alcohols (FTOHs), acrylates (FTACs) and methacrylates (FTMACs). The results showed that weathering could impact the presence of PFASs including POPs in the durable water-repellent coating of outdoor clothing, affecting both the PFAS profile in extracts and the measured concentrations. In most weathered samples, the PFAA concentrations increased from 5 to over 100 times. Additionally, the concentrations of volatile PFASs also increased, reaching up to 20 times higher levels (van der Veen *et al.* 2020). The increase in concentration of PFAAs is attributed to hydrolysis and other forms of degradation of SFPs and other precursors.

The studies showed that the majority of PFOA and other ionic PFASs are not extractable in new textiles with durable water-repellent coatings but that degradation and associated release occur during the aging of textiles. A study comparing the total fluorine content in such textiles with the amount of extractable PFAS found that less than 3% of the fluorine was extractable or volatile and even after

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[16] Most monitoring of POPs and other chemicals of concern in textiles are conducted by textile companies and retailers and most of these monitorings are not published.

application of the Total Oxidizable Precursor (TOP) Assay, only up to 14% of the fluorine could be quantified as extractable PFAS (Robel *et al.* 2017).

This issue related to ide-chain fluorinated polymers has been discussed in IPCP webinars on POPs in plastic through various presentations, including an introduction to POPs-PFAS and plastics[17], the screening of fluorine content for PFAS monitoring[18], and the application of the TOP-Assay for monitoring of PFOS/PFOA and related compounds[19].

5.2.3.2 *Monitoring fluorinated POPs in leather*

In a national screening study for PFOS in 34 consumer products, the highest levels were found in two leather products, including office furniture (pool of 3) and black shoes, with concentrations of 38 and 21 µg/m^2, exceeding the EU regulation of 1 µg PFOS/m^2. Carpets were near the regulatory limit of 1 µg PFOS/m^2. The relatively low levels detected indicate that PFOS were not applied as a high-performance chemical but rather as a by-product or contaminant of other PFASs (Hertzke *et al.* 2009).

5.2.3.3 *Monitoring fluorinated POPs in carpets*

In the past, synthetic carpets, especially those made of nylon, were one of the major use of PFOS and PFOA related compounds (Vallette *et al.* 2017). The California Department of Toxic Substance Control (DTSC) has identified carpets, rugs, indoor upholstered furniture, and their associated care and treatment products as the most significant and widespread sources of PFAS exposures (California DTSC 2016). More than 40 chemicals of concern were identified including PFOS and PFOA, DecaBDE, c-PentaBDE, as well as chlorinated paraffins (Vallette *et al.* 2017). Still monitoring studies are rare (Lang *et al.* 2016; Wu *et al.* 2020).

5.2.3.4 *Monitoring brominated POPs in textiles*

Depending on the flammability standards, textiles can be treated with flame retardants, including PBDEs (decaBDE exemption for textiles) and HBCD (until 2013).

Kajiwara *et al.* (2008 and 2009) conducted an analysis of textiles, such as curtains and other products available in the Japanese market, using a handheld XRF analyser to measure bromine content. Ten bromine-containing textiles, mainly curtains, were selected and analysed. All analysed textiles contained HBCD in percentage range. This indicates that HBCD was one of the major brominated flame retardant used in textiles in Japan.

5.2.3.5 *Monitoring SCCPs/MCCPs in textiles*

The use of SCCPs in textiles is exempted by the Stockholm Convention. Only a few studies have been conducted to measure SCCP/MCCP in textiles. A study in the Czech Republic determined the presence of SCCPs and MCCPs in 28 samples of T-shirts and socks. CPs were found above the limits of quantification in all samples, with concentrations ranging from 34 to 5940 ng/g (with a mean of

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[17] Prof. Ian Cousins “Introduction to fluorinated POPs (PFOS, PFOA, PFHxS and other PFAS) related to polymers & plastics”. IPCP webinar Part 1. 25 April from 2:38:56 on https://www.youtube.com/watch?v=u5Ht6vg8Y04&t=2s

[18] Dr. Roland Weber “Monitoring of PFAS in products & recycling including screening methods for fluorine in plastics and side-chain fluoropolymer coatings” IPCP webinar Part 2. 19 May from 3:10:08 on https://www.youtube.com/watch?v=WOHifcF71Xo&t=3s

[19] Prof. Jun Huang „UV-activated Total Oxidizable Precursor (TOP) Assay – option to “extract” PFOS, PFOA and other PFAS from side-chain fluoropolymers?“ IPCP webinar Part 3, 21 May from 2:08:28 on https://www.youtube.com/watch?v=o341GAxt2nY&t=1s

1260 ng/g and a median of 417 ng/g). Samples with a substantial proportion of synthetic fibres contained higher CP concentrations, up to 22 times higher on average for SCCPs and 7 times higher on average for MCCPs, compared to garments composed exclusively of cotton (Tomasko *et al.* 2023).

In a monitoring study of SCCPs and MCCPs in products in China, including fire-protective clothing (3), tent materials (4), car seat fabric (3), blackout fabric (3), and gauze (6), no SCCP/MCCP were detected in the 19 textile materials (Chen *et al.* 2021). However, it is important to note that the detection limit in this study was considerably high (50,000 ng/g), in contrast to the Czech study, which had a detection limit four orders of magnitude lower (5 ng/g) (Tomasko *et al.* 2023).

5.2.3.6 Monitoring UV-328 in textiles

Regarding the use of UV-328 in textiles, the typical loading of UV-328 is not known. Avagyan *et al.* (2015) measured UV-328 in various clothing articles. Among the 26 clothing articles made from various materials and produced across 14 different countries, two samples primarily composed of cotton revealed the presence of UV-328 at concentrations of 8.05 and 108 ng/g. These levels indicate unintentional contamination rather than intentional additive use in this limited set of samples. Other ultraviolet absorbers (UVAs) like UV-234 and UV-P were detected in over 50% of the samples and in higher concentrations, suggesting their intentional use for UV protection in the analysed textiles and major use of these (Avagyan *et al.* 2015).

More monitoring studies with larger sample numbers would be interesting to have a more robust understanding if UV-328 is to some extent intentionally used in textiles.

5.2.3.7 Monitoring unintentional POPs in textiles

The monitoring of unintentional POPs in textiles has been the subject of limited research, with only a few studies addressing PCDD/PCDFs or PCBs in textile materials (Horstmann and McLachlan 1995; Klasmeier and McLachlan 1998). These studies have revealed that synthetic textiles were less affected by unintentional POP contamination when compared to cotton-based textiles (Horstmann and McLachlan 1995; Klasmeier and McLachlan 1998).

Moreover, a study on textiles treated with PBDEs or HBCD and exposed to natural sunlight revealed the presence of polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/PBDFs) in textiles containing PBDEs. In contrast, textiles treated with HBCD did not exhibit these contaminants. Notably, the study indicated that PBDF levels can increase due to the degradation of PBDEs to PBDFs (Kajiwara *et al.* 2013).

5.2.4 POPs monitoring of textile waste

A rapid extraction method was developed for monitoring PBDEs and HBCD in plastic waste and successfully applied to real consumer products entering the waste stream, reducing analysis time, solvent consumption, and increasing sample throughput, which is crucial to compliance with the POP legislation (Abdallah *et al.* 2017). The monitored samples included textiles from end-of-life vehicles with POP-BFR concentrations exceeding 3% (Abdallah *et al.* 2017). A systematic assessment of POPs and other chemicals of concern in textile waste has not been conducted yet.

5.2.5 POPs monitoring in textile recycling

A recent review has emphasized the lack of studies monitoring contaminants in textile recycling, underscoring the need for further research (Undas *et al.* 2023). Monitoring POPs (and other chemicals of concern) in the textile recycling process represents a valuable opportunity to understand the presence of POPs in textiles in end-of-life, similar to what is done with shredded plastics from WEEE (see Section 2.3.2) or vehicles (see Section 3.3.2). Gathering robust data is essential to mitigate the risks associated with textile recycling, whether in the creation of new textile products or in the reuse of textiles containing POPs, such as tents in exposure sensitive contexts[20]. Moreover, recycled textiles are even suggested as possible substrate for low-cost hydroponic systems for growing vegetables (Brockhagen *et al.* 2021).

Despite efforts, average recycling rates of textiles is still below 20%, with only Europe reporting recycling rates slightly above 20% (Bureau of International Recycling 2022). The implementation of the "2020 Circular Fashion System Commitment" by the international fashion industry, aimed at enhancing textile circularity[21], should lead to an increase in the recycling rate. However, this increase will necessitate ongoing monitoring of POPs and other chemicals of concern in textile recycling.

Synthetic carpets, where several POPs can be present (including PFOS/PFOA related compounds, PBDEs, and SCCPs/MCCPs), are often subjected to downcycling and repurposed in various applications such as outdoor equestrian areas (manèges), plastic recovery, the production of carpet fibres, automotive padding, and as a growth medium for plants (Changing Markets Foundation 2019). The fate of POPs additives and other chemicals of concern has not been thoroughly investigated in these scenarios. Additionally, some carpets find a second life in gardens, where they serve as mulch and could release POPs and other chemicals of concern to the environment.

5.2.6 Further monitoring need of POPs in textile materials

There is an imperative need for more extensive monitoring of POPs in textiles throughout their lifecycle, including the chemicals and chemical mixtures used in their manufacturing (see Section 5.2.2.4), textiles available on the market, textile waste (see Section 5.2.4), and, particularly, textiles undergoing recycling , including carpets (See Section 5.2.5).

In the specific case of PFOS, PFOA, and PFHxS-related compounds, it is important to consider that the monitoring process must contend with the fact that a large share of POP-PFAS related compounds are found within side-chain fluorinated polymers (SFPs) (Fiedler *et al.* 2019; OECD 2022; UNEP 2023c). This aspect introduces unique challenges related to the extraction process.

5.3 Monitoring POPs in plastic packaging

5.3.1 Background

Plastic packaging is the largest overall use of plastics (see Figure 2 and Figure 3; Geyer *et al.* 2017; Plastics Europe 2022a). POPs such as flame retardants are normally not used in packaging materials. However, UV stabilizers are used in plastic packaging and even in food packaging. Therefore, with the recent listing of UV-328 as a POP in the Stockholm Convention (IISD 2023), a first POP additive used in packaging is now listed, demanding control and monitoring in packaging in particular in food contact materials.

Additionally, SCCPs and MCCPs[2] are used to some extent in the production of plastic packaging as auxiliary and can be detected in plastic packaging, including food packaging (Dong *et al.* 2020; Wang *et al.* 2022; see below Section 5.3.2.1).

POPs can also be introduced through recycling into packaging materials. This is relevant for HBCD used in EPS/XPS (see Section 5.3.2.3).

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[20] https://cleaning-hacks.sharkclean.co.uk/15-ways-to-recycle-your-old-festival-tent/

[21] https://www.oneplanetnetwork.org/knowledge-centre/resources/2020-circular-fashion-system-commitment-final-report

5.3.2 Monitoring POPs in packaging materials

5.3.2.1 SCCPs/MCCPs in plastic packaging

A monitoring study of 31 unused commercial PE and PP packaging for animal feed in China revealed a high contamination of SCCP and MCCP[2] within a range of ppm. The average SCCP values in the PP and PE samples were 60.0 and 54.5 mg/kg, respectively, with a maximum level of 600 mg/kg (Dong *et al.* 2020). The average MCCP[2] concentrations in the PP and PE samples were 62.7 and 9.23 mg/kg, respectively.

In another study, the presence of CPs was assessed in packaging for chips, cookies, dried fruit, and pie, primarily made from biaxially oriented polypropylene (BOPP) and vacuum metallized PET (VMPET). SCCPs were detected in all food packaging, with concentrations ranging from 14.0 to 8,334 ng/g, while MCCPs were below the detection limit in some samples, reaching a maximum concentration of 10,338 ng/g (Wang *et al.* 2018).

A third study examined the presence of SCCPs and MCCPs in tea packaging from various regions of China, primarily made from PE and PP. These compounds were found in all 19 samples analyzed, with concentrations in the range of 43.7 to 3858 ng/g and 7.51 to 1835 ng/g, respectively. The study also highlighted that CPs in tea packaging could potentially migrate into Chinese green tea, becoming a potential source of CP contamination (Wang *et al.* 2022).

5.3.2.2 UV-328 in new plastic packaging

Several studies have found UV-328 in plastics and packaging materials (Chang *et al.* 2013; Zhang *et al.* 2016; Rani *et al.* 2017). Zhang *et al.* (2016) found UV-328 concentrations ranging from 25 to 76 µg/g in milk packaging and snack packaging, along with other UV absorbers.

Chang *et al.* (2013) reported a concentration of 2.0 µg/g of UV-328 in commercial polyethylene terephthalate (PET) beverage packaging and 13.9 µg/g in low-density polyethylene (LDPE) packaging. Rani *et al.* (2017) reported concentrations in the range of 0.0027–0.4 µg/g in newly produced plastics.

In addition, UV-328 has been detected in post-consumer recycled PET intended for subsequent manufacturing of food contact materials, although the concentration of UV-328 was not reported (Dutra *et al.* 2014).

Concentrations of nine representative UV absorbers were measured in the plastic bottle caps of 10 beverages, 4 food packages, and 4 plastic shopping bags purchased from Japanese grocery stores. Eight UV absorbers were detected, including UV-328. Specifically, 2-(2-hydroxy-5-methylphenyl) benzotriazole (UV-P) and 2-(2-hydroxy-3-tert-butyl-5-methylphenyl)-5-chlorobenzotriazole (UV-326) were detected in all the bottle caps at concentrations in the order of ng/g while UV-328 was only detected in some of the caps (Sakuragi *et al.* 2021).

5.3.2.3 HBCD in plastic packaging

Rani *et al.* (2014) determined the presence of HBCD in 34 polystyrene products, including EPS and XPS. Some food related EPS products contained relatively high concentration of HBCD including an ice box (960 mg/kg) and a disposable tray (8.4 mg/kg) used in fish market. HBCD was also detected in buoy used in aquaculture (53.5 mg/kg). This study showed that HBCD enters packaging, including food packaging, and that PS containing HBCD is recycled to some extent, including packing and other products.

In another study, 50 samples of PS packaging materials from the UK and 20 from Ireland were collected to evaluate the occurrence of HBCD in EPS/XPS packaging, which might result from the recycling of contaminated PS (Abdallah *et al.* 2018). HBCD was detected in 63 (90 %) of the samples, with concentrations in 4 samples from Ireland exceeding the EU's low POP concentration limit of 0.1% above which articles may not be recycled. Moreover, 2 further samples contained HBCD >0.01%, the EU limit above which articles may not be placed on the market. A shift towards α-HBCD in EPS packaging compared to EPS insulation foam is consistent with the additional thermal processing experienced by recycled PS and suggests the source of HBCD in PS packaging is recycled PS insulation foam (Abdallah *et al.* 2018).

5.3.3 Pollutants mixtures in recycled packaging

In a recent review, it was concluded that the recycling may lead to the accumulation of BFRs (some of which are POPs), CPs, phthalates, toxic metals, and polycyclic aromatic hydrocarbons (PAHs) in plastics when subjected to continuous recycling. Furthermore, the recycling process itself can introduce metals, especially metal salts, and BFRs to end up in the recycled product. This review underscored the need for the implementation of a comprehensive assessment strategy for contaminants associated with plastic packaging (Undas *et al.* 2023).

5.3.4 Recommendation for further monitoring of POPs in plastic packaging materials

With the inclusion of POPs in packaging, increased monitoring is essential, especially in the case of UV-328. Also, the detection of SCCPs and MCCPs in packaging, including food packaging, highlights the importance of monitoring and establishing control measures. This includes the assessment of the use of SCCPs/MCCPs in plastic packaging production processes.

Furthermore, packaging produced from recycled plastic might be screened for different POPs groups. Also, other chemicals of concern like metals, PAHs and phthalate should be assessed in recycled packaging (Undas *et al.* 2023; UNEP and BRS Secretariat 2023).

5.4 Monitoring POPs in agricultural plastic

Agricultural plastics account for around 3.5 to 4% of all plastic produced, with approximately 12.5 Mt produced in 2017 and 15.6 Mt produced in 2021 (FAO 2021; Plastics Europe 2022a and Figure 3). The major plastic types used are LDPE, linear low-density polyethylene (LLDPE), PP, and PVC (Figure 4). Additives in agricultural plastics can be released directly into the environment, potentially contaminating agricultural soils and affecting food safety. As a result, agricultural plastics are considered as one of the priority sectors of chemicals of concern in plastics (UNEP and BRS Secretariat 2023).

5.4.1 Monitoring of UV-328 in agricultural plastic

An assessment of UV absorbers in 6 different types of biodegradable plastic products in China revealed a total concentration ranging from 0.037 to 1,139 mg/kg (Yao *et al.* 2023). Various UV absorbers, including UV-328, UV-234, UV-326, UV-329, UV-360, UV-P, as well as BP (benzophenone), BP-3, and BP-12, were detected in plastic bags, garbage bags, food packaging bags, plastic lunch boxes, tableware, product packing bags, and mulch films. The biodegradable mulch films showed significantly higher UV absorber concentrations (mean: 1,139 mg/kg) compared to other sample categories (mean: 0.037–0.19 mg/kg). Specifically, UV-328 and BP-1 were the predominant UV absorbers in the biodegradable mulch films, with levels ranging from 727 to 1,063 mg/kg and 317 to 506 mg/kg, respectively (Yao *et al.* 2023).

Furthermore, a second study on UV absorbers in mulch films found notably higher levels in bioplastic, which were 400 times higher compared to PE mulch films (Li *et al.* 2023a). Biodegradable plastic films are usually made of bio-based polymers, which are brittle and prone to crack. It is necessary to add UV stabilizers to mitigate degradation (Li *et al.* 2023a). Carbon black is generally used for UV stabilization in mulch films, while its UV absorption spectrum is relative narrow and cannot completely prevent the aging of the films when used alone. To maintain stability within the planting cycle of biodegradable mulch, organic UV absorbents are also frequently added by manufacturers to extend its lifetime, which may also cause the accumulation of these chemicals in soils. This second study also assessed soil contamination, revealing that the average UV absorber concentration was up to 10 times higher in soils mulched with biodegradable films compared to soils mulched with PE films (Li *et al.* 2023a).

Both studies concluded that there may be a potential risk of UV absorber contamination and exposure in the environment due to the widespread use of biodegradable plastics.

5.4.2 SCCP/MCCP in PVC plastic films

PVC foils are used in agricultural films with associated release of additives (Yan *et al.* 2021).

In an initial screening of PVC in 4 plastic films, SCCPs were detected in one film at 100 mg/kg, and MCCPs were found at concentrations ranging from 70 to 1600 mg/kg, indicating certain use of CPs in PVC films (Chen *et al.* 2021).

5.4.3 Recommendation of further monitoring of POPs in agricultural plastic

The recent findings regarding the use of UV-328 as an additive in biodegradable mulch films in China (Li *et al.* 2023a; Yao *et al.* 2023) and the resulting contamination of agricultural soils underscore the relevance of UV-328 in this application. Therefore, further studies of UV-328 in agricultural plastic in other regions are needed to monitor its use and release into the environment.

Since PVC is another type of plastic used in agricultural applications, such as pipes, mulch films, and other uses, monitoring of SCCPs and MCCPs in agricultural PVC products is needed, considering the widespread use of these compounds as additives in PVC (Chen *et al.* 2021; Chen *et al.* 2022).

Furthermore, there have been no studies on the use of recycled plastic in agriculture and its POP content. A screening of recycled plastics used in agriculture and their POP content is recommended to fill this knowledge gap.

6 Monitoring of plastic pellets and shreds produced from recycled plastic and related control

6.1 Background on recycled plastic pellets and shreds

The production and control of plastic shreds and the subsequent production of recycled plastic pellets represent an important step in the life cycle of a circular economy of plastics (see Section 1.5). This stage provides an opportunity to monitor and eliminate POPs and other hazardous chemicals, with the aim of reducing and ultimately preventing the transfer of these compounds to newly manufactured plastic products with a priority for those products that come into direct contact with food, skin, or vulnerable population such as kids (e.g. toys).

6.1.1 Loss of pellets to the environment and related environmental contamination

Plastic pellets (sometimes referred to as nurdles), including recycled pellets, can be released into the environment in large amounts during their production and transportation, as recently evidenced by the spill of 70-75 billion individual pellets in a ship accident off the coast of Sri Lanka (Karlsson *et al.* 2018; UNEP 2022). This situation poses a high risk of releasing POPs associated with these plastics into the environment. Initial country assessments suggest that both the formal and informal sectors manage recycled pellets within companies because they are valuable products (see country reports on recycling situation in Annex 8.1 to 8.6). However, plastic which cannot be recycled contributes to pollution due to the lack of waste management and thermal recovery options (see Section 6.1.3).

6.1.2 Contamination of products from recycling

The recovery of inefficiently sorted plastic from sectors with major (former) POPs use such as WEEE (Section 2.1.2), ELV (Section 3.1.2), and construction (Section 4.1.2) can results in the contamination of recyclates with POPs and other chemicals of concern in new plastic consumer products. This can result in POPs such as PBDE[22] contamination of exposure-sensitive products like children's toys and food contact materials, such as kitchen utensils (Chen *et al.* 2009; Puype *et al.* 2015; Kuang *et al.* 2018, Kajiwara *et al.* 2022, UNEP and BRS Secretariat 2023). However, in many countries, there is a lack of awareness on the presence of POPs in recycling streams (see country experiences Annex 8.1 to 8.6), inadequate regulatory controls, or a lack of implementation, particularly concerning food contact products (see, e.g., assessment of plastic recycling in Nigeria Annex 8.2), and limited analytical capacity (Haarman and Gasser 2016).

6.1.3 Contamination of the wider environment and humans

Currently, most of plastic waste containing POPs additives in low- and middle-income countries are disposed of in dumpsites and can contaminate the environment, food, and humans at the end-of-life due to POP releases from these sites from open burning and in leachates with associated pollution (Weber *et al.* 2011; Oloruntoba *et al.* 2019, 2021). Waste management, including recycling activities, involving open burning of plastic waste or the use of combustion facilities not operated according to BAT/BEP and associated mismanagement of ashes result in significant environmental contamination along with POP contamination of the food chain and related exposure of humans (Wong *et al.* 2007; Petrlik & Bell 2020; Oloruntoba *et al.* 2019, 2021; Petrlik *et al.* 2022). By recycling plastic to pellets and new products this pollution is reduced (UNEP 2023d). However, it was discovered that plastic which could not be recycled into new plastic products was sold as fuel for cooking in some countries (see, e.g., assessment of plastic recycling in Nigeria Annex 8.2). Similarly, plastic waste from recycling was sold in India as cheap fuel to brick kilns (Haarman and Gasser 2016). The use of non-recyclable plastic as fuel in small boilers and lime kilns resulted in environmental contamination with PCDDs/PCDFs, including in the food chain (Petrlik *et al.* 2022).

6.2 Monitoring of POPs in plastic pellets and shreds

Monitoring and controlling POPs in recycled plastic pellets are essential to ensure sustainability and safety in the supply chain and mitigate risks to public health and associated environmental contamination (see Section 6.1). Only two study on POPs in recycled plastic pellets have been conducted including a study from the International Pollutant Elimination Network (Brosché *et al.* 2021) and UNEP initiated a study in the frame of the GMP to monitor POPs in recycled pellets and shreds in different regions for assessment of this important plastic material category in the circular

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[22] In addition, PBDD/PBDF are present in high concentration in WEEE plastic containing PBDEs (Sindiku *et al.* 2015b) and can be transferred e.g. to children's toys and other consumer plastic at significant levels (Budin *et al.* 2020; Behnisch *et al.* 2023).

economy and the connections between environmental monitoring and the potential emission/release from high POP impact sectors (UNEP 2023e). These two studies are shortly described below.

6.2.1 Study on POPs in recycled HDPE pellets

Brosché *et al.* (2021) analyzed 24 samples of plastic pellets sold as high-density polyethylene (HDPE), purchased from recycling facilities in 23 countries, mostly low- and middle-income countries. These samples underwent testing to determine the presence of PBDEs, HBCD, and UV stabilizers, including UV-328. The result revealed that PBDEs were detected in 92% of the samples, with concentrations ranging from 0.001 to 15 mg/kg (Brosché *et al.* 2021). None of the samples were above the Basel Convention lowest provisional limit for the low POP content, which is 50 mg/kg.

HBCD were only detected in 4% of the samples, and at a low concentration of 0.0003 mg/kg. This is because HBCD has been primarily used in polystyrene polymers (EPS, XPS, and HIPS), resulting in low cross contamination of HDPE.

As for UV-328, it was detected in 71% of the samples, with concentrations ranging from 0.0001 to 0.33 mg/kg. Other UV stabilizers, such as UV-234, UV-326, UV-327, and UV-329, were also detected (Brosché *et al.* 2021).

6.2.2 Study on monitoring POPs in recycled pellets in the frame of the GMP

Due to the limited research on POPs in recycled plastic pellets and to get basic information on the interlink to environmental POPs pollution, UNEP initiated a screening study of POPs in recycled pellets and shreds in 9 countries in Africa, Asia, and the GRULAC region as part of the GMP (UNEP 2023e). Experiences related to plastic recycling practices were gathered from these selected countries and are attached as Annexes in this report. A wide range of POPs were analysed in various types of recycled plastic pellets/shreds, including the listed PBDEs, HBCD, SCCPs, POP-PFAS, Dechlorane Plus, and UV-328, as well as MCCPs evaluated for listing. The data has been compiled in another report (UNEP 2023e). Additionally, from selected plastic pellets, different endocrine activity, genotoxicity, and cell toxicity were measured with bioassays (UNEP 2023e).

6.3 Production of plastic pellets/shreds from recycled plastic and related contamination

Additives such as POPs in plastic can be transferred to pellets if they are not separated before pellet production.

6.3.1 Insight in the situation of production of recycled pellets and shreds

In the assessment of the production and availability of recycled plastic pellets in the frame of the UNEP GMP project, it was found that the control of the use of pellets differs between countries (see, e.g., the situation in Nigeria in Annex 8.2 and Thailand in Annex 8.3). While Thailand enforces a strict separation of recycled plastic used in food contact material, the recycling of plastics in Nigeria seems uncontrolled, in particular within the informal sector. On the other hand, it was discovered in Thailand that all types of plastic pellets, including those with high bromine content to meet specific flammability standards, were being produced, resulting in elevated PBDEs content in some pellet samples (UNEP 2023e). In contrast, no production of recycled pellets meeting flammability standards was found in Nigeria.

6.4 Control of plastic recycling by separation of POPs-containing plastic

There are different options to control the presence of POPs in the plastic recycling process to prevent contamination of recycled materials and new plastic products. These options are shortly outlined below, with regulatory aspects detailed in Section 6.5.

6.4.1 Selection of input materials for recyclates

After understanding the presence of POPs in major plastic waste, the plastic waste containing POPs could be excluded from the recycling process if suitable separation technologies are not available. Alternatively, the POP fraction in these materials can be separated using appropriate techniques (see Section 6.4.2 and Stockholm Convention PBDE BAT/BEP guidance (UNEP 2021i)).

It's worth noting that other hazardous additives must also be considered in the plastic recycling process (Hahladakis *et al.* 2018; UNEP and BRS Secretariat 2023a; UNEP 2023a).

6.4.2 Separation of POPs-containing plastic

There are different technologies applied in full scale to separate certain POPs-containing plastic in the recycling of plastic from WEEE or ELVs. In the frame of the Stockholm Convention, a "*Guidance on best available techniques and best environmental practices relevant to the polybrominated diphenyl ethers listed under the Stockholm Convention*" has been published (UNEP 2021i). This document provides an introduction to commercial PBDE mixtures and their use in different sectors and related products to inform the management of these products and control the recycling of affected plastic flows. The guidance describes BAT/BEP processes for the screening and separation of plastic containing PBDEs with the aim of eliminating PBDE-containing plastics during recycling.

Recycling processes for both waste electrical and electronic equipment (WEEE) and end-of-life vehicles (ELV) involve the separation of parts potentially containing brominated flame retardants, including PBDEs, either manually at the beginning of the treatment process in the dismantling or depollution or, in most cases, during mechanical recycling with shredding where separation itakes place at the end of the recycling process. Different methods and a list of full-scale recycling plants are described in the SC BAT/BEP guidance (UNEP 2021i).

Since key separation steps use the sink-float approach or XRF screening, it is likely that plastics containing chlorinated flame retardants can also be separated using these methods. However, the listing of UV-328, the first non-halogenated POP in the Stockholm Convention, poses challenges to its separation because it cannot be screened-out by XRF or separated using the sink-float approach.

A technology recently developed in full scale for the recycling of HBCD-containing EPS/XPS involves a solvent dissolution process that separates the polymers from the additive (HBCD). The separated PS can be recycled for the production of new EPS/XPS insulation[23]. A similar separation process can be applied to WEEE plastics containing BFRs (Schlummer *et al.* 2006).

6.4.3 Control of the use of plastic pellets from recycling

While POPs can be partially separated within recycling streams (Section 6.4.2), some POPs may persist after separation, although their levels are normally below the low POP content threshold established by the Basel Convention or the limits for unintentional trace contaminant established by the European Union (European Commission 2019). Consequently, the recycling of these recycled materials into new products is permitted, but certain specific uses may be restricted. This is the case, e.g., with food contact materials, where in the EU, only recycled plastic materials from clean PET fractions, such as PET beverage bottles, are allowed to be recycled into food contact materials (see Section 6.5.3; European Commission 2022). A similar restriction might be considered for toys, which also pose a particular risk of exposure to children by mouthing and other exposure pathways (Aurisano *et al.* 2021b; Aurisano *et al.* 2022).

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[23] https://polystyreneloop.eu/

6.5 Regulatory control of plastic recycling and recyclates

6.5.1 Basel Convention low POPs limits

The Basel Convention has established low POPs limits for the environmentally sound management of waste containing POPs, including plastic wastes (UNEP 2023b). Some of the low POPs limits for POPs in plastic are provisional and include various suggested values, such as those for PBDEs (50 mg/kg, 500 mg/kg, or 1000 mg/kg). The determination of a final low POP limit for POPs will be subjects to further assessment in the Open-Ended Working Group. Countries might choose specific low POP limit for national regulation and control (see, e.g.. European Commission 2019). The International Pollutant Elimination Network also publishes regular briefings on low POP limit (IPEN 2023).

6.5.2 Unintentional trace contamination and regulatory limits of POPs in plastic

If POPs are transferred through recycling to new plastic products, they are considered non-intentionally added substances (NIAS) since they were not intentionally added. These NIAS can be addressed by setting a regulatory limit for “Unintentional trace contaminants”, as established, e.g., by the European Union for POPs in Annex 1 of the POP Directive (European Commission 2019).

6.5.3 Regulatory control of food contact materials

As described in the current document, POPs can be detected in various plastic sectors and in plastic waste and recycling streams. In Europe, the use of recycled plastic for food contact materials is regulated by Commission Regulation (EU) 2022/1616 on recycled plastic materials and articles intended to come into contact with foods (European Commission 2022). This regulation states that “*On the basis of the evaluations done by the Authority of the applications for authorisation submitted in accordance with Regulation (EC) No 282/2008, mechanical PET recycling and product loops in a closed and controlled chain may be considered as suitable recycling technologies to recycle waste plastic into plastic meeting the requirements of Article 3 of Regulation (EC) No 1935/2004, and the specific conditions concerning their use should be laid down. In particular, mechanical PET recycling processes should be subject to individual authorisation as the severity and duration of the treatment of the plastic input applied in the decontamination operations, and thus their capacity to decontaminate, depend on the specific configuration of those processes, and, therefore, requires a case-by-case evaluation based on established criteria. Conversely, it is not necessary to require the authorisation of individual recycling processes obtaining only plastic from a closed and controlled chain that prevents contamination, as the introduction of contaminants in the chain is then sufficiently controlled to ensure that the only contamination of the plastic input can be removed with the simple cleaning and heating processes needed in any case for the remoulding of the materials*.” (European Commission 2022). Therefore, currently only PET is allowed to be recycled into new food contact material.

In low- and middle-income countries plastic is often recycled in products which can have food contact (kitchen tools, spoons, chop sticks). From the countries where information on plastic recycling has been gathered within the GMP POPs in plastic recyclates study (UNEP 2023e) several countries had regulation such as Brazil, Chile and Thailand. E.g. in Thailand food contact materials, need to comply with the Notification of the Ministry of Public Health (No. 435) B.E. 2565 (2022) (for details see Annex 3).

6.6 Need of future monitoring studies of plastic recyclates

Given the need to increase recycling rates as an important contribution to control and improve the global plastic pollution towards a more circular economy, more recycled plastic will be incorporated into new products. The control of POPs and other chemicals of concern in recycling is one key for protecting a circular plastic economy (UNEP 2023a). Therefore, plastic recyclates and shreds destined to produce recycling pellets require greater attention and control. Hence, a more systematic monitoring and analytical concept is needed. This concept should consider the situation in different regions, especially in low- and middle-income countries (see country reports on recycling situation in Annexes 8.1 to 8.6), and the recycling situation in both the formal and informal plastic recycling needs to be explored and assessed in more details. The above-described monitoring of POPs in recycled plastic pellets within the framework of the GMP project was conducted within a short period of 4 month and, therefore, could not provide a comprehensive overview on the situation but rather a good initial perspective.

In conclusion, enhancing the monitoring and oversight of plastic recyclates is pivotal in fostering sustainable recycling practices and working towards a circular plastic economy. A more comprehensive and region-specific approach would shed light on potential challenges, and it is essential for both the effective implementation of the Stockholm Convention and the global fight against plastic pollution. The understanding the large reservoir of POPs in plastics and their fate and release routes to the environment (Figure 1) is important to improve the management of these plastics in the frame of the Stockholm Convention and to develop targeted action plans in the National Implementation Plans (NIPs) and implement activities to reduce the release of these POPs to the environment and stop exposure routes to humans and biota. The environmental monitoring of POPs related to plastics and the monitoring of POPs in plastics are two important activities to find hot spots of releases and support the environmentally sound management of plastics which is an important synergy of the implementation of the Stockholm convention and the upcoming plastic treaty.

7 Conclusions and recommendations

Following a comprehensive assessment of the current state of knowledge and gaps in the monitoring and control of POPs and potential POP candidates in plastic products across major use sectors, as well as in related plastic categories at various stages of their life cycle, including products in use, waste, and recycled materials (shreds and pellets), several conclusions and recommendations emerge:

1. **Strengthening control of POPs in plastic products:** Monitoring and controlling POPs in plastic products, especially in critical-use sectors, are prerequisites to ensure the safety of human health and environmental well-being. These measures are key to achieving the goals set forth in the Stockholm Convention and progressing towards sustainable development.
2. **A holistic understanding of the lifecycle of POPs:** Recognizing the impact of POPs on plastics throughout their entire lifecycle and environmental releases and related food and human exposure is essential. The stages of production, usage, and plastic waste management including recycling have a direct influence on the level of exposure to POPs and their release to the environment (**Figure 1**). Therefore, it is crucial to comprehensively address and control these major phases of the plastic lifecycle to reduce and eliminate POPs pollution and plastic contamination of the environment and human exposure.
3. **Guidance for effective implementation:** This report provides meticulous technical guidance, empowering countries and organizations to effectively tackle the challenges associated with monitoring POPs in plastic products. The implementation of these guidelines not only ensures the accuracy and reliability of the results but also represents a critical component of POP control within these products.

4. **Embracing circular economy principles:** The adoption of a circular economy approach in plastic production and use becomes an urgent necessity to reduce waste generation and promote reuse and recycling, which are essential elements for achieving sustainable development goals. However, in this document, a comprehensive review of available information about the presence of POPs in plastics across major use sectors revealed that certain plastics may not be suitable for recycling due to high concentrations of POPs, such as flame retardants. It is imperative to monitor the content of POPs in plastics and implement measures to eliminate them from the production chain.
5. **Research and robust data:** Data collection and the promotion of additional research are vital to support policies and strategies. The acquisition of robust scientific evidence is fundamental to address knowledge gaps and facilitate effective management of POPs in plastic products, especially those recently listed in the Stockholm Convention and in developing countries.

In summary, this report underscores the urgency of monitoring and controlling POPs in plastic products and plastic recycling and includes recommendations to better achieve these objectives. Through international collaboration, regulatory action, public awareness, and capacity development, it is possible to mitigate the risks posed by POPs and pave the way towards a safer and more sustainable future.

8 Annex: Some country experience of the production and use of plastic pellets and shreds from plastic recycling

For the sampling campaign of the recycled plastic pellets, a questionnaire has been developed and distributed to the countries which they could fill during their rather short sampling campaign to compile information on observations of the situation of plastic recycling and information sources for plastic recycling in the countries. Selected filled questionnaires are included in this Annex which gives some insight into the recycling situation of selected countries including Argentina, Brazil, and Chile (Annex 8.1), Nigeria (Annex 8.2), Thailand (Annex 8.3), Mongolia (Annex 8.4), Vietnam (Annex 8.5), and Indonesia (Annex 8.6).

8.1 Annex 1: Information on plastic recycling situation in Argentina, Brazil and Chile compiled during collection of recycled pellets/shreds

8.2 Annex 2: Information on plastic recycling situation in Nigeria compiled during collection of recycled pellets/shreds

8.3 Annex 3: Information on plastic recycling situation in Thailand compiled during collection of recycled pellets

8.4 Annex 4: Information on plastic recycling situation in Mongolia compiled during collection of recycled pellets/shreds

8.5 Annex 5: Information on plastic recycling situation in Vietnam compiled during collection of recycled pellets/shreds

8.6 Annex 6: Information on plastic recycling situation in Indonesia compiled during collection of recycled pellets/shreds

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