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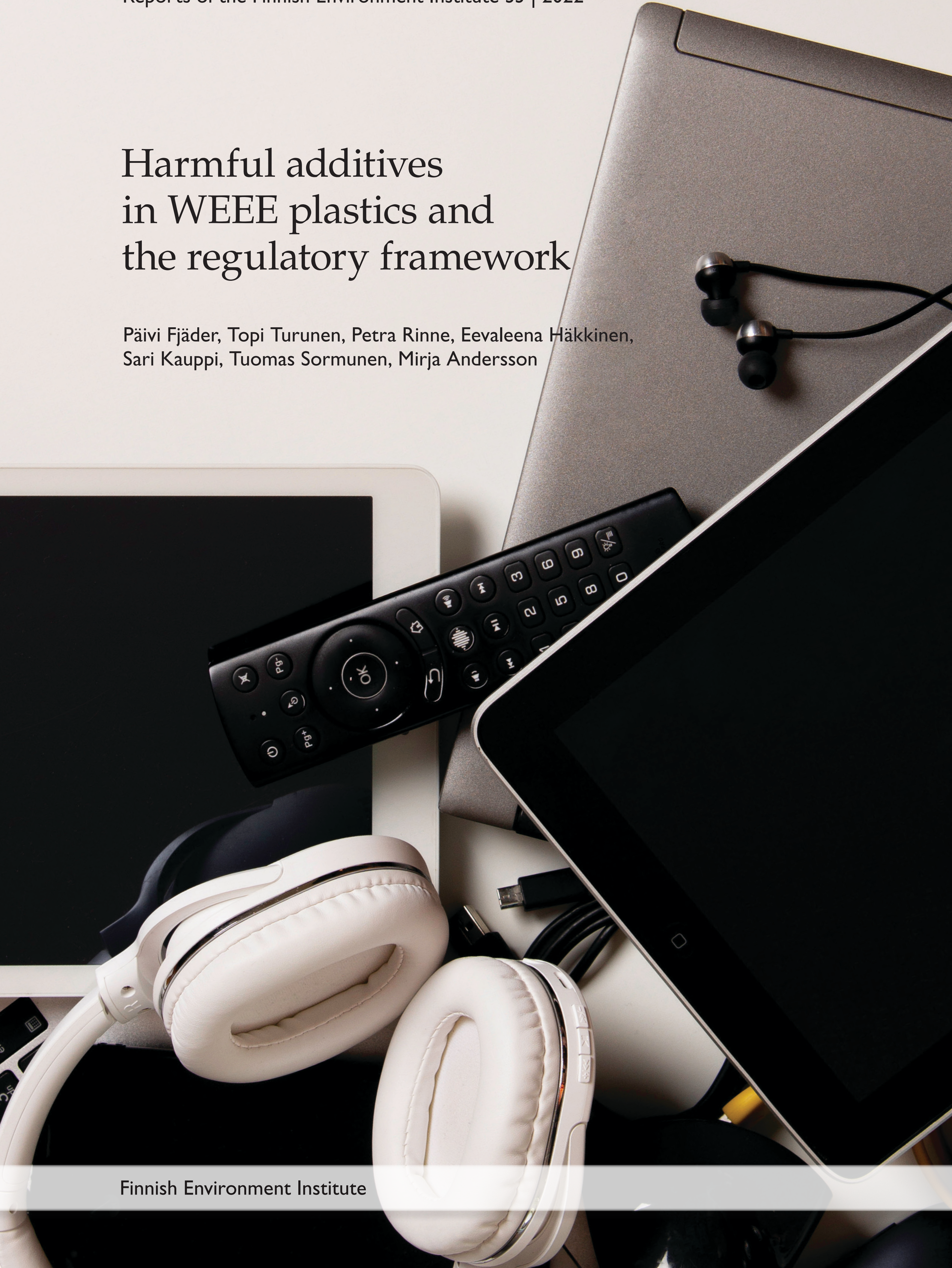

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Abstract

Harmful additives in WEEE plastics and the regulatory framework

One of the targets of the circular economy is to keep different materials and substances in circulation for as long as possible. The need for fossil-based virgin materials is efficiently reduced by substituting them with recycled materials. The European Union has set recycling targets for different waste materials. To achieve these ambitious circular economy objectives, new sources of recyclable waste materials in addition to packaging are needed. It has been suggested that a possible source for enhancing the recycling rate of plastics could be materials in waste electrical and electronic equipment (WEEE). It has been estimated that plastic concentrations in WEEE are about 9% in large household appliances, 48% in small household appliances, 30% in ICT equipment, and 31% in TVs, radios, etc. of the total weight of these devices. It is also one of the fastest growing waste streams in our society. Hence, WEEE offers a great potential source of materials for plastics recycling and recovery.

The properties of plastics used in these special applications often need to be improved, for example, for safety reasons, by adding various chemical additives that can act as flame retardants, stabilisers, biocides, lubricants, colourants, fillers, and reinforcements, depending on their use. Recycling of WEEE plastics has proved challenging due to the possibly high concentrations of hazardous additives used in plastics in electrical and electronic equipment (EEE).

Requirements to remove restricted or phased out substances from recycling processes are getting stricter. In general, the regulatory framework of harmful chemicals at the interface of wastes and products is complex. A consideration of this interface is particularly relevant when waste materials are turned into products in recycling processes. According to the chemicals legislation, recycled materials must fulfil the same requirements for the content of harmful substances as virgin raw materials. The possible presence of certain harmful substances in WEEE plastics can therefore restrict recycling or the use of recycled materials.

Preventing the recycling of restricted chemicals also requires the development of identification methods for these substances. In addition, efficient separation techniques are also needed for different matrices and waste streams. The existing chemical legislation should also continuously be followed, because new chemicals are subject to the restriction all the time. Increasing information and new solutions like databases may in the future facilitate the monitoring of the use and occurrence of harmful chemicals in recycling WEEE plastics. An example of this is the already existing SCIP database, which contains information about articles placed on the EU market that contain Substances of Very High Concern (SVHC). In future, the chemical content of products should also already be considered when designing new products. More efficient chemicals management in recycling promotes a safe and sustainable circular economy.

This report surveys the occurrence of the most relevant harmful substances in WEEE plastics and their legislative framework. Special attention has been paid to flame retardants and certain plasticisers due to their high concentrations in EEE plastics. Additionally, various chemical additives that have been considered suitable alternatives for already restricted or phased out harmful chemicals in EEE plastics have been evaluated.

Keywords: plastic, harmful substances, additives, electrical and electronic equipment recycling, legislation

Tiivistelmä

Haitalliset lisäaineet SER-muoveissa ja niiden lainsäädäntö

Yksi kiertotalouden tavoitteista on pitää erilaiset materiaalit ja aineet kierrossa mahdollisimman pitkään. Fossiilipohjaisten neitseellisten materiaalien tarvetta voidaan vähentää tehokkaasti korvaamalla niiden käyttö kierrätysmateriaaleilla. Euroopan Unioni on asettanut kierrätystavoitteet eri jätemateriaaleille. Näiden kunnianhimoisten kiertotaloustavoitteiden saavuttamiseksi tarvitaan pakkausten lisäksi uusia kierrätettävien jätemateriaalien lähteitä. Yhtenä mahdollisena materiaalilähteenä kierrätysasteen lisäämiseksi on nähty sähkö- ja elektroniikkalaiteromun (SER) sisältämät muovit. Sähkö- ja elektroniikkalaitteiden muovipitoisuuksien on arvioitu olevan suurissa kodinkoneissa noin 9 %, pienissä kodinkoneissa 48 %, ICT-laitteissa 30 % ja television, radion jne. tyyppisissä laitteissa 31 % niiden kokonaispainosta. Sähkö- ja elektroniikkalaitteet on myös yksi yhteiskunnassamme nopeimmin kasvavista jätevirroista. Näin ollen SER tarjoaa suuren potentiaalisen materiaalilähteen muovin kierrätykselle ja talteen ottamiselle.

Näissä erityisissä sovelluksissa käytettävien muovien ominaisuuksia on usein parannettava, esimerkiksi turvallisuussyistä, lisäämällä niihin erilaisia kemiallisia lisäaineita, jotka voivat toimia mm. palonestoaineina, stabilointiaineina, biosideina, voiteluaineina, väriaineina, täyteaineina ja lujiteaineina. SER muovien kierrätys onkin osoittautunut haastavaksi, sähkö- ja elektroniikkalaitteiden muoveissa esiintyvien haitallisten lisäaineiden vuoksi.

Vaatimukset rajoitettujen tai jo kiellettyjen yhdisteiden poistamisesta kierrätysprosesseista tiukentuvat koko ajan. Haitallisten kemikaalien sääntelykehys jäte-tuote-rajapinnassa onkin monimutkainen. Tämän rajapinnan huomioiminen on erityisen oleellista silloin, kun jätemateriaaleja muutetaan tuotteiksi kierrätysprosesseissa. Kemikaalilainsäädännön mukaan kierrätysmateriaalien on täytettävä samat vaatimukset haitallisten aineiden pitoisuuksien osalta kuin neitseellisten raaka-aineiden. Tästä syystä tiettyjen haitallisten aineiden mahdollinen esiintyminen SER muoveissa voi rajoittaa kierrätystä tai kierrätettyjen materiaalien käyttöä.

Rajoitettujen kemikaalien kierrätyksen estäminen edellyttää myös näiden aineiden tunnistamiseen soveltuvien menetelmien kehitystä. Tämän lisäksi tarvitaan myös tehokkaita erotustekniikoita eri matriiseille ja jätevirroille. Voimassa olevaa kemikaalilainsäädäntöä tulee myös jatkuvasti seurata, sillä uusia kemikaaleja tulee rajoitusten piiriin jatkuvasti. Tiedon lisääntyminen ja erilaiset ratkaisut kuten tietokannat, voivat jatkossa helpottaa haitallisten kemikaalien käytön ja esiintymisen seuraamista SER-muovien kierrätyksessä. Esimerkkinä tästä jo olemassa oleva SCIP-tietokanta (Substances of Concern In articles as such or in complex objects (Products)), joka sisältää tietoa EU:n markkinoille saatettujen esineiden sisältämistä erityistä huolta aiheuttavista aineista (Substances of Very High Concern, eli SVHC). Jatkossa tuotteiden kemiallinen sisältö tulisi huomioida entistä paremmin jo tuotteita suunniteltaessa. Tehokkaampi kemikaalien hallinta kierrätyksessä edistää osaltaan turvallista ja kestävää kiertotaloutta.

Tässä raportissa tarkastellaan tärkeimpien haitallisten aineiden esiintymistä sähkö- ja elektroniikkalaiteromun muoveissa sekä niiden hallintaan liittyvää lainsäädäntökehystä. Yhdisteiden osalta on keskitytty pääasiassa palonestoaineisiin sekä tiettyihin pehmittimiin, sillä niiden tiedetään esiintyvän korkeina pitoisuuksina SER-muoveissa. Lisäksi on luotu katsaus sellaisiin yhdisteisiin, joita on pidetty sopivina vaihtoehtoina korvaamaan jo rajoitettuja tai kiellettyjä haitallisia lisäaineita SER-muoveissa.

Asiasanat: muovit, haitalliset aineet, lisäaineet, sähkö- ja elektroniikkalaitteet, kierrätys, lainsäädäntö

Sammandrag

Skadliga tillsatser i EE-plast och relevant lagstiftning

Ett av målen med cirkulär ekonomi är att så länge som möjligt hålla olika material och ämnen i kretslopp. Man kan på ett effektivt sätt minska behovet av fossilbaserade jungfruliga material genom att ersätta dem med återvunnet material. Europeiska unionen har ställt upp mål för återvinning av olika slags avfallsmaterial. För att uppnå de ambitiösa målen behövs, utöver förpackningar, nya källor till återvinningsbart avfallsmaterial. Den plast som finns i elektroniskt och elektriskt avfall (EE) anses vara en möjlig källa till material för att öka återvinningsgraden. Man uppskattar att andelen plast i el- och elektronikapparater i stora hushållsapparater utgör cirka 9%, i små hushållsapparater 48%, i ICT-produkter 30% och i apparater som tv:ar, radior o.s.v. 31% av totalvikten. El- och elektronikprodukter är också ett av samhällets snabbast växande avfallsflöden. Därmed utgör EE en stor potentiell materialkälla för att ta vara på och återvinna plast.

Av till exempel säkerhetsskäl bör egenskaperna i den plast som används i specifikt dessa tillämpningar ofta förbättras genom att, beroende på dess användning, tillsätta olika kemiska tillsatser som kan fungera som flamskyddsmedel, stabiliseringsmedel, biocider, smörjmedel, färgmedel, fyllnadsmaterial och förstärkningsmedel. Återvinning av EE-plast har visat sig vara utmanande på grund av de skadliga tillsatser som finns i plasten i el- och elektronikapparater.

Kraven på att avlägsna begränsade eller redan förbjudna föreningar från återvinningsprocesser skärps hela tiden. Regelverket för skadliga kemikalier i gränssnittet mellan avfall och produkt är i allmänhet komplicerat. Det är speciellt viktigt att beakta det här gränssnittet när avfallsmaterialet omarbetas till produkter i återvinningsprocesserna. Enligt kemikalielagstiftningen måste det återvunna materialet uppfylla samma krav för halten av skadliga ämnen som jungfruliga råvaror. Av den här anledningen kan vissa skadliga ämnen begränsa återvinning eller användning av återvunnet material om de finns i EE-plast.

För att kunna förhindra återvinningen av begränsade kemikalier krävs också utveckling av lämpliga metoder för att identifiera ämnena. Förutom det här behövs också effektiva separationstekniker för olika matriser och avfallsflöden. Man bör också i fortsättningen följa med den gällande kemikalielagstiftningen, eftersom nya kemikalier kontinuerligt begränsas. Ökad kunskap och olika lösningar som databaser kan i fortsättningen förenkla uppföljandet av användningen och förekomsten av skadliga kemikalier när man återvinner EE-plast. Ett exempel på det här är SCIP-databasen (Substances of Concern In articles as such or in complex objects (Products)) som redan finns, och som innehåller information om särskilt farliga ämnen (Substances of Very High Concern SVHC) i varor som släppts ut på marknaden inom EU. I fortsättningen ska man redan vid utformningen av produkterna beakta det kemiska innehållet i produkter bättre än tidigare. Effektivare hantering av kemikalier i återvinningen bidrar till en säker och hållbar cirkulär ekonomi.

I den här rapporten undersöks hur de viktigaste skadliga ämnena förekommer i plasten i elektroniskt och elektriskt avfall, samt lagstiftningsramen gällande hanteringen av dem. Vad gäller föreningar har man framför allt fokuserat på flamskyddsmedel och vissa mjukgörare, eftersom man vet att EE-plast innehåller en stor andel av dem. Dessutom har man skapat en översikt över sådana föreningar som har ansetts vara lämpliga alternativ för att ersätta de skadliga tillsatser i EE-plast som redan är begränsade eller förbjudna.

Nyckelord: plast, skadliga ämnen, tillsatser, el- och elektronikapparater, återvinning, lagstiftning

Preface

Most plastics in Europe are currently used for packaging. Often those plastics also represent multilayer materials that are difficult to recycle. Another challenging plastic stream from recycling perspective is plastic waste from electronic and electrical equipment, EEE. The relative share of plastics in waste electronic and electrical equipment, WEEE, is also constantly increasing. WEEE plastics can contain many harmful additives, which are problematic both for their recycling and re-use. To evaluate the feasibility of the use of recycled WEEE plastics, it is important to have the overall picture of the presence of the harmful chemicals in these plastics streams. It is also essential to identify the possible restrictions for the use of recycled plastic materials by the existing regulatory framework. To utilize the WEEE plastic in a better manner, new cost-efficient ways to identify and separate plastics that do not contain these harmful additives must be developed. Sometimes even ways to separate certain harmful additives from these plastic materials might be needed.

The ALL-IN for Plastics Recycling (PLASTin) project, funded by Business Finland (9030/31/2019, 2022), was established to support the plastic industry actors to develop systemic, and environmentally optimized recycling concepts. The project focused on the recycling of these difficult plastics and turning the challenges into new business opportunities of the plastic cluster in Finland. By this way, the circular economy targets were promoted.

The PLASTin project had a wide range of partners and stakeholders. The industrial partners, called as core partners, included BMH Technology Ltd, Borealis Polymers Ltd, Fortum Waste Solutions Ltd, Kuusakoski Ltd and Extron Engineering Ltd. The industrial partners, called as collaborative partners, included Neste PLC, Griffin Refineries Ltd, Rosk'n Roll Ltd, Muovipoli Ltd and Suomen Uusiomuovi Ltd. The research organisations taking part in the consortium were Finnish Environment Institute (SYKE), Lappeenranta-Lahti University of Technology (LUT), Tampere University (TUNI), VTT Technical Research Centre of Finland (VTT) and Arcada University of Applied Sciences (Arcada).

The steering group and the expert members of the project is acknowledged for the active discussions and guiding, including Tiina Malin (Kuusakoski Ltd), Reetta Anderson (Fortum Waste Solutions Ltd), Anne Fraser-Vatto (Griffin Refineries Ltd), Vesa Heikkonen (Rosk'n Roll Ltd), Jarmo Kela (Neste PLC), Auli Nummila-Pakarinen (Borealis Polymers Ltd), Peter Wallenius (BMH Technology Ltd), Mirja Andersson (Arcada University of Applied Sciences), Mika Horttanainen (Lappeenranta-Lahti University of Technology LUT), Sari Kauppi (Finnish Environment Institute SYKE), Ilari Jönkkäri (Tampere University TUNI), Eetta Saarimäki (VTT Technical Research Centre of Finland), Sauli Eerola (Muovipoli Ltd), Peter Rasmussen (Suomen Uusiomuovi Ltd), Pirjo Kaivos (CLIC Innovation Ltd), Taina Kujanpää (CLIC Innovation Ltd), Sisko Sipilä (Business Finland) and Sampo Tukiainen (Business Finland).

Recycling of WEEE plastics is a worldwide challenge and new practices that enables its higher recovery rate would have significant environmental impacts. The main objective of this task 3.1 in the PLASTin project was to evaluate recycling of WEEE plastic streams that are currently not utilized. This requires development of new identification and separation techniques for harmful additives. The focus of this specific report was on the occurrence of harmful additives in WEEE plastics and on the regulatory framework governing WEEE plastics recovery.

Helsinki August 2022

Päivi Fjäder, Finnish Environment Institute

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1 Plastics in Waste Electrical and Electronic Equipment (WEEE)

To achieve the ambitious circular economy objectives set by the European Union (EU), new sources of recyclable waste materials are needed. Along with the tightening regulations, it is evident that the recovery of non-packaging plastics needs to be improved. One possible source for enhance the recycling rate of plastics could be materials in waste electrical and electronic equipment (WEEE). This is also one of the fastest growing waste streams in society. The EU has set recycling targets for WEEE in the Annex 5 of the WEEE directive.

A sustainable recycling system retains the value of the material as much as possible to avoid fast downcycling. In the EU, from 2006 to 2016, the volume of total plastic waste collected for recycling already increased by 79%, energy recovery increased by 61% and landfilling decreased by 43% (Plastics Europe 2018). According to the statistics, the recycling rate of packaging waste and WEEE is slowly increasing in Europe but remains below half of the total waste generation, being 48% in 2016 (EEA 2021). At the same time, the composition of waste destined for recycling has developed, due to evolved plastic products and collection schemes, sorting technologies and legislation. In addition, developed collection and pre-sorting technologies still affect the recovery rate.

Challenges with plastics are related to their use, recovery (including recycling), and disposal. For some plastics, there are no recycling systems available. In addition, some plastic streams are extremely difficult and expensive to recycle. Therefore globally, much of the plastic ends up in low-efficiency incineration, landfilling or may even be released intentionally or unintentionally into the environment. In some cases, different additives make it difficult to recycle some types of plastics because of their potential unwanted health impacts and because additives could have various adverse effects on the structure and/or properties of the recycled product. Increasing the overall recycling rate of plastic waste requires new and improved technological solutions, both for mechanical and for chemical recycling processes. These are needed to achieve better control of challenging materials, mainly those plastics that contain various additives, as well as better processing of so-called multilayer materials.

To evaluate the feasibility of recycling WEEE plastics, it is important to have the whole picture of all the pros and cons. One aspect that makes this stream very challenging for recycling is the occurrence of various harmful chemical additives in these plastics and possible restrictions related to the use of these recycled materials. The main objective of this survey was to evaluate the occurrence of most harmful additives in WEEE plastics and their regulatory framework.

1.1 Plastic materials used in the electrical and electronic devices

The WEEE Directive (2012/19/EU)[1] defines electrical and electronic equipment (EEE) as equipment dependent on electric currents or electromagnetic fields to work properly and equipment for the generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1,000 volts for an alternating current and 1,500 volts for a direct current.

The intensive growth of the market for electronical devices also means growing amounts of electrical and electronic waste. According to a January 2019 report from the World Economic Forum, WEEE is the fastest-growing waste stream globally, with an estimated waste stream of close to 50 million tonnes in 2018 (WEF 2019, Sing et al. 2020, Chaine et al. 2021).

[1] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (OJ L 197, 24.7.2012, p. 38–71).

Annexes III and IV of the WEEE Directive divide WEEE into six categories: (1) temperature exchange equipment; (2) screens, monitor and equipment with screens having a surface greater than 100 cm^2; (3) lamps; (4) large equipment (any external dimension more than 50 cm); (5) small equipment (no external dimension more than 50 cm); and (6) small IT and telecommunication equipment (no ex-ternal dimension more than 50 cm).

It has been estimated that about 20% of the total weight of EEE could be plastics (Cesaro et al. 2017). More detailed plastic concentrations in EEE have been calculated to be about 9% in large household appliances, 48% in small household appliances, 30% in ICT equipment, and 31% in TV, radio and similar appliances (Buekens & Yang 2014). In the telecom category, plastic concentrations are large (74%; Buekens and Yang 2014). The other components in EEE are metals (including heavy metals; 65%) and glass, ceramics, wood, and rubber (15%; Cesaro et al. 2017). There is a huge potential source of plastic materials, especially in small household appliances and in ICT equipment.

The most common plastic polymers used in EEE are styrenics such as polystyrene (PS), high-impact polystyrene (HIPS), acrylonitrile butadiene styrene (ABS); polyolefins such as polypropylene (PP); engineering plastics such as polycarbonate (PC), polyoxymethylene (POM), polyurethane (PU), polyamide (PA) and polyvinyl chloride (PVC); and thermosets (Buekens & Yang 2014, Delgado et al. 2007). More detailed uses of certain plastic polymers are described in Table 1 (Delgado et al. 2007).

Table 1. Commonly used plastics in various applications. Table modified from Delgado et al. (2007).

Polymer	Application
PP	Components inside washing machines and dishwashers, casings of small household appliances (coffee makers, irons), Internal electronic components.
PS (HIPS)	Components inside refrigerators (linear, shelving). Housing of small household appliances, data processing and consumer electronics.
ABS	Housing and casing of phones, small household appliances, microwave ovens, flat screens and certain monitors. Enclosures and internal parts of ICT equipment.
PPO* (blend HIPS/PPE)	Housing of consumer electronics (TVs) and computer monitors and some small household appliances (e.g. hairdryers). Components of TV, computers, printers and copiers.
PC	Housing of ICT equipment and household appliances, Lighting.
PC/ABS	Housing of ICT equipment and some small household appliances (e.g. kettles, shavers).
PET (PBT**)	Electrical motor components, circuits, sensors, transformers, lighting. Casings and components of certain small household appliances (e.g. toasters, irons). Handle, grips, frames for ovens and grills. Panel component of LCD displays.
PU (foam)	Insulation of refrigerators and dishwashers.
PMMA***	Lamps, lighting, small displays (e.g. mobile phones).
PA	Lighting equipment, small household appliances. Switches, relays, transformer parts, connectors, gear, motor basis.
POM	Gears, pinions.
PVC	Cable coating, cable ducts, plugs, refrigerator door seals, casings.
PE****	Cable insulation and sheathing.
UP resins*****	Housing, handles and soles of domestic irons, handles and buttons of grills and pressure cookers, Structural elements, bodies, roofs and doors for display units, refrigerated window displays. Capasitor casings.
EP resins******	Printed circuit boards.

* Poly(p-phenylene oxide)
** Polybutylene terephthalate (note; the same abbreviation for pentabromotoluene and persistent bioaccumulative and toxic)
*** Poly(methyl methacrylate)
**** Polyethylene
***** Unsaturated polyester resins
****** Epoxy resins

1.2 Recycling potential of WEEE plastics

A report by JRC estimated the increase in trends for WEEE -plastic generation and that its collection would double in 10 years (Delgado et al. 2007). The average amount of EEE put on the market during 2015–2017 was estimated to be 19.1 kg per inhabitant whereas the amount of WEEE collected in 2018 was 8.9 kg per EU inhabitant (Eurostat online data). According to the statistics, in 2018, the EU reached the set target of 45% total collection rate (comparison with the average weight of EEE put on the market in the three preceding years, 2015–2017). The dominating categories of WEEE plastics were ICT equipment, large household appliances and consumer electronics, accounting for about 85% of plastic consumption and 90% of generated domestic WEEE plastic (Delgado et al. 2007).

For small household electronics and teletechnical equipment (categories 5 and 6 according to Annexes III and IV of the WEEE Directive), the recovery target is 75% and the reuse and recycling target is 55%. The targets were reached in 2019. In 2019, the WEEE collection rate in Finland was 57.9%, which was almost 13.3 kg per inhabitant. In 2019, approximately 33,300 tons of EEE category 5 equipment were put on domestic markets, and about 9,982 tons of WEEE category 5 equipment were collected from domestic use, and about 5,184 tons of such equipment were collected from other sources. Statistics of the same year reveal that about 2,820 tons were prepared for reuse, 11,006 tons were recycled, 524 tons were used for energy recovery, and 788 tons were disposed of. Statistics revealed information by categories but not by materials (e.g. plastics). Of WEEE, category 5, 12,343 tons were processed in Finland and 66 tons in the EU. (Pirkanmaa Centre for Economic Development Transport and the Environment 2022).

Because of the large volume of WEEE plastics generated and their relatively large volume in devices (especially those belonging to categories 5 and 6 in Annexes III and IV of the WEEE Directive), it is important for solutions for proper recycling processes to be developed. In general, plastics from these waste streams are not yet recycled in Finland. Increasing recycling would mean, however, the development of more efficient detection and separation systems for the potentially harmful additives and preventing the harmful additives from entering the recycled plastic.

2 Harmful additives in plastics

There are many additives that can be used to improve different properties of plastic materials. Some are used to prevent degradation of the polymer during processing or degradation due to environmental factors (UV, temperature, humidity, microorganisms) and others to improve resistance to heat and fire, for example. Some of the additives can be called legacy chemicals, because they were already phased out years ago. Some additives can be called emerging substances, which are used to substitute those already restricted or banned chemicals. This chapter contains general descriptions on commonly used additive groups and their functions in plastics. Detailed information on individual substances used as additives in EEE plastics can be found in Chapters 4–7.

Properties of plastic materials in specific applications such as electrical and electronic devices need to be improved by using several chemical additives. In addition, safety issues set certain requirements. Electronic devices tend to heat during use, so the materials in these applications need to be resistant to overheating. For these reasons, electrical and electronic devices contain various chemical additives. Additives can be divided, for example, into (1) functional additives (stabilisers, flame retardants [FRs], plasticisers, biocides, lubricants), (2) colourants, (3) fillers (clay, kaolin, carbonate, talc, mica etc.) and (4) reinforcements (glass, fibers etc.) (Hansen et al. 2013). Due to the rather long life cycle of certain electronic devices, some of the additives can be called legacy chemicals, because they were already phased out years ago. Some additives, on the other hand, can be called emerging substances, which are used to substitute those already restricted or banned chemicals. In particular, many old electrical and electronic devices contain these legacy additives identified now as substances that are harmful to the environment or human health. These may include heavy metals such as lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr) and halogenated compounds containing bromine (Br), chlorine (Cl), phosphorus (P) and fluorine (F).

Because so many potentially harmful additives can be present in WEEE plastics, a more detailed selection of the relevant chemicals reviewed in this report had to be done within the project. It was decided to pay special attention to those chemicals already restricted or regulated at the EU level or listed in international conventions. The selected substances include chemicals listed as persistent organic pollutants (POPs) under the Stockholm Convention and EU POP Regulation (EU) No 2019/1021[2], chemicals defined as substances of very high concern (SVHC) in the EU REACH Regulation (EU) No. 1907/2006[3], chemicals subject to authorization according to Annex XIV of the REACH Regulation, and those chemicals mentioned in Directive 2011/65/EU on the restriction of the use of certain hazardous substances in EEE (RoHS) (2011/65/EU)[4]. In addition to these rather well-known substances, it was decided to take an overview of so-called emerging substances as well. These include various other chemicals that have been used as alternatives substituting those already restricted or banned chemicals.

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[2] Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on persistent organic pollutants (OJ L 169, 25.6.2019, p. 45–77).

[3] Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC (OJ L 396, 30.12.2006, p. 1–849).

[4] Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (OJ L 174, 1.7.2011, p. 88–110).

2.1 **Flame retardants (FRs)**

2.1.1. FRs in general

FRs are chemicals that have been added to materials to prevent combustion and to delay the spreading of fire after ignition (Van Deer Veen 2012). There are various FRs on the market. Some are halogenated (containing bromine and chlorine) whereas some can contain phosphorus, nitrogen, metals or minerals (based on aluminium and magnesium). In addition, some might be based on borax, antimony trioxide or molybdenum (Van Deer Veen 2012). The typical amount of (brominated) FRs added to the materials varies between 12% and 18% in wet weight (Hansen et al. 2013). Many halogenated FRs have been shown to be persistent in the environment, bioaccumulative, or even toxic to organisms and humans (Van Deer Veen 2012). Therefore, many brominated FRs (BFRs) are now banned, or their production and use is strongly restricted.

When solid materials burst into fire they can be turned by heat into flammable gases, which will also catch fire. There are several mechanisms by which ERs can prevent fire. Reactions in the gas phase and reactions in the solid phase are the most effective ones. In the former case, halogenated FRs remove hydrogen (H^+) and hydroxy ion (OH^-) radicals from these flammable gasses, by reaction with bromine (Br) and chlorine (Cl) atoms. This results in a slowdown of the burning and prevents the spreading of the fire. It has been shown that the effectiveness of the halogenated FRs is dependent on the number of halogen atoms present in the molecule (Van Deer Veen 2012).

Where halogenated FRs act in the gas phase, non-halogenated FRs (such as phosphorus FRs [PFRs]) mainly act in the burning of solid phase materials (Van Deer Veen 2012). Phosphorus will react when it is heated and form a polymeric form of phosphoric acid. This reaction creates a char layer to shield the material from oxygen and thereby prevents the formation of flammable gasses. Another mechanism by which these PFRs function is by offering a partial gas phase contribution to the flame-extinguishing effect. This is comparable to the mechanism of bromine- and chlorine-containing FRs (Van Deer Veen 2012). There are advantages to have both halogens and phosphorus in the same polymer systems. When halogens and phosphorus are both present, they act independently and therefore additively.

2.1.2 Reactive flame retardants

Reactive FRs are bound to the polymeric materials by covalent bonding between the polymer and the FR in chemical reactions. Final materials thus contain a built-in FR that cannot easily migrate out of the material (Rahman et al. 2001).

2.1.3 Additive flame retardants

Additive FRs are not bound to the polymer and therefore have a greater tendency to be released into the environment. Additive FRs are blended with or coated onto materials to make them flame resistant. To avoid migration out of the plastic material, FRs with higher molecular weight are being developed (Rahman et al. 2001).

2.2 **Plasticisers**

Plasticisers are used to increase materials' flexibility or workability. They are incorporated into the material in which they are used (Gadogan et al. 2012). There are approximately 300 plasticisers manufactured, but only 100 are commercially important. Phthalates are the most common group of chemicals used as plasticisers, due to their low co. Typical amounts of plasticisers added to the material vary between 10% and 70% in wet weight (Hansen et al. 2013). It has been estimated that around 80% of the plasticisers are used in PVC and the remaining 20% in cellulose plastics (Hansen et al. 2013).

2.3 Other

In addition to FRs and plasticisers, certain other chemicals are used in plastics as well. They can act as stabilisers, biocides, lubricants, colourants, fillers, and reinforcements (Hansen et al. 2013). This report focuses mainly on FRs, plasticisers, and certain heavy metals because they are known to have harmful properties and are subject to restrictions. It should be noted that certain substances included in other groups of chemical additives could also have harmful impacts to recycling of these materials. For example, organotin compounds or arsenic is sometimes used as a biocide in certain plastics (Hansen et al. 2013). The amount of stabilisers, antioxidants, UV stabilisers (0.05–3% in wet weight), heat stabilisers (0.05–3% in wet weight), slip agents (0.1–3% in wet weight), lubricants (0.1–3% in wet weight), antistatics (0.1–1% in wet weight), biocides (0.001–1% in wet weight), and colourants added to the material depends on chemical structure of additive and of plastic polymer (Hansen et al. 2013). Unfortunately, these other functions and chemicals are out of the scope of this report and have therefore not been reviewed in this survey.

3 Legislative framework

Chemical management within WEEE is addressed in legislation from many different perspectives. The essential legislation focuses specifically on EEE such as the WEEE Directive or RoHS directive. There are also generally applicable regulations on chemical management such as the EU POP Regulation and the REACH Regulation that are applied to other types of products. In addition, the EU Waste Directive lays down a regulatory framework for waste management generally. It also sets out criteria for commodification of waste and promotes the reuse, recycling, and recovery of waste materials. The regulatory framework governing the chemical management within WEEE thus consists of multiple different provisions of regulation that might be applicable to certain products, chemicals, or a certain stage of their life cycle.

This chapter discusses the regulatory framework on the EU level as the main requirements and principles of the regulatory framework are laid down on the EU. The EU regulations (such as REACH- and POP regulations) are directly applicable in the Member States and do not have to be implemented into the national legislation. Nonetheless, many of the obligations are laid down in directives (such as the WEEE- and RoHS -directives). Directives must be implemented into national law in Member States within a certain time frame. They also offer certain leeway for Member States to choose the measures best suited to their national legislation. For example, the details of the extended producer responsibility scheme arrangement for WEEE are left to Member States to determine. In national implementation, it must be considered that directives lay down concrete objectives that Member States must reach and provide a certain framework of concepts and processes that limit the national discretion.

The regulatory framework for chemical management is constantly changing, and new chemical restrictions are added to the REACH and POP Regulations. Often these amendments have transition periods and only have to be enacted later. Because of the transition periods and their possible extensions, the manufacturing year of a product does not necessarily give comprehensive information about its potential chemical content. Moreover, new requirements and restrictions for chemical substances of concern do not automatically remove these substances from circulation. Even when a certain chemical is no longer used in new products, it might still be present in older products and recovered waste-based materials. Chemical management also involves the assurance of safety of waste-based materials: Regulating the whole life cycle of products can provide the best overall outcome in chemical management.

3.1 **WEEE directive**

Directive 2012/19/EU on WEEE lays down rules for the management of WEEE within the EU. The directive defines EEE as ‘equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation transfer and measurement of such currents and fields and designed for uses with a voltage rating not exceeding 1,000 volts for alternating current and 1,500 volts for direct current’. WEEE is defined as ‘electrical or electronic equipment which is waste within the meaning of Article 3(1) of Directive 2008/98/EC, including all components, sub-assemblies and consumables which are part of the product at the time of discarding’.

Extended producer responsibility sets out duties for producers of EEE. The manufacturer, the EU importer, the reseller using their own name or trademark, or the actor selling EEE by means of distance communication directly to private households or users other than private households in a Member State is considered a producer and therefore subject to the duties of the extended producer responsibility laid down in the directive. The extended producer responsibility scheme aims to reduce the negative environmental impact of products throughout their whole life cycle, from production to end of life. EEE producers are required to be registered on a national register, and they must make regular declarations of the products they place on the market. In addition, they are required to inform end users about the disposal of the products and to add appropriate marking to their products (crossed-out wheelie bin). Producers must also make available dismantling guides and recommendations for easy dismantling and recovery of WEEE. Moreover, they shall organise and finance a take-back system for the collection and recycling of WEEE. They are also required to regularly report to the national authority the quantities that they have collected and treated through the take-back system. More detailed provisions on the functioning of the extended producer responsibility scheme are set out in national implementation measures of the directive. The directive encourages cooperation between producers and recyclers in product design and separate collection. Regarding separately collected WEEE there are recovery targets (minimum 50%–85% depending on the appliance category) to recover, recycle or prepare for reuse, set in Annex V of the directive.

The directive lays down minimum rules on proper treatment of WEEE. These include removal of all fluids as well as selective treatment for materials and components listed in Annex VII of the directive. This annex sets out a list of the substances, mixtures and components that should be removed from any separately collected WEEE. This list also contains certain plastic-containing components (e.g. plastic-containing BFRs, external electric cables and printed circuit boards).

3.2 Commodification of waste

Whether recycled materials are considered waste according to the definition of the Waste Framework Directive (2008/98/EC, WFD)[5] is crucial. According to Article 3(1) of the WFD, 'waste' means any substance or object which the holder discards or intends or is required to discard. As noted above, EEE that is considered 'waste' is WEEE according to the WEEE Directive definitions. Essentially, waste legislation is applied to 'waste', and applicable product and chemicals legislation is applied to 'non-waste'. To manufacture normal products from recycled materials, the materials must cease to be waste. The regulatory framework concerning ceasing to be waste is often called End-of-Waste regulation. Article 6 of the WFD states that 'waste' can cease to be waste after it has undergone recycling (or other recovery operation) if it complies with the following conditions:

- (a) the substance or object is to be used for specific purposes;
- (b) a market or demand exists for such a substance or object;
- (c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
- (d) the use of the substance or object will not lead to overall adverse environmental or human health impacts.

General EU-wide or national legislation can be enacted on the End-of-Waste criteria for a specified waste material. In the absence of general legislation, End-of-Waste criteria can be laid down on a case-by-case basis. To date, there are no EU-wide End-of-Waste criteria for plastics and of the Member States, only Portugal has enacted national End-of-Waste criteria (Ordinance No: 245/2017) for recovered plastics. Currently, Finland is also drafting national criteria for mechanically recycled plastics. In all cases, the materials must comply with the conditions of Article 6. After the material reaches End-of-Waste status, waste legislation is no longer applied to the material and it falls under the scope of applicable product and chemicals legislation, standards, and other technical requirements. Particular focus is put on whether the material is fit-for-use and whether it is safe to use from the perspective of environmental and human health impacts. Following the general definition of 'waste', the waste status does not truly indicate whether the material is safe to use again in new products.

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[5] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (OJ L 312, 22.11.2008, p. 3–30).

As a general rule, the obligations of chemicals regulation are not applied to 'waste'. This report examines the obligations for waste-based materials deriving from the POP Regulation and Stockholm Convention, REACH Regulation, and RoHS Directive. The following subchapters elaborate the relevant chemical management related obligations deriving from the legislative framework.

3.3 Stockholm Convention and POP Regulation

The Stockholm Convention on Persistent Organic Pollutants is a global treaty which protects human health and the environment from chemicals that remain intact in the environment for long periods, become widely distributed geographically, accumulate in humans and wildlife, and have harmful impacts on human health or on the environment. The Convention entered into force on 17 May 2004. The Stockholm Convention restricts or bans these chemicals as products or chemicals, as well as recycling of materials and articles containing these chemicals. The provisions of the Stockholm Convention are implemented in the EU with the EU POP Regulation.

The EU POP Regulation bans or restricts the manufacturing, placing on the market, and use of POPs in both chemical products and articles, with the exception of their presence as unintentional trace contaminants (UTCs). Essentially, the regulation prohibits the introduction of new POPs to the market and the recovery and disposal of waste in a manner that can lead to reintroducing the POPs into the materials streams.

The POP Regulation sets in Annex IV a concentration limit for each POP substance in wastes (Table 2). Wastes that contain POP substances above the Annex IV concentration limit (referred to also as 'POP wastes') are to be treated in a manner in which the POP substances are destroyed or irreversibly transformed into substances that do not exhibit similar characteristics.

The appropriate waste management measures for POP wastes are listed in Annex V of the POP Regulation. Other waste management options may be used for wastes that do not exceed the Annex IV concentration limit, in accordance with the EU waste legislation. According to Annex V, POP wastes exceeding the Annex IV concentration limit can only be managed in the following ways:

- Physico-chemical treatment (D9[6])
- Incineration on land (D10)
- Used principally as a fuel or other means to generate energy, excluding waste containing PCBs (R1[7])
- Recycling/reclamation of metals and metal compounds, under the following conditions: The operations are restricted to residues from iron- and steel-making processes, such as dusts or sludges from gas treatment or mill scale or zinc-containing filter dusts from steelworks, dusts from gas cleaning systems of copper smelters and similar wastes, and lead-containing leaching residues of non-ferrous metal production. Waste containing PCBs is excluded. The operations are restricted to processes for the recovery of iron and iron alloys (blast furnace, shaft furnace and hearth furnace) and non-ferrous metals (Waelz rotary kiln process, bath melting processes using vertical or horizontal furnaces), provided the facilities meet as minimum requirements the emission limit values for PCDDs and PCDFs laid down in accordance with Directive 2010/75/EU[8] , whether or not the processes are subject to that directive and without prejudice to the other provisions of the directive (R4).

[6] Annex I WFD: List of disposal operations.
[7] Annex II WFD: List of recovery operations.
[8] Directive 2010/75/EU of the European parliament and of the council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast) (OJ L 334, 17.12.2010, p. 17–119)

Table 2: Concentration limits set for POP substances in wastes and planned amendments to the existing limit values. The Annex IV concentration limits define which wastes must be treated in a manner in which the POP substances are destroyed or irreversibly transformed into substances that do not exhibit similar characteristics. The European Commission has proposed amendments to the Annex IV concentration limits (COM 2021, 656 final, 28 Oct. 2021)

POP substance	Current Annex IV limit for wastes	Commission proposal for amending Annex IV limit
Aldrin	50 mg/kg	
Bromodiphenyl ethers (BDEs), sum of the concentrations of tetra-, penta-, hexa-, hepta- and deca-BDEs	1,000 mg/kg	500 mg/kg; and 5 years after entry into force: 200 mg/kg
Chlordane	50 mg/kg	-
Chlordecone	50 mg/kg	-
DDT	50 mg/kg	-
Dicofol	–	50 mg/kg
Dieldrin	50 mg/kg	-
Endosulfan	50 mg/kg	-
Endrin	50 mg/kg	-
Hexabromobiphenyl (HBB)	50 mg/kg	-
Hexabromocyclododecane (HBCDD)	1,000 mg/kg	500 mg/kg
Hexachlorobenzene (HCB)	50 mg/kg	-
Hexachlorobutadiene (HCBD)	100 mg/kg	-
Hexachlorocyclohexanes (incl. lindane) (HCH)	50 mg/kg	-
Heptachlor	50 mg/kg	-
Mirex	50 mg/kg	-
Perfluorooctanesulfonic acid and its derivatives (PFOS)	50 mg/kg	-
Perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds	–	PFOA and its salts: 1 mg/kg PFOA-related compounds: 40 mg/kg
Polychlorinated biphenyls (PCB)	50 mg/kg	-
Pentachlorobenzene	50 mg/kg	-
Pentachlorophenol, its salts and esters	–	100 mg/kg
Polychlorinated dibenzodioxins and -furans (PCDD/F)	15 µg TEQ/kg	-
Polychlorinated dibenzodioxins and -furans (PCDD/Fs), including dioxin-like PBCs	–	5 µg TEQ/kg
Polychlorinated naphthalenes (PCN)	10 mg/kg	-
Short-chain chlorinated paraffins (SCCP) (alkanes C10-C13)	10,000 mg /kg	1,500 mg/kg
Toxaphene	50 mg/kg	-

Annex V allows for pretreatment of POP waste prior to its destruction or irreversible transformation if the POP substances are isolated from the waste in the pretreatment process and handled according to Annex V of the regulation. This also applies to a situation where only a part of the waste contains POPs. Intentional diluting of POP wastes (i.e. mixing POP-containing wastes with a POP content above the Annex IV concentration limit with a waste stream with little or no contamination to reduce the POP content to below the concentration limit) is not considered environmentally sound (UNEP 2019). Article 7 of the regulation states that producers and holders of waste shall undertake all reasonable efforts to avoid, where feasible, contamination of such waste with POPs.

In addition to POP thresholds laid down for wastes, the POP Regulation sets limit values for POP substances in substances, mixtures or articles that are manufactured, placed on the market and used in the EU (Annex I limit values for UTCs). Additionally, new products produced from recycled materials, such as recycled plastics that have reached End-of-Waste status, must fulfil the UTC concentration requirements for POP substances in products set in Annex I of the POP Regulation. Products not complying with the requirements of the POP Regulation cannot be put on the market.

WEEE may contain several POP substances, depending on the date of their manufacture. Brominated diphenyl ethers (BDEs) and hexabromocyclododecane (HBCDD) have been used as FRs in plastic parts of EEE, and short-chain chlorinated paraffins (SCCPs) have been used as plasticisers, for example, in PVC cables. The main challenge is how to identify and detect POP substances from the WEEE management and recycling flows. The concentration of POP substances in the WEEE will have a significant impact on the waste treatment options. The regulation prohibits recycling of wastes that contain POPs above the concentration limits set in Annex IV.

3.4 Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS)

Directive 2011/65/EU (the RoHS Directive) limits the use of certain hazardous substances in EEE. Its aim is to contribute to the protection of human health and the environmentally sound recovery and disposal of WEEE. The RoHS Directive applies to both imported and domestically manufactured EEE that are put on the market in the EU (with certain exemptions). Substances restricted under the RoHS are heavy metals lead (Pb), cadmium (Cd), mercury (Hg) and chromium (Cr)(VI); BFRs PBB and PBDEs; and phthalates DEHP, BBP, DBP and DIBP. The applicable limit value is 0.01% for cadmium and 0.1% for all other aforementioned substances (calculated by weight in homogeneous material[9]).

It should be noted that the POP Regulation sets stricter limit values for BDE substances in recycled plastics than the RoHS limit value of 0.1% for polybrominated diphenyl ethers (PBDEs). Although Annex I of the POP Regulation allows new EEE that fulfil the requirements of the RoHS Directive to be placed on the market, recycled plastics that have reached End-of-Waste status and are placed on the market must comply with the UTC limit value of 500 mg/kg (0.05%) for POP BDE substances (see Section 3.3 above). This UTC limit value for BDE substances also applies to such recycled plastics that are used for EEE manufacturing.

3.5 Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH Regulation)

The REACH Regulation lays down provisions on the registration, evaluation, authorisation and restriction of chemical substances[10] as such, in mixtures[11] and in articles[12]. According to Article 1, the regulation aims to ensure a high level of protection of human health and the environment, including the promotion of alternative methods for assessment of hazards of substances, as well as the free circulation of substances on the internal market while enhancing competitiveness and innovation. To comply with the regulation, companies must identify and manage the risks linked to the substances they manufacture and market within the EU. They must demonstrate how the substance can be safely used, and they must communicate the risk management measures to the users. If the risks cannot be managed, authorities can

[9] 'Homogeneous material' means one material of uniform composition throughout or a material, consisting of a combination of materials, that cannot be disjointed or separated into different materials by mechanical actions such as unscrewing, cutting, crushing, grinding and abrasive processes.

[10] 'Substance' means a chemical element and its compounds in the natural state or obtained by any manufacturing process, including any additive necessary to preserve its stability and any impurity deriving from the process used, but excluding any solvent which may be separated without affecting the stability of the substance or changing its composition.

[11] 'Mixture' means a mixture or solution composed of two or more substances.

[12] 'Article' means an object which during production is given a special shape, surface or design which determines its function to a greater degree than does its chemical composition.

opt for different regulation processes. In the long run, the most hazardous substances should be substituted with less dangerous ones.

The REACH Regulation lays down three kinds of main obligations: registration, authorisation and restriction. In REACH registration, manufacturers and importers must obtain information on the substances they manufacture or import and use this information to assess the risks arising from the manufacture and use of the substances and to ensure that these risks are controlled. For substances manufactured or imported in quantities of 1 tonne or more per year, per company, the information and assessment must be demonstrated in a registration dossier submitted to the European Chemicals Agency (ECHA). This obligation applies to substances on their own, in mixtures or in articles where the substance is intended to be released under normal or reasonably foreseeable conditions of use. The registration aims to define and characterise the identity of the substance, identify the hazardous properties for hazard communication, identify and quantify the hazardous properties for risk assessment, as well as obtain the parameters necessary for exposure assessment and risk characterisation. Manufacturing under REACH also includes all forms of recovery operations that result in one or several substances as such or in a mixture or article that have ceased to be waste (ECHA, 2010).

The substances under registration can be divided into two categories: well-defined substances and substances of unknown or variable composition, complex reaction products or biological materials (UVCB). The first category refers to substances with a composition that can be quantitatively and qualitatively defined, and the registrant is able to provide a chemical specification of the constituents. If one constituent is present at a concentration of at least 80% (w/w) and the impurities make up no more than 20% (w/w), the substance will be considered as a mono-constituent substance[13]. If more than one main constituent is present in a concentration between 10% and 80% (w/w), the substance is considered as a multi-constituent substance. UVCBs have a high number of constituents, or; the composition is, to a significant extent, unknown; or the variability of composition is large or unpredictable and their clear identification based on the chemical composition only is not possible. Typically, they should be identified by considering the origin material of the substance, the most relevant steps during the manufacturing process and, according to the specific case, other relevant parameters.

REACH authorisation aims to ensure that the risks from SVHCs are properly controlled and that those substances are progressively replaced by suitable alternative substances or technologies. Substances subject to authorisation are listed in Annex XIV of the REACH Regulation. Once included in the annex, a substance cannot be placed on the market for use or used after a given date (the so-called ‘sunset date’) unless the companies concerned are granted authorisation for the specific use(s). Authorisations are granted by the commission after obtaining the opinion of the Committee for Risk Assessment and the Committee for Socio-economic Analysis of the ECHA. Applications for authorisation can be made by the manufacturer(s), importer(s) and/or downstream user(s) of the substance, covering one or more uses and/or one substance or a group of substances. An authorisation can be granted on two bases:

- the risk to human health or the environment from the use of a substance is adequately controlled; or
- it is shown that socio-economic benefits outweigh the risk to human health or the environment arising from the use of the substance and if there are no suitable alternative substances or technologies.

REACH restrictions are an instrument to protect human health and the environment from unacceptable risks posed by chemicals. They are normally used to limit or ban the manufacture, placing on the market (including imports) or use of a substance but can impose any relevant condition, such as requiring technical measures or specific labels. A restriction may also apply to any substance that does not require registration, for example, substances manufactured or imported below 1 tonne per year or certain

[13] Intentionally added substances other than those added to stabilise the substance are separate substances that are not to be considered in the main mass balance.

polymers. On-site isolated intermediates, substances used in scientific research and development, and substances only posing risks to human health from their use in cosmetics are exempted from REACH restrictions. Annex XVII of REACH includes all the restrictions adopted in the framework of REACH and the previous legislation, Directive 76/769/EEC. Each annex entry shows a substance or a group of substances or a substance in a mixture and the consequent restriction conditions.

3.6 **REACH Regulation and recycled plastics**

Article 2(2) of REACH states that materials that are considered 'waste' under the WFD are not considered substances, mixtures or articles according to REACH. Therefore, most of the obligations deriving from REACH are not applicable to wastes. Nevertheless, REACH does apply to materials that have ceased to be waste after recovery: The recovery of a substance, mixture or article should be considered manufacturing it (ECHA 2010). Hence, most of the REACH obligations are applied to waste-based material the same manner as they are applied to virgin raw materials.

In some cases, End-of-Waste products can be exempted from the REACH registration with the so-called recovery exemption. According to Article 2(7d), no registration is required for recovered substances if the substance that results from the recovery process is the same as a substance that has already been registered and the information required by Article 31 or 32 relating to the substance is available to the establishment undertaking the recovery. The applicability of the exemption is evaluated on the basis of 1) the 'sameness' between the recovered substance and the already registered substance and 2) the availability of information regarding that substance. The applicability of the exemption is not bound to the purpose of use or the volume of the original registration.

In most cases, the recovery exemption cannot be applied to waste-based materials, and hence, the normal REACH obligations must be followed. There are, however, some REACH provisions that are relevant to (both virgin and waste-based) plastics. Plastic products consist of polymers that in turn consist of monomers[14]. In the REACH Regulation, a polymer means a substance consisting of molecules characterised by the sequence of one or more types of monomer units. Such molecules must be distributed over a range of molecular weights wherein differences in the molecular weight are primarily attributable to differences in the number of monomer units[15]. A polymer comprises the following:

- (a) simple weight majority of molecules containing at least three monomer units which are covalently bound to at least one other monomer unit or other reactant;
- (b) less than a simple weight majority of molecules of the same molecular weight.

The manufacturer or importer of monomers must register them according to the REACH Regulation. Substances used as monomers in the manufacturing of polymers are by definition intermediates, and thus, they cannot be subject to the authorisation process in this purpose of use. However, these substances cannot be registered in accordance with the provisions that normally apply to on-site or transported isolated intermediates. Otherwise, the manufacturer or importer of a monomer substance has the same obligations as for any other substance.

Polymers are exempt from the registration obligation. However, the REACH authorisation process can apply to monomers, other substances used in the manufacturing of polymers, and polymers themselves (ECHA 2012). Additionally, monomers, any other substances used to manufacture a polymer, and polymers themselves may all be subject to restrictions. Restrictions on a monomer apply to polymers only if the concentration of the unreacted monomer in the polymer exceeds specific concentration limits listed for the monomer in Annex XVII (ECHA 2012).

[14] Monomer means a substance which is capable of forming covalent bonds with a sequence of additional like or unlike molecules under the conditions of the relevant polymer-forming reaction used for the particular process.
[15] In the context of this definition a 'monomer unit' means the reacted form of a monomer substance in a polymer.

Although manufacturers and importers are not obliged to register polymers, they must submit a registration to the ECHA for monomer substances or any other substances that have not already been registered by an actor up the supply chain if both of the following conditions are met:

- the polymer consists of 2% weight by weight (w/w) or more of such monomer substance(s) or other substance(s) in the form of monomeric units and chemically bound substance(s);
- (b) the total quantity of such monomer substance(s) or other substance(s) makes up 1 tonne or more per year (the total quantity in this context is the total quantity of the monomer or other substance ending up chemically bound to the polymer).

The recovery exemption can be applied to recovered plastics as well: Operators recovering polymers that have ceased to be waste are exempted from the obligation to register the monomer(s) or any other substance(s) in the recycled polymer provided that the monomers have been registered and the information on the registered substance is available to the company undertaking the recovery (Article 2(7)(d)).

3.7 SCIP database

The 2018 amendment of the WFD introduced Article 9(1)(i) that requires all suppliers of articles to notify the ECHA if their articles contain any SVHCs more than 0.1% weight by weight. The data is to be gathered in the so-called SCIP (Substances of Concern In articles as such or in complex objects [Products]) database, with the purpose of providing information on the presence of SVHCs to waste treatment operators and consumers.

The ECHA publishes the information as received on its website. Hence, the usefulness and accuracy of the information is mostly dependent on the companies submitting data in a transparent manner in their SCIP notifications. Moreover, the SCIP notifications only help to identify SVHCs, which constitute a small proportion of substances of concern. The SCIP database does not contain information, for example, on POP substances. The improved availability of the data in the SCIP database helps to ensure safer material cycles but as such does not set out any legal obligations for the reduction of chemical risks in products (Alaranta & Turunen 2021).

4 Persistent organic pollutants (POPs)

Certain chemicals/additives used in WEEE plastics are considered extremely harmful to the environment and human health. These chemicals are more specifically categorised as persistent, bioaccumulative and toxic (PBT) substances. This means that these chemicals are very persistent in the environment, they have the potential to bioaccumulate, and they are toxic to animals and humans. Some of these chemicals can also be transported long distances from their original emission sources. If substances meet these PBT and long-range atmospheric transportation criteria, they can be listed under the Stockholm Convention. This global treaty aims to phase out, ban or restrict the production, use and marketing of these most harmful POPs. Many old pesticides, FRs and plasticisers are now listed under the Stockholm Convention.

WEEE plastics may contain several different POPs which have been used, for example, as FRs and plasticisers in EEE plastics. The relevant POPs related to WEEE plastics and included in this report are presented in Table 3.

Table 3. Relevant POPs concerning WEEE plastics.

Name	Abbreviation	CAS
Commercial pentabromodiphenyl ether	c-pentaBDE	40088-47-9, 32534-81-9
Commercial octabromodiphenyl ether	c-octaBDE	68631-49-2, 207122-15-4, 446255-22-7, 207122-16-5
Commercial decabromodiphenyl ether	c-decaBDE	1163-19-5
Hexabromocyclododecane	HBCDD	25637- 99-4, 3194-55-6
Short-chain chlorinated paraffins	SCCP	85535-84-8
Hexabromobiphenyl	HBB	36355-01-8
Perfluorooctanoic acid	PFOA	335-67-1
Perfluorohexane sulfonate	PFHxS	355-46-4

4.1 Polybrominated diphenylethers (PBDEs)

4.1.1. PBDEs in general

PBDEs are a group of organic substances with various degrees of bromination. PBDEs act as additive FRs in different materials including plastics. The group consists of altogether 209 congeners with different degrees of bromination. The plastics industry is the major user of FRs, and the largest quantities of FRs are supplied to raw-material manufacturers. PBDEs occur in three commercial formulations: c-pentaBDE, c-octaBDE and c-decaBDE.

BDE-209 (decaBDE) has been recently detected in a number of articles, made from recycled material. This indicates that it is rather difficult to control the content of c-decaBDE in plastic material destined for recycling. Cost-efficient technical solutions for detecting and sorting out components containing these hazardous chemicals are not available on an industrial scale. In practice, the recycling industry separates plastics based on their total bromine content, not individual BFRs.

4.1.2 Commercial pentabromodiphenyl ether (c-pentaBDE)

Description

Commercial pentabromodiphenyl ether (c-pentaBDE) was a mixture of congeners with different degrees of bromination. Molecules with four (tetrabromodiphenyl ether) and five bromines (pentabromodiphenyl ether) predominated in the mixture but overall, it contained congeners from three to seven bromines in the molecule (UNEP 2006).

Emissions of pentaBDE to the environment occurred during its whole life cycle. Releases occurred from the manufacturing phase of the commercial product or products containing the substance to usage of these products or articles and after they have been discarded as waste. Even though pentaBDE production has been phased out globally, different articles with long lifespan containing it may still be in use at least for some extent. This leads to continuing releases from the waste management sector and sometimes further to the environment (UNEP 2006). Major releases of pentaBDE to air occurred from the emissions of articles and products during use, through volatilisation and dust-borne emissions. Emissions from recycling and dismantling activities also occur, for example from demolition of vehicles, buildings and constructions. Emissions also occurred from electronic waste recycling plants and shredder plants. During incineration of articles containing pentaBDE, potentially toxic products such as brominated dibenzo-p-dioxins and furans might also be generated (UNEP 2006).

Usage

The most common use of pentaBDE has been in PU foam (PUF). This accounts for 95-98% of the usage. PUF may contain pentaBDE constituting between 10% and 18% of the formulation. Other uses of pentaBDE have been in rigid PU elastomers in instrument casings, in epoxy resins and phenolic resins in electrical and electronic appliances, and construction materials (UNEP 2006). However, pentaBDE was substituted in these applications with decaBDE. In addition, pentaBDE has been added in minor amounts to textiles, paints, lacquers, in rubber goods (conveyor belts, coatings and floor panels) and to oil drilling fluids. Levels range in these applications from 5% to 30% by weight (UNEP 2006).

PentaBDE has been used for several applications and industrial sectors. The most common use has been in electrical and electronic appliances such as computers, office equipment, household appliances and other items containing printed circuit laminates, plastic outer casings and internal plastic parts such as small-run components with rigid PU elastomer instrument casings (UNEP 2006). PentaBDE has also been used in the traffic and transportation sector in cars, trains, aircraft and ships containing textile and plastic interiors and electrical components. Some building and construction materials such as foam fillers, insulation boards, foam insulation, wall and floor panels, plastic sheeting and resins have also contained this substance. PentaBDE has been added to various textiles and furniture as well. These include upholstered furniture, furniture covers, mattresses, flexible foam components, curtains, carpets, foam sheeting under carpets, tents, tarpaulins, work clothes and protective clothing (UNEP 2006).

Restrictions

PentaBDE and tetraBDE were added to the Stockholm Convention in 2009 in Annex A. Some specific exemptions were defined for recycling of articles that contain or may contain those substances, which will expire at the latest in 2030 (decision SC-4/18). PentaBDE and tetraBDE are included in the EU POP Regulation. According to Annex I of the POP Regulation, substances manufactured, placed on the market and used may not contain more than 10 mg/kg of tetraBDE or pentaBDE as UTCs. In mixtures and articles, the sum of tetra-, penta-, hexa-, hepta- and decaBDEs may not exceed 500 mg/kg. However, by way of derogation, the manufacturing, placing on the market and use of electronic equipment in accordance with the RoHS Directive are allowed.

4.1.3 Commercial octabromodiphenyl ether (c-octaBDE)

Description

Commercial octabromodiphenyl ether (c-octaBDE) was a complex mixture of several polybrominated diphenyl ethers and congeners (Stockholm Convention 2006). OctaBDE consisted typically of ≤0.5% pentaBDE, ≤12% hexaBDE, ≤45% heptaBDE, ≤33% octaBDE, ≤10% nonaBDE and ≤0.7% decaBDE. It should also be noted that the composition of older products or products from non-EU countries may be different from this (UNEP 2007a). Commercial octabromodiphenyl ether (c-octaBDE) was a complex mixture of several PBDEs and congeners (Stockholm Convention 2006). OctaBDE consisted typically of ≤ 0.5% pentaBDE, ≤ 12% hexaBDE, ≤ 45% heptaBDE, ≤ 33% octaBDE, ≤ 10% nonaBDE and ≤ 0.7% decaBDE. It should also be noted that the composition of older products or products from non-EU countries might be different (UNEP 2007a). Although the production of c-octaBDE has been phased out worldwide, releases during the service life of articles containing the commercial mixtures and at the end of articles' service life during disposal and waste management are still relevant (UNEP 2007a).

Usage

OctaBDE has been used as an additive FR mainly in the plastics industry for polymers used for housings of equipment containing electronics (UNEP 2007a). The main use of octaBDE has been (70% globally and 95% in Europe) in acrylonitrilebutadiene styrene (ABS) at 12–18% weight loadings in the final product. Other minor uses include HIPS, polybutylene terephthalate (PBT) and PA polymers at typical loadings of 12–15% weight in the final product (UNEP 2007a). In addition to previous uses mentioned above, other uses have been reported as well. These include nylon and low-density polyethylene (LDPE), PC, phenol-formaldehyde resins and unsaturated polyesters, as well as in adhesives and coatings (UNEP 2007a).

Restrictions

In 2009, hexabromodiphenyl ether (hexaBDE) and heptabromodiphenyl ether (heptaBDE) were listed in Annex A of the Stockholm Convention with specific exemptions for recycling of articles that contain or may contain those substances. This specific exemption will expire at the latest in 2030 (decision SC-4/14). HexaBDE and heptaBDE are included in the EU POP Regulation. According to Annex I of the POP Regulation, substances manufactured, placed on the market and used may not contain more than 10 mg/kg of hexaBDE or heptaBDE as UTCs. In mixtures and articles, the sum of tetra-, penta-, hexa-, hepta- and decaBDE may not exceed 500 mg/kg. However, by way of derogation, the manufacturing, placing on the market and use of electronic equipment in accordance with the RoHS Directive are allowed.

4.1.4 Commercial decabromodiphenyl ether (c-decaBDE)

Description

Intentionally produced synthetic c-decaBDE is a product consisting of fully brominated decaBDE congener (10 bromine atoms) or BDE-209 (≥90–97%). It might also contain small amounts of nona- and octaBDE. Production of c-decaBDE continued longer than production of pentaBDE and octaBDE, and consumption of decaBDE peaked in the early 2000s (UNEP 2014).

Emissions of decaBDE to the environment occur during all stages of its life cycle and are expected to be highest during service life and in the waste management phase. The average service life for EEE is thought to be about 10 years. Because of that, decaBDE will continue to be released from the waste management sector and to the environment through articles in use for years to come. This means that efficient control and detecting measures for handling of waste containing decaBDE will be needed. During incineration of articles containing decaBDE, potentially toxic products such as brominated dibenzo-p-dioxins and furans might also be generated (UNEP 2014). It is known that decaBDE can also be degraded to lower brominated PBDEs. Due to debromination and historical reservoirs of c-penta congeners in the environment, organisms are exposed to a complex mixture of PBDEs. Combination of these various congeners poses an even higher risk than BDE-209 alone (UNEP 2014).

Usage

DecaBDE has been used as an additive FR in many applications and articles. These have been, for example, plastics such as HIPS/other polymers/composites, textiles, adhesives, sealants, coatings and inks (UNEP 2014).

Plastics containing decaBDE have been used in housings of computers and TVs, wires, cables, pipes and carpets. The amount of decaBDE used in plastics and textiles globally varied, but it is estimated that up to 90% of decaBDE ended up in plastics and electronics (UNEP 2014). The remaining 10% ended up in coated textiles, upholstered furniture and mattresses. EEE applications included different casings, wires and cables, and small electrical components. Other identified uses of decaBDE in plastics have been in buildings, construction materials, storage and distribution products such as plastic pallets, and the transportation sector (cars, airplanes, trains and ships).

In the early 2000s, decaBDE was reportedly still used in toys in China and in the synthetic rubber industry as an FR (in conveyor belts for use in mines etc.). The aviation industry has also used decaBDE in electrical wiring and cables, interior components and EEE in older airplanes and spacecraft. DecaBDE is expected to be present in several waste streams such as end-of-life vehicles (ELVs), WEEE, textile waste, and mixed waste in plastic and textile materials.

BDE-209 has been frequently found (92–100%) in the shredded material from e-waste or ELVs and in recycled plastic pellets (100%) at higher concentrations than other POP-BDEs. This is explained by the fact that these waste streams and materials are mixed during shredding. Sorting out and removing decaBDE-containing parts prior to shredding and recycling operations might be an important and effective measure to avoid further contamination of waste materials with c-decaBDE (UNEP 2014).

Restrictions

DecaBDE was listed to the Stockholm Convention in Annex A in 2017 with specific exemptions for the production and use of c-decaBDE. DecaBDE is included in the EU POP Regulation. According to Annex I of the POP Regulation, substances manufactured, placed on the market and used may not contain more than 10 mg/kg of decaBDE as UTCs. In mixtures and articles, the sum of tetra-, penta-, hexa-, hepta- and decaBDE may not exceed 500 mg/kg. However, by way of derogation, the manufacturing, placing on the market and use of electronic equipment in accordance with the RoHS Directive are allowed. Additionally, the POP Regulation lists specific exemptions to the use of decaBDE, for example, in the manufacturing of certain aircraft and spare parts for aircraft and vehicles.

4.2 **Hexabromocyclododecane (HBCDD)**

Description

HBCDD has been used as an additive FR, providing fire protection during the service life of vehicles, buildings or articles. The use of HBCDD in insulation boards started in the 1980s (UNEP 2010). According to some estimates, the emissions from construction materials will continue for several decades and be potentially long-term sources of HBCDD. Additionally, this indicates possible problems that could arise in the recycling sector in the future, when buildings of the present period are renovated or demolished and materials end up in waste management (UNEP 2010).

Usage

The main uses of HBCDD have been in expanded and extruded polystyrene foam (EPS and XPS) insulation, with HBCDD concentrations ranging from 0.7% to 3.0%. Other use in textile applications and electric and electronic appliances has been smaller. According to some studies, HBCDD concentrations in the back-coating of textiles can range from 2.2% to 4.3% (UNEP 2010). Minor application of HBCDD has also been in HIPS, which is used in housings of EEE and appliances and wiring parts. In these applications, HBCDD levels have ranged from 1% to 7%. The use of HBCDD in EPS in packaging material is believed to have been small. HBCDD has not been used in food packaging (UNEP 2010).

HBCDD has been used in various end products and applications. For example, insulation boards with EPS foam or XPS foam containing HBCDD may be found in vehicles, buildings, and road and railway embankments. Estimates of HBCDD releases from insulation boards during their service life (assumed to be 30 years) have been based on the results of experiments measuring the loss of HBCDD from a sample of foamed PS (UNEP 2010). Moreover, HIPS containing HBCDD has been used in electric and electronic appliances, such as in audiovisual equipment cabinets, refrigerator lining, distribution boxes for electrical lines, and certain wire and cable applications. No estimates on releases of HBCDD from HIPS in articles are available. Nevertheless, electrical and electronic appliances containing HIPS treated with HBCDD are sometimes recycled. In these processes, HBCDD may end up in the recycled plastics. HBCDD has also been used in textile coating agents (UNEP 2010). The main use has been in upholstery fabrics, but it has also been used in bed mattress ticking, residential and commercial furniture upholstery, vehicle seating upholstery, interior textiles (roller blinds) and automobile interior textiles. HBCDD has also been used in EPS filling in bean bags used as easy chairs. Granulated EPS waste has also been used to improve the texture of agricultural and horticultural soil (UNEP 2010).

Restrictions

HBCDD was listed in Annex A of the Stockholm Convention in 2013, with specific exemptions. HBCDD has also been included in REACH Annex XIV. HBCDD is included in the EU POP Regulation. According to Annex I of the POP Regulation, substances, mixtures or articles may not contain more than 100 mg/kg of HBCDD as UTCs. This also applies to its presence as a constituent of flame-retarded articles.

4.3 **Short-chain chlorinated paraffins (SCCP)**

Description

SCCPs (alkanes C_{10-13}) cover those products that contain more than 48% by weight chlorination. Emissions of SCCPs can be released during their whole life cycle, from production to the storage, transportation, usage and disposal of SCCPs and SCCP-containing products (UNEP 2015). The major sources of SCCPs are assumed to be the manufacturing of products containing SCCPs, such as PVC, and use in metalworking fluids. Additionally, application of sewage sludge to soil can be a source of SCCP load to the terrestrial environment because historical use of SCCPs has been rather high in several countries (UNEP 2015).

Usage

SCCPs are primarily used in processing PVC. SCCPs have also been used as plasticisers and FRs in plastics, rubber (natural rubber, styrene and butadiene rubber, polybutadiene rubber, acrylonitrile and butadiene rubber, butadiene or isoprene rubber, and ethylene propylene diene monomer-elastomer) and in paints, adhesives and sealants, leather fat liquors, textiles and polymeric materials (UNEP 2015).

Restrictions

SCCPs were listed to the Stockholm Convention in Annex A in 2017. When listing SCCPs with decision SC-8/11, some specific exemptions were identified. SCCPs are included in the EU POP Regulation. According to Annex I of the POP Regulation, the manufacturing, placing on the market and use of substances or mixtures containing SCCPs in concentrations lower than 1% by weight (10,000 mg/kg) or articles containing SCCPs in concentrations lower than 0.15% by weight (1,500 mg/kg) are allowed.

4.4 **Hexabromobiphenyl (HBB)**

Description

Hexabromobiphenyl (HBB) is an intentionally produced chemical that belongs to a wider group of polybrominated biphenyls (PBBs). The term refers to a group of brominated hydrocarbons formed by substituting hydrogen with bromine in biphenyl. HBB has been used as an FR. According to the available information, the production and use of the substance ceased years ago. Based on an expected lifetime of 10 years for electrical and electronical devices, all of the products are assumed to have been disposed of. Therefore, assumingly, HBB should no longer cause problems in the recycling sector unless extremely old articles enter the waste management sector.

Usage

HBB has been used as a fire retardant in ABS thermoplastics.

HBB has mainly been used in ABS plastics and coated cables and for constructing business, machine housings, and industrial and electrical products (e.g. radio and TV parts); in PUF for vehicle upholstery; and as a fire retardant in coatings and lacquers. Approximately 40% of HBB produced in 1974 was used in ABS plastic products and an even larger amount in cable coatings. HBB was also one of the main components in technical FR (FireMaster(R)) containing several other PBB compounds, isomers and congeners.

Restrictions

HBB was listed to the Stockholm Convention in Annex A in 2009 with no specific exemptions. All uses of HBB are prohibited in Annex I of the EU POP Regulation.

4.5 **Perfluorooctanoic acid (PFOA)**

Description

Perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds are included in a family of perfluoroalkyl and polyfluoroalkyl substances (PFASs). Substances in this group consist of carbon chains of different chain length, where the hydrogen atoms are completely (perfluorinated) or partly (polyfluorinated) substituted by fluorine. This extremely stable bond between carbon and fluorine can only be broken with high energy input.

Usage

PFOA and its salts are most widely used as processing aids in the production of fluoroelastomers and fluoropolymers. The most important fluoropolymer is polytetrafluoroethylene (PTFE). Other important uses of PFOA-related compounds are as surfactants and surface treatment agents (e.g. in textiles, paper and paints, fire-fighting foams, cleaners, wetting agents). PFOA is usually not directly contained in electronic products, yet fluoropolymers are a base for plastic materials used in a wide variety of electronic applications. Fluoropolymers are used in many product applications in the consumer electronics industry. Fluoropolymers are used in applications such as communications chips and printed circuit boards and other electronic parts. Fluoropolymers are also used in structural components of electronic products (Digitaleurope 2015).

Restrictions

PFOA was listed in 2019 under Annex A of the Stockholm Convention with specific exemptions. PFOA, its salts and PFOA-related compounds are included in Annex I of the EU POP Regulation. According to Annex I, substances, mixtures and articles may not contain more than 0.025 mg/kg of PFOA and its salts and not more than 1 mg/kg of PFOA-related compounds as UTCs. The concentrations of any individual PFOA-related compound or a combination of PFOA-related compounds may not exceed 1 mg/kg when they are present in substances, mixtures or articles. However, in Annex I, there are several exemptions listed for PFOA, its salts and PFOA-related compounds in specified uses.

4.6 **Perfluorohexane sulfonate (PFHxS)**

Description

Perfluorohexane sulfonate (PFHxS), its salts and related substances are members of the PFAS group (UNEP 2017). PFHxS is a completely fluorinated strong organic acid that has both hydrophobic and hydrophilic properties (UNEP 2018)

Usage

PFHxS and its salts have the ability to resist both oil and water, which has led to their use for a variety of purposes. The main uses of PFHxS are in aqueous film-forming foams (AFFFs) for firefighting, metal plating, textiles, leather and upholstery, polishing and cleaning/washing agents, coatings, impregnation/proofing (for protection from damp, fungus etc.) and within the manufacturing of electronics and semiconductors (UNEP 2019b). Other potential uses may include in pesticides, FRs, paper and packaging, the oil industry and hydraulic fluids (UNEP 2019b).

Restrictions

The Persistent Organic Pollutants Review Committee of the Stockholm Convention has recommended that PFHxS, its salts and PFHxS-related compounds be added to the Stockholm Convention (decision POPRC-15/1). The decision on their inclusion in Annex I of the EU POP Regulation will be made once they have been listed under the Stockholm Convention.

5 Substances of Very High Concern (SVHC)

SVHCs are chemicals that can have serious effects on human health and the environment They can be carcinogenic, mutagenic or toxic to reproduction (i.e. carcinogenic, mutagenic and reprotoxic [CMR] substances), or have persistent (non-degradable), bioaccumulative (accumulate in living organisms) or toxic characteristics (i.e. PBT substances). Other substances that show evidence of probable serious effects to human health or the environment, giving rise to a similar level of concern as CMR and PBT substances, can be included in SVHCs. These substances causing similar concern include, for example, endocrine-disrupting chemicals (EDCs) and respiratory sensitisers.

CMR substances are very hazardous to human health due to their ability to interfere with the DNA causing uncontrolled cell growth (cancer) or disturbance of sexual development. The most hazardous CMR substances may be identified as SVHCs[16] based on certain criteria. Substances classified as PBT have unpredictable long-term effects once they are released into the environment. In addition, exposure to PBT substances is difficult to estimate, and they can accumulate in plants and organisms and end up in humans via the food chain.

After a substance has been officially identified in the EU as being an SVHC, it will be added to the Candidate List[17] including all SVHCs. Companies manufacturing or importing articles containing substances on the Candidate List in a concentration above 0.1% weight of the article have legal obligations. Substances placed on the Candidate List can be further added to the Authorisation List[18]. The aim of the authorisation is to phase out SVHCs from the market eventually. Substances included on the Authorisation List are not allowed to be placed on the market after a given date (sunset date) unless the user of the substance has been authorised by the EU to do so.

5.1 **Phthalates**

5.1.1 Phthalates in general

Phthalate esters (PAEs) are a group of chemicals synthesised by phthalic anhydride and alcohols with a wide spectrum of industrial and commercial applications (Tran et al. 2022). PAEs are chemically stable, colourless, odourless and flavourless chemicals that exist as liquids at a broad temperature range (25−50°C). They are widely used as plasticisers in PVC resins. In particular, di(2-ethylhexyl)phthalate (DEHP) has been added to PVC since the 1930s to improve flexibility and elasticity. Other uses include applications and fields such as household goods (furnishings, toys, food packaging, clothing etc.), building materials, industrial fields (adhesives, electronics, inks, lubricants, paints and vanishes etc.) and agriculture (pesticides, fertilisers, mulch plastic etc.) (OECD 2018).

Due to high production volumes and relatively continuous release into the environment, PAEs can be found at measurable concentrations in various environmental matrices, such as air, soil, sediment, wastewater (Salaudeen et al. 2018) and surface water (Fromme et al. 2002), worldwide (Liu et al. 2009). PAEs are classified as toxic EDCs that might cause substantial harm to the respiratory, reproductive and endocrine systems. Altogether, 17 phthalates were selected for review in this report (Table 4).

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[16] This introduction of SVHCs based on the information provided by ECHA: https://echa.europa.eu/chemicals-in-our-life/which-chemicals-are-of-concern/svhc
[17] https://echa.europa.eu/fi/candidate-list-table
[18] https://echa.europa.eu/fi/authorisation-list

Table 4. Relevant phthalates concerning WEEE plastics

Name	Abbreviation	CAS
Bis(2-ethylhexyl) phthalate	DEHP	117-81-7
Dibutyl phthalate (Di-n-butyl phthalate)	DBP	84-74-2
Benzyl butyl phthalate	BBP	85-68-7
Di-isobutylphtalate	DIBP	84-69-5
Bis(2-ethylhexyl) terephthalate	DEHT	6422-86-2
Diethyl phthalate	DEP	84-66-2
Dimethyl phthalate	DMP	131-11-3
Diisohexyl phthalate	DIHP	71850-09-4
Dicyclohexyl phthalate	DCHP	84-61-7
Dihexyl phthalate	DHP or DnHP	84-75-3
Dipentyl phthalate	DPP or DPeP	131-18-0
n-pentyl-isopentylphthalate	nPIPP	776297-69-9
Diisopentyl phthalate	DIPP or DiPeP	605-50-5
Diisodecyl phthalate	DIDP	26761-40-0 (or 68515-49-1)
Diisononyl phthalate	DINP	28553-12-0 and 68515-48-0
Di-n-octyl phthalate	DNOP	117-84-0
Bis(2-methoxyethyl) phthalate	DMEP	117-82-8

5.1.2 Bis(2ethylhexyl)phthalate (Di-2-ethylhexyl phthalate) (DEHP)

Description

DEHP is a widely used phthalate plasticiser synthesised from phthalic acid, which is esterified with various alcohols to form liquid DEHP (Erythropel et al. 2014). From the global production of DEHP, 97% is used as a plasticiser in polymers (ATSDR 2022). Approximately 50% of the produced DEHP is used to form more flexible and malleable PVC (Murphy 2001). As a result, PVC can contain up to 40% of plasticiser by weight (ATSDR 2022). DEHP is also used as a plasticiser in products such as PVA, PVB, PU resins, natural and synthetic rubber, chlorinated rubber, ethyl cellulose and nitrocellulose (CPSC 2010).

The typical applications of PVC plasticised with DEHP include medical equipment, food wrapping, wire and cable insulation, and automobile upholstery and tops (Rahman & Brazel 2004, Erythropel et al. 2014). In addition, DEHP is used in manufacturing plastic products, chemicals and electrical, electronic and optical equipment, and it can be found in products with material based on plastic (e.g. packaging films and sheets, toys, mobile phones, wire and cable sheathing), rubber (e.g. tyres, shoes, toys) and fabrics, textiles and apparel (e.g. clothing, mattresses, curtains or carpets, textile toys) (ATSDR 2022).

DEHP is not chemically bound to the PVC, which is why it is possible for DEHP to migrate within the material, and reach the polymer surface, and finally leach out of the material (Kastner et al. 2012). Therefore, DEHP has been labelled as an omnipresent environmental contaminant for several decades (Wams 1987). It has a wide range of toxic effects related to reproduction and fertility, it is endocrine disrupting, and it is very toxic to aquatic life. Furthermore, the breakdown pattern of DEHP, where stable metabolites are produced, is seen as very important (Erythropel et al. 2014). These metabolites, such as 2-ethyl hexanol, 2-ethyl hexanoic acid, and its monoester, mono(2-ethylhexyl)phthalate (MEHP), have been shown to be more toxic than DEHP itself (Horn et al. 2004, Nalli et al. 2006a, 2006b, 2006c). Release to the environment can occur from industrial use (production of articles) or from indoor and outdoor use of long-life materials with low release rates, such as furniture, plastic construction and building materials, and electronic equipment.

Usage

DEHP is primarily used as a plasticiser in the manufacturing of PVC; other applications consist of polymers such as PVA, PVB and PU resins. Accordingly, PVC as a material is used in various consumer products, flooring and wall coverings, food packaging and storage, and medical devices, including cardiac catheters, flexible tubing, syringes, and blood, dialysis, and storage bags.

DEHP can be found in a diverse group of electronic products and components and other plastic parts, such as cables, wires, plastic enclosures, plugs, handles, shock absorbers, anti-slip coatings, keys, tubes, coated baskets, sealing lists, decoration, straps, cuffs, and glues and sealants. A particular use of DEHP has been in capacitors (Maag et al. 2010).

Restrictions

The RoHS (Directive 2015/863) maximum concentration value for DEHP in any EEE component, including electrical plastics, is 0.1% by weight. This restriction does not apply to cables or spare parts for the repair, reuse, updating of functionalities or upgrading of capacity of EEE placed on the market before the RoHS restriction came into force.

DEHP is an SVHC and requires authorisation before it is used (Annex XIV of REACH; (EC) No 1907/2006). Currently, this provision does not apply to food contact materials under Regulation (EC) No 1935/2004; immediate packaging of medical products under Regulation (EC) No 726/2004, Directive 2001/82/EC and/or Directive 2001/83/EC; medical devices under Directives 90/385/EEC, 93/42/EEC and 98/79/EC; and mixtures containing DEHP at or above 0.1% and below 0.3% weight by weight.

In December 2021, the EU released the Commission Regulation (EU) 2021/2045 to amend entries 4–7 (DEHP, BBP, DBP and DIBP) of REACH Annex XIV, replacing entries 4–7 in the table in Annex XIV of Regulation (EC) No 1907/2006. According to the regulation, the use of DEHP is prohibited without authorisation after the sunset date 14 December 2024, including for uses in food contact materials, immediate packaging of medical products, and mixtures containing DEHP at or above 0.1% and below 0.3% weight by weight. The sunset date for use in medical devices is 27 May 2025.

Restrictions on the manufacture, placing on the market and use of DEHP are given in Annex XVII of REACH ((EC) No 1907/2006).

According to this,

- DEHP shall not be used as a substance or in mixtures, in concentrations greater than 0.1% by weight of the plasticised material, in toys and childcare articles.
- Toys and childcare articles[19] containing DEHP in a concentration greater than 0.1% by weight of the plasticised material shall not be placed on the market.

DEHP was one of the substances that were analysed from WEEE plastics in this project (see Chapter 8).

5.1.3 Dibutyl phthalate (DBP)

Description

DBP is a synthetic phthalic ester often added to hard plastics, such as PVC, to increase their workability and distensibility (European Commission 2003). The most common usage of DBP in general is as a plasticiser in resins and polymers, but DBP is further used in applications such as printing inks, adhesives (e.g. in paper and packaging, wood building and the automobile industry), sealants/grouting agents, lacquers, nitrocellulose paints, film coatings and glass fibres. DBP is widely used in consumer products and personal care products, for example, as a solvent and fixative, a suspension agent, a lubricant, an antifoamer, a skin emollient and a plasticiser in cosmetics (IPCS/WHO 1995).

DBP may be released into the environment during its production and its life cycle stages, ending with its final disposal (European Commission 2003). Phthalate plasticisers are so-called external plasticisers, meaning that they are not bound chemically in the polymer matrix (Maag et al. 2010). They can

[19] For the purpose of this entry 'childcare article' shall mean any product intended to facilitate sleep, relaxation, hygiene, the feeding of children or sucking on the part of children.

therefore move out of the plasticised polymer products by extraction with, for example, soapy water or oils, by evaporation, or by diffusion, thereby becoming available in the environment over long periods (Maag et al. 2010). Emissions to water and air are expected to be the most important entry routes of DBP (European Commission 2003). Therefore, DBP is widespread in the environment, and humans can be exposed to DBP through air, water and food or through direct skin contact with plastics containing DBP (ATSDR 2001).

DBP is considered an environmental endocrine disruptor, with reproductive toxicity, developmental toxicity and potential carcinogenic effects (European Commission 2003, EPA 2020). It also has possible long-term adverse effects in the aquatic environment and a potential for bioaccumulation (European Commission 2003, Maag et al. 2010).

Usage

A considerable proportion of DBP use (more than 50%) is in polymer formulation and processing (Maag et al. 2010). In the polymer industry, DBP is used as a plasticiser in PVA, PVC, polychloroprene rubber and nitrile rubber; in PP catalytic systems; and as a solvent for nitrocellulose esters, colours, oils and natural resins (European Commission 2003, Maag et al. 2010). Compared with other plasticisers, DBP has relatively high volatility and is therefore only used in combination with other plasticisers, mostly high molecular phthalates.

DBP has been used in plastics that are part of many consumer products, such as home furnishing, paints, clothing and cosmetic products (European Commission 2003), as well as floor coverings, automotive components, garden hoses, PUFs, epoxy resin and coatings (Maag et al. 2010).

DBP has already been substituted in many of its former applications, and consumption has decreased significantly (Maag et al. 2010). Still, DBP use in EEE parts or manufacturing processes cannot be ruled out. The possible application areas of DBP in polymers and plasticised non-polymers used in EEE are cables, plugs, 'rubber' feet, shock absorbers, handles, anti-slip coatings, keys, and tubes and, to some extent, in coated baskets, sealing lists, decoration, straps, cuffs, and glues and sealants.

Restrictions

The RoHS (Directive 2015/863) maximum concentration value for DBP in any EEE component, including electrical plastics, is 0.1% by weight. This restriction does not apply to cables or spare parts for the repair, reuse, updating of functionalities or upgrading of capacity of EEE placed on the market before the RoHS restriction came into force.

DBP is an SVHC and requires authorisation before it is used (Annex XIV of REACH; (EC) No 1907/2006). Currently, this provision does not apply to immediate packaging of medical products under Regulation (EC) No 726/2004, Directive 2001/82/EC, and/or Directive 2001/83/EC and mixtures containing DBP at or above 0.1% and below 0.3% weight by weight.

In December 2021, the EU released the Commission Regulation (EU) 2021/2045 to amend entries 4–7 (DEHP, BBP, DBP and DIBP) of REACH Annex XIV, replacing entries 4–7 in the table in Annex XIV of Regulation (EC) No 1907/2006. According to it, the use of DBP is prohibited without authorisation after the sunset date 14 December 2024, including for uses in immediate packaging of medical products and mixtures containing DBP at or above 0.1% and below 0.3% weight by weight.

Restrictions on the manufacture, placing on the market and use of DBP are given in Annex XVII of REACH ((EC) No 1907/2006).

According to this,

- DPB shall not be used as a substance or in mixtures, in concentrations greater than 0.1% by weight of the plasticised material, in toys and childcare articles.

- Toys and childcare articles[20] containing DBP in a concentration greater than 0.1% by weight of the plasticised material shall not be placed on the market.

DBP was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

5.1.4 Benzyl butyl phthalate (BBP)

Description

BBP is a synthetic phthalate ester, which is typically used together with other plasticisers (e.g. DEHP or DINP) and used to add special performance to the polymer: During processing, BBP offers faster gelation of the polymer, and in the end product (e.g. vinyl flooring), a hardened and stain-resistant surface. In 2007, more than 70% of BBP was used as a plasticiser in polymer products, mainly in PVC for flooring, accounting for about 50% of the total consumption (COWI 2009). The second largest application area, polysulphide sealants, accounts for about 19% of the total BBP consumption. Thus, the market for BBP has been decreasing since the beginning of the 2000s.

BBP is not bound chemically in the polymer matrix and can therefore move out of the plasticised polymer products by extraction with, for example, soapy water or oils, by evaporation or by diffusion, thereby becoming available in the environment over long periods (Maag et al. 2010). BBP is a reproductive toxicant as it has been found in experimental animal studies to adversely affect the reproductive organs, which could affect fertility. Furthermore, the substance has been found to be endocrine disrupting and a developmental toxicant, as well as to have possible long-term adverse effects in the aquatic environment.

Usage

BBP is used in concentrations of low percentages in flexible PVC applications, packaging films and some non-polymer materials such as paints, adhesives (e.g. polyvinyl acetate), sealants (polysulphide, PU or acrylic based), printing inks, and coating for textiles and leather (COWI 2009). BBP is used to increase the flexibility of plastic and rubber products, which can be used industrially, commercially and by consumers. These applications include vinyl floor tiles, vinyl wallpaper, shower curtains, toys, packaging films and products used in transportation equipment manufacturing.

BBP can be used in a low percentage in flexible or rigid PVC, sheets, adhesives, sealants and other non-polymer applications of EEE devices (Maag et al. 2010). Maag et al. (2010) estimated in 2010 that the consumption of BBP for EEE production in the EU is likely in the range of 20–200 t/y, as any confirmed estimates of BBP usage in EEE have not been found. Still, an unknown amount of BBP might be used in imported EEE and imported EEE parts.

Restrictions

The RoHS (Directive 2015/863) maximum concentration value for DBP in any EEE component, including electrical plastics, is 0.1% by weight. This restriction does not apply to cables or spare parts for the repair, reuse, updating of functionalities or upgrading of capacity of EEE placed on the market before the RoHS restriction came into force.

BBP is an SVHC and requires authorisation before it is used (Annex XIV of REACH; (EC) No 1907/2006). Currently, this provision does not apply to immediate packaging of medical products under Regulation (EC) No 726/2004, Directive 2001/82/EC, and/or Directive 2001/83/EC and mixtures containing DBP at or above 0.1% and below 0.3% weight by weight.

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[20] For the purpose of this entry 'childcare article' shall mean any product intended to facilitate sleep, relaxation, hygiene, the feeding of children or sucking on the part of children.

In December 2021, the EU released the Commission Regulation (EU) 2021/2045 to amend entries 4–7 (DEHP, BBP, DBP and DIBP) of REACH Annex XIV, replacing entries 4–7 in the table in Annex XIV of Regulation (EC) No 1907/2006. According to it, the use of BBP is prohibited without authorisation after the sunset date 14 December 2024, including for uses in immediate packaging of medical products and mixtures containing BBP at or above 0.1% and below 0.3% weight by weight.

Restrictions on the manufacture, placing on the market and use of BBP are given in Annex XVII of REACH ((EC) No 1907/2006).

According to this,

- BBP shall not be used as a substance or in mixtures, in concentrations greater than 0.1% by weight of the plasticised material, in toys and childcare articles.
- Toys and childcare articles[21] containing BBP in a concentration greater than 0.1% by weight of the plasticised material shall not be placed on the market.

BBP was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

5.1.5 Di-isobutylphthalate (DIBP)

Description

DIBP is a phthalate ester with good heat and light stability. When used as a plasticiser in PVC, it is often combined with other phthalates due to its high volatility (EPA 2009). In addition, DIBP has similar properties to DBP, which is why it can be used as a substitute for DBP (ECHA 2009).

DIBP is classified as toxic to reproduction and development and as an endocrine-disrupting substance based on evidence given by several studies about adverse effects on the reproductive organs in adult and developing rodents (ECHA 2009). People are exposed to DIBP via food and indoor environments because of its use in household products (Wormuth et al. 2006). In the body, DIBP undergoes primary metabolism and is rapidly hydrolysed to its primary metabolite, monoisobutyl phthalate (MIBP), before excretion (Yost et al. 2019). The substance information provided by the ECHA identifies DIBP as very toxic to aquatic life with long-lasting effects. It is expected to volatilise from water and moist soil surfaces but not from dry soil, which is why it is expected to have low mobility in soil (EPA 2019). In addition, some ECHA substance registrants indicate DIBP as PBT, but consistent research data is not yet available to form a basis for regulation.

Usage

DIBP has been used as a plasticiser for nitrocellulose, cellulose ether, PVC, and polyacrylate and polyacetate dispersions (EPA 2009, ECHA 2009). It has several uses in industrial and consumer products, including PVC, rubber, paints, lacquers, varnishes, lubricants printing inks, printing inks for paper and packaging, pulp and paper, carpets, concrete, and cosmetics (ECHA 2009, Yost et al. 2019). DIBP is also used as a component of industrial adhesives and catalyst systems for PP and fiberglass manufacturing (NICNAS 2008a, EPA 2019). Therefore, DIBP can be found in commercially used plastic and rubber products. For example, in the recently published study of Berenstein et al. (2022), DIBP (as well as DBP and DEHP) was found in polytunnel (PT) films, greenhouse polyethylene crystal film (GF) and greenhouse polyethylene crystal film with EVA as a copolymer (GF-EVA).

According to the substance information provided by the ECHA, DIBP can be found in complex articles, such as vehicles, machinery, mechanical appliances, and electrical and electronic products (e.g. computers, cameras, lamps, refrigerators, washing machines) and electrical batteries and accumulators. In particular, DIBP can be found in products with material based on plastic that is used for EEE devices.

[21] For the purpose of this entry 'childcare article' shall mean any product intended to facilitate sleep, relaxation, hygiene, the feeding of children or sucking on the part of children.

Restrictions

The RoHS (Directive 2015/863) maximum concentration value for DIBP in any EEE component, including electrical plastics, is 0.1% by weight. This restriction does not apply to cables or spare parts for the repair, reuse, updating of functionalities or upgrading of capacity of EEE placed on the market before the RoHS restriction came into force.

DIBP is an SVHC and requires authorisation before it is used (Annex XIV of REACH; (EC) No 1907/2006). Currently, this provision does not apply to mixtures containing DIBP at or above 0.1% and below 0.3% by weight.

In December 2021, the EU released the Commission Regulation (EU) 2021/2045 to amend entries 4–7 (DEHP, BBP, DBP and DIBP) of REACH Annex XIV, replacing entries 4–7 in the table in Annex XIV of Regulation (EC) No 1907/2006. According to it, the use of BBP is prohibited without authorisation after the sunset date 14 December 2024, including in mixtures containing BBP at or above 0.1% and below 0.3% by weight.

Restrictions on the manufacture, placing on the market and use of DIBP are given in Annex XVII of REACH ((EC) No 1907/2006).

- DIBP shall not be used as a substance or in mixtures, in concentrations greater than 0.1% by weight of the plasticised material, in toys and childcare articles.
- Toys and childcare articles containing DIBP in a concentration greater than 0.1% by weight of the plasticised material shall not be placed on the market.

DIBP was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

5.1.6 Bis(2-ethylhexyl) terephthalate (DEHT)

Description

DEHT is a clear and viscous para-phthalate ester and an isomer of DEHP (Faber et al. 2007a, Wirnitzer et al. 2011). It is used as alternative plasticiser to DEHP because it has been shown to be less toxic than DEHP (Wirnitzer et al. 2011). As a plasticiser, DEHT offers good mechanical and permanence properties, as well as excellent low-temperature flexibility (Faber et al. 2007a).

As with DEHP and other plasticisers, DEHT is not chemically bound to the polymer matrix, which is why it is possible that DEHT migrates within the material and, after reaching the polymer surface, finally leaches out of the material. Migration of plasticisers into foodstuff, consumer products and medical devices has led to concern with regard to human exposure (Wirnitzer et al. 2011). In addition, because of its widespread use, DEHT has been found in indoor air and dust samples of children's day care centres and homes (Nagorka et al. 2011, Takeuchi et al. 2014).

As far as currently known from animal studies, DEHT has no carcinogenic, genotoxic or developmental effects, especially on reproductive organs, kidneys and the liver, which usually indicate DEHP toxicity (Faber et al. 2007a & 2007b, Deyo 2008, SCENIHR 2015, Wirnitzer et al. 2011). Furthermore, according to the recent study of Larsson et al. (2022), DEHT is a viable non-phthalate substitute for DEHP used as a plasticiser for blood bank storage bags.

Usage

DEHT is used as a plasticiser for flexible PVC and PVC/VA copolymers (Faber et al. 2007b) in, for example, medical devices and plastic toys (Wirnitzer et al. 2011). In Wirnitzer et al.'s (2011) study, DEHT was the most common plasticiser, dominating the composition of plasticisers in four out of six backpacks and six out of seven plastic toys. DEHT's applications also include vinyl floorings, coatings, electric connectors, vinyl water stops, coatings for clothes, bottle caps, toys and medical devices (Nagorka et al. 2011).

Confirmed information on the presence of DEHT in WEEE plastics was not found. As DEHT is used as an alternative plasticiser to DEHP, especially in PVC and PVC/VA plastics, it is possible that DEHT can be found in diverse groups of plastic parts of electronic products and components. DEHT was detected from the chemical analyses performed in this study (Chapter 8). The concentrations seem to be rather low when considering the actual amounts of phthalates added to the plastics when they are used. Therefore, these concentrations detected refer to the residual concentrations in these studied materials.

Restrictions

The ECHA published a final opinion on the safety of DEHT in 2016[22]. According to this opinion, DEHT is not expected to pose any health or environmental risks, and therefore, no regulatory risk management actions were recommended.

Furthermore, DEHT is not listed among the banned phthalates reported in Directives 1999/815/EC and 2005/84/EC related to toys, nor is it listed among the banned substances in accordance with Annex VI of (EC) No 1272/2008 related to medical devices.

DEHT was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

5.1.7 Diethyl phthalate (DEP)

Description

DEP is a clear, colourless, practically odourless oily liquid with slight water solubility (Api 2001, Weaver et al. 2020). It is used as a solvent and softener and most commonly as a carrier for fragrances. Therefore, DEP is a common ingredient in scented mixtures and articles (ECHA 2015).

DEP is ubiquitous in the environment due to its extensive industrial use (Api 2001). In addition, DEP is not chemically bound to products and therefore, it is readily released into the environment, where it may be absorbed orally, dermally, or by inhalation (Wormuth et al. 2006, Clark et al. 2011). DEP has been measured in air, water and soil, as well as in tissues of human and fish and in foods wrapped in cellulose acetate (Api 2001). The results Weaver et al.'s (2020) systematic review provide moderate evidence that DEP causes male reproductive toxicity, developmental toxicity and liver toxicity, as well as slight evidence for female reproductive toxicity and indeterminate evidence for kidney toxicity and cancer.

Usage

DEP is used as a plasticiser in plastic polymers to maintain flexibility in products, such as cellulose ester plastics and PS[23] (Okita & Okita 1992, Weaver et al. 2020). As a plasticiser, DEP is added to products such as plastic films, tape, rubber, tool handles, toys, toothbrushes, food wrapping and automotive components (Okita & Okita 1992, Weaver et al. 2020). In addition to plastics, DEP is used in a wide range of personal care products (e.g. cosmetics, perfumes, fragrances, hair sprays, nail polishes, soaps, detergents and lotions), industrial materials (e.g. polishes, fillers, putties, varnishes, wax blends, paints and paint removers, sealants and lubricants, and packaging) and medical products (e.g. pharmaceutical coatings, enteric coatings on tablets and dental impression materials) (Okita & Okita 1992, ECHA 2015, Weaver et al. 2020)

Confirmed information on the presence of DEP in WEEE plastics was not found. As DEP is used as plasticiser, it is very likely that DEP can be found in diverse groups of plastic parts of electronic products and components, especially those made of PS. DEP was detected through the chemical analyses

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[22] ECHA 2016: Analysis of the most appropriate risk management option (RMOA) for Di ethyl hexyl terephthalate. https://echa.europa.eu/documents/10162/ad151e2f-b765-c69c-ef8e-e9d996e50651.
[23] Hazardous Substances Data Bank (HSDB): https://pubchem.ncbi.nlm.nih.gov/source/hsdb/926.

performed in this study (Chapter 8). The concentrations seem to be rather low when considering the actual amounts of phthalates added to the plastics when they are used. Therefore, these concentrations detected refer to the residual concentrations in these studied materials.

Restrictions

DEP is included in the Community Rolling Action Plan (CoRAP) and is under assessment as an endocrine-disrupting substance. After evaluation, proposals may be made for further regulatory action regarding the substance.

DEP was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

5.1.8 Dimethyl phthalate (DMP)

Description

DMP is one of the PAEs occurring in colourless and oily liquid form (U.S. CPSC 2011a). It is the most extensively used compound for manufacturing various consumer products (NICNAS 2008b). As a solvent and plasticiser, DMP is used for nitrocellulose, cellulose acetate and cellulose acetate-butyrate compositions and as a plasticiser in children's toys.

DMP is not chemically bound into plastics, and therefore, it can disperse in the ecosystem easily (Mersiowsky 2002, Latini 2005) and migrate and accumulate in soils via irrigation and the application of pesticides and plastic films (Cartwright et al. 2000, Wang et al. 2014). The main concern with DMP is that it is indicated as a potential hazard due to high aquatic toxicity and endocrine disruption (Engel et al. 2017, Lee et al. 2019, ECHA 2021b).

Usage

DMP has been extensively used in consumer products such as cosmetics, hair products, detergents, soaps, deodorants, insecticides, insect repellents, printing inks, paints, paper coatings and adhesives, and plastic products, as well as in fabric treatment (NICNAS 2008b). According to the ECHA's substance infocard, DMP can be found in plastic products and materials such as food packaging and storage, toys, automotive parts and mobile phones[24]. In particular, DMP is used in nitrocellulose, cellulose acetate and cellulose acetate-butyrate compositions (NICNAS 2008b), as well as, to some extent, as a plasticiser in PVC compounds for cables and flexible pipes[25].

DMP can be found in complex articles in electrical or electronic products, such as computers, cameras, lamps, refrigerators and washing machines. DMP can be added in PVC used for encapsulation of electrical wiring.[24] DMP was detected from the chemical analyses performed in this study (Chapter 8). The concentrations seem to be rather low, when considering the actual amounts of phthalates added to the plastics when they are used. Therefor these concentrations detected refer to the residual concentrations in these studied materials.

Restrictions

There are no existing restrictions on the substance. However, DMP does appear to show a high aquatic toxicity hazard profile. Referring to assessment of regulatory needs by the ECHA (2021b), because there are remaining uncertainties with the available data, further data generation is required. In addition,

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[24] Substance Infocard (European Chemicals Agency): https://echa.europa.eu/fi/substance-information/-/substanceinfo/100.004.557.

[25] The information is based on the information provided by the supplier: https://fornarolipolymers.com/en/products/plasticizer-dmp/.

SVHC identification confirming the endocrine disruptive properties of DMP for the environment would be needed first.

DMP was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

5.1.9 Diisohexyl phthalate (DIHP)

Description

DIHP is a phthalate ester with limited available information. According to the REACH Regulation Annex XV report for DIHP [26], DIHP is a component of 1,2-benzenedicarboxylic acid, dihexyl ester, branched and linear (CAS 68515-50-4), which might be used as a substitute for other low/transitional molecular weight phthalates of carbon backbone lengths of C4–C6.

There is no data available on the toxic properties of DIHP, but information from structurally similar phthalates has been used in a chemical grouping approach to confirm the potential toxicity of DIHP (SCA 2016). Structurally similar substances to DIHP (e.g. DEHP, BBP, DBP, DIBP and 1,2-benzenedicarboxylic acid, dihexyl ester, branched and linear) demonstrate significant effects on male reproductive organs and developmental effects of the selected phthalates in the category. The similarity of reproductive toxicity across the category of phthalates supports the notion that DIHP very likely has similar properties to those of the reference phthalates. Thus, DIHP has been categorised as meeting the criteria for classification as toxic for reproduction category 1B in accordance with Article 57 (c) of REACH[27].

Usage

There is limited information on the commercial uses of DIHP, but substances structurally similar to DIHP might indicate its possible uses in the same types of applications. The Annex XV report for 1,2-benzenedicarboxylic acid, dihexyl ester, branched and linear, indicates potential use as a sealant, lubricant in steering fluid, or plasticiser in polymers. In addition, DIHP has been found to be used in air fresheners[28].

DIHP could also be used as a substitute for phthalates. Thus, it is possible that DIHP is used, for example, as a plasticiser in polymers.

Because information on the uses of DIHP is not available, DIHP use in EEE devices and other applications is uncertain.

Restrictions

DIHP is an SVHC and requires authorisation before it is used (Annex XIV of REACH; (EC) No 1907/2006).

DIHP is classified as toxic for reproduction, category 1B, in the CLP Regulation. DIHP is listed in Annex XVII, Group 30, of the REACH Regulation. It should not be placed on the market or used for supply to the general public as a substance or in mixtures in concentrations equal to or greater than the generic concentration limit for reproduction toxicants (≥ 0.3%).

According to the Toy Safety Directive (2009/48/EY), the concentration of such substances shall not exceed 0.3% in toys or their parts.

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[26] Annex XV report for 1,2-Benzenedicarboxylic acid, dihexyl ester, branched and linear: https://echa.europa.eu/documents/10162/7c5c54dc-e0bb-4d8b-b759-437044f82af8.

[27] Support Document for Identification of Diisohexyl Phthalate as a Substance of Very High Concern Because of It Is Toxic for Reproduction (Artile 57C) Properties: https://echa.europa.eu/documents/10162/cc11a6e1-0b26-8a5d-189d-417eb06a60d4.

[28] Cohen, A., Janssen, S., & Solomon, G. (2007). Clearing the Air. https://cdn.dynamixse.com/ragsdaleair-com/ragsdaleair_com-airfresheners.pdf.

5.1.10 Dicyclohexyl phthalate (DCHP)

Description

DCHP is a white crystalline solid which is considered to belong to the group of transitional PAEs (SCA 2014). Transitional phthalate esters are used primarily as industrial chemicals for formulation use of plastisol in sealants or in textile printing and as a co-plasticiser in PVC, rubber and plastic compounds (ECHA 2021c). In addition, DCHP is used in organic peroxides as, for example, a phlegmatizer, dispersion agent or adhesive. Based on structural similarities with other phthalates, DCHP might be used as a substitute for other phthalates used as plasticisers in polymers.

Because DCHP does not bind to polymers, it is easily released into the environment during manufacturing, storage and usage (Li et al. 2022). Thus, DCHP has been found, for example, in indoor particulate matter (Rakkestad et al. 2007) and indoor air and dust samples (Otake et al. 2004, Li et al. 2022).

The EU Commission identifies DCHP as an SVHC due to its toxicity for reproduction and endocrine-disrupting properties for humans. This conclusion was based on the evidence in animals of DCHP-induced toxicity to the liver, kidney, testes, foetus, thyroid and other tissues (Lake et al.1982, Hoshino 2005, Yamasaki 2009). In a recently published study, DCHP was associated with a possible increase in atherosclerotic cardiovascular disease in humans (Liu et al. 2022).

Usage

DCHP is a plasticiser ingredient in the production of nitrocellulose, ethyl cellulose, benzyl cellulose, chlorinated rubber, PVA, PVB, PVC, PS, acrylic plastics when products are intended for food or drink contact, and other polymer resins (U.S. CPSC 2011b, ECHA 2021c). DCHP can be used in the same type of applications as DEHP, BBP, DBP and DIBP (e.g. as a plasticiser in polymers) (ECHA 2021c).

DCHP is used in sectors that produce articles, such as machinery, electrical/electronic articles, computers, electronic and optical products, electrical equipment or vehicles, to which adhesives have been applied (ECHA 2021c). In particular, DCHP is used in manufacturing PVC, which is common in EEE and thereby in e-waste (Schlummer et al. 2007).

Restrictions

DCHP is an SVHC and requires authorisation before it is used (Annex VI of REACH; (EC) No 1907/2006) due to its classification as toxic for reproduction, category 1B, H360D, and its endocrine-disrupting properties (Article 57(f) of REACH).

DCHP uses fall under the restriction on substances that are toxic for reproduction (REACH Annex XVII, entry 30) used in concentrations equal to or above 0.3%. These substances shall not be placed on the market or used, as substances, as constituents of other substances, or in mixtures, for supply to the general public when the concentration limit is exceeded.

According to the Toy Safety Directive (2009/48/EY), the concentration of substances classified as toxic for reproduction, category 1B, shall not exceed 0.3% in toys or their parts.

Furthermore, DCHP is included in the CoRAP and is under assessment for environmental endocrine disruption in non-mammalian (fish) species. After evaluation, proposals may be made for further regulatory action regarding the substance.

5.1.11 Dihexyl phthalate (DHP)

Description

DHP is a clear liquid with a chemical structure (a backbone of 6 carbons) typical to transitional phthalates (NICNAS 2008c). DHP is used in the making of plastisols and added, for example, to PVC with other commercial phthalate substances containing DHP.

There is sufficient evidence from rodent studies that DHP can cause reduced fertility, developmental toxicity, liver damage, reduced serum cholesterol and triglycerides, and thyroid hyperactivity (Reel et al. 1985, Lamb et al. 1987, NICNAS 2008c, Howarth et al. 2001). Still, toxicity data for DHP is incomplete, so information from structurally similar phthalates has been used to extrapolate the potential toxicity of DHP (NICNAS 2008c, Annex XV report 2013a). The reproductive effects of DHP are similar to those of other transitional phthalates, which is why the EU Commission identifies DHP as an SVHC.

Usage

DHP is used in the making of plastisols that are used in the manufacturing of automobile parts (e.g. air filters, battery covers) and dip-moulded products (e.g. tool handles, dishwasher baskets. DHP may be added to PVC along with other commercially used phthalate substances PVC is utilised, for example, in the manufacturing of flooring, canvas tarps and notebook covers. In addition, substances containing DHP may be used in traffic cones, vinyl gloves, weather stripping, flea collars, shoes, toys and conveyor belts used in food packaging operations.

Confirmed information on the presence of DHP in WEEE plastics was not found. As DHP is used in the making of plastisols and as part of other phthalate substances, it is possible that DHP can be found in a diverse group of plastic parts of electronic products and components, especially those made of PVC.

Restrictions

DHP is an SVHC. It has been included in Annex XIV of the REACH Regulation (Entry 45) as toxic for reproduction, category 1B, H360D. Therefore, its use will require authorisation from the sunset date 27 February 2023 onwards.

DHP is listed in Annex XVII, Group 30, of the REACH Regulation. It shall not be placed on the market or used for supply to the general public as a substance or in mixtures in concentrations equal to or greater than the generic concentration limit for reproduction toxicants (≥ 0.3%).

5.1.12 Dipentyl phthalate (DPP)

Description

DPP is a clear, colourless to light yellow liquid (NTP 1992). Its main use is as a plasticiser in plastics, especially PVC (Annex XV report 2013b). The general population may be exposed to DPP via dermal contact with consumer products (e.g. textiles, paper or paints) containing DPP (Annex XV report 2013b). Occupational exposure can occur through dermal contact at workplaces where DPP is used as a plasticiser or where plastics are produced and/or processed, as well as through inhalation of aerosols. Studies have shown that DPP causes reproductive toxicity with testicular atrophy and a fertility-impairing effect (Foster et al. 1980, Foster et al. 1982, Creasy et al. 1983, Granholm et al. 1992, Howdeshell et al. 2008, Hannas et al. 2011).

Usage

The main use of DPP is as a plasticiser in PVC. Furthermore, the structural similarities of DPP with other phthalates could indicate its potential use in the same types of applications.

Confirmed information on the presence of DPP in WEEE plastics was not found. As DPP is used as a plasticiser of PVC, it is possible that DPP can be found in a diverse group of plastic parts of electronic products and components, especially those made of PVC.

Restrictions

DPP is an SVHC and requires authorisation before it is used (Annex XIV of Regulation (EC) No 1907/2006 of REACH, Entry 38) as toxic for reproduction, category 1B, H360D (Article 57c).

DPP is classified as toxic for reproduction, category 1B, in the CLP Regulation ((EC) No 1272/2008).

DPP is listed in Annex XVII, Group 30, of the REACH Regulation. It shall not be placed on the market or used for supply to the general public as a substance or in mixtures in concentrations equal to or greater than the generic concentration limit for reproduction toxicants (≥ 0.3%).

5.1.13 n-pentyl-isopentylphthalate (nPIPP)

Description

Information on the use and properties of nPIPP is not available. nPIPP has similarities in terms of structure and physico-chemical properties with other transitional phthalates (e.g. DBP, DPIPP) (Annex XV report 2012).

A risk characterisation for nPIPP is not possible due to a lack of information about possible exposure.

Usage

There are indications on the potential use of nPIPP in the same types of applications as other phthalates, such as plasticisers in plastic material (Annex XV report, 2012).

There is no information available on the use of nPIPP in EEE plastics.

Restrictions

nPIPP is an SVHC and requires authorisation before it is used (Annex XVI of Regulation (EC) No 1907/2006 of REACH, Entry 39) as toxic for reproduction, category 1B, H360D (Article 57c). nPIPP is classified as toxic for reproduction, category 1B, in the CLP Regulation ((EC) No 1272/2008).

nPIPP is listed in Annex XVII, Group 30, of the REACH Regulation. It shall not be placed on the market or used for supply to the general public as a substance or in mixtures in concentrations equal to or greater than generic concentration limit for reproduction toxicants (≥ 0.3%).

According to the Toy Safety Directive (2009/48/EY), the concentration of substances classified as toxic for reproduction, category 1B, shall not exceed 0.3% in toys or their parts.

5.1.14 Diisopentyl phthalate (DIPP)

Description

DIPP is a clear, slightly yellow liquid that has been used as a plasticiser in the manufacturing of nitrocellulose propellants, in nitrocellulose and resin lacquers, to prevent foam in glue manufacturing, and in rubber cements (Annex XV Report 2012). Plasticisers that have relatively high volatility, such as DBP and DIB, are used in many PVC formulations, principally for ease of gelation. DIPP is generally used in a similar manner (Ullmann 2012).

However, due to high reproductive toxicity, DIPP has not been used widely as a general purpose plasticiser (Annex XV Report 2012). Exposure to DIPP may occur on industrial sites during the production of propellants, and ammunition including DIPP as part of the propellant may be sold to the general public. Consumer exposure to propellant powder containing DIPP is possible during the reloading of empty cartridges.

Usage

According to the Annex XV Report of DIPP (2012), a patent for an adhesion membrane (using soft PVC) identifies DIPP as a possible plasticiser. In addition, its potential use as a substitute for other phthalates is possible. Like other phthalates, DIPP can also be used as a plasticiser for PVC products and other polymers due to their similar structure and physicochemical properties. Still, no information is available on the amounts of DIPP potentially present in final articles.

Confirmed information on the presence of DIPP in WEEE plastics was not found. Because DIPP may be used as a plasticiser of PVC, it is possible that DIPP can be found in a diverse group of plastic parts of electronic products and components, especially those made of PVC.

Restrictions

DIPP is an SVHC and requires authorisation before it is used (Annex XVI of Regulation (EC) No 1907/2006 of REACH, Entry 33) as toxic for reproduction, category 1B, H360D (Article 57c).

DIPP is classified as toxic for reproduction, category 1B, in the CLP Regulation ((EC) No 1272/2008).

DIPP is listed in Annex XVII, Group 30, of the REACH Regulation. It shall not be placed on the market or used for supply to the general public as a substance or in mixtures in concentrations equal to or greater than the generic concentration limit for reproduction toxicants (≥ 0.3%).

According to the Toy Safety Directive (2009/48/EY), the concentration of substances classified as toxic for reproduction, category 1B, shall not exceed 0.3% in toys or their parts.

5.1.15 Diisodecyl phthalate (DIDP)

Description

DIDP is a complex mixture of branched C9-11 dialkyl PAEs created from a reaction of phthalic anhydride and isodecyl alcohol with an acid catalyst (NICNAS 2008d, U.S. CPSC 2010b). DIDP is an organic, viscous, oily liquid that is a plasticiser and softener used in the polymer industry and also categorised as a lubricant and additive (U.S. CPSC 2010b). As the least expensive option, DIDP is used as a direct substitute for DEHP and sometimes together with DINP (Høibye et al. 2011).

Human exposure to DIDP can occur via oral, dermal and inhalation routes (U.S. CPSC 2010b). DIDP is considered a probable toxicant in humans based on sufficient evidence of systemic, reproductive and developmental effects in animals resulting in, for example, growth retardation, skeletal and visceral variations, decrease in ovary weight and significant increases in relative testes, increased liver and kidney weight, and mortality at high doses (U.S. CPSC 2010b). Recent findings show effects in the development of the male reproductive system (Zhang et al. 2020), learning and memory disabilities in rodents at low doses (Ge et al. 2019), as well as indications of endocrine disruption potency (Lee et al. 2019).

At the EU level, DIDP does not have a harmonised classification in Annex VI of the CLP Regulation, does not fulfil the criteria for PBT/vPvB substances according to REACH, and does not show endocrine-disrupting effects (Groß et al. 2008).

Usage

DIDP is used as a plasticiser for PVC and other vinyl products (U.S. CPSC 2001, NICNAS 2008d). It is indicated that DIDP is used as a plasticiser for heat-resistant electrical cords, leather for car interiors and PVC flooring due to its properties of volatility resistance, heat stability and electric insulation (ECPI 2011). Besides its uses in cables, DIDP is preferably used in extruded and calendared articles, such as roofing sheets, profiles and pool liners, and blended into plastisols used for coating (e.g. flooring, wall covering, production of tarpaulins, and artificial leather), as well as for rotational moulding in production of certain toys and sporting articles (ECHA 2013). In addition, DIDP has been detected in a few samples of indwelling plastic medical devices (Malarvannan et al. 2019) and PVC hospital wrist-bands (Hill & Ive 1993).

Plasticised PVC is also utilised in film, car undercoating and sealants, and in the injection moulding process for hose, wire and cable, and footwear (NICNAS 2008d). The typical content of DIDP in flexible PVC products is between 25% and 50% (w/w) (ECPI 2011).

Other polymer, non-PVC uses include sensitive adhesives, printing inks, anti-corrosion and anti-fouling paints, packaging materials and food wraps (Freire et al. 2006) (NICNAS 2008d).

Because DIDP is used as a plasticiser of PVC, it is very likely that DIDP can be found in a diverse group of plastic parts of electronic products and components, especially those made of PVC. DIDP is used as an alternative plasticiser to DEHP in cable and wire insulations (Høibye et al. 2011). Høibye et al. (2011) reported that DIDP represents 80% of the phthalates used for this application area.

Restrictions

Entry 52 of Annex XVII of REACH, as amended by Commission Regulation (EC) No 552/2009, contains restrictions on the manufacture, placing on the market and use of DIDP in mixtures and articles. According to the annex,

- DIDP shall not be used as a substance or in mixtures, in concentrations greater than 0.1% by weight of the plasticised material, in toys and childcare articles[29] which can be placed in the mouth by children.
- Such toys and childcare articles containing these phthalates in a concentration greater than 0.1% by weight of the plasticised material shall not be placed on the market.

5.1.16 Diisononyl phthalate (DINP)

Description

DINP is an extremely hydrophobic liquid compound with low vapour pressure and low water solubility (Staples et al. 1997). DINP is not a single compound but a complex mixture composed of different alcohol chains depending on the production method (ECPI 2011). DINP-1 (CAS 68515-48-0) contains alcohol groups made from octene, DINP-2 (CAS 28553-12-0) contains alcohol groups made from n-butene, and DINP-3 (also CAS 28553-12-0) contains alcohol groups made from n-butene and i-butene. Despite the difference in their isomeric composition, the various types of DINP are considered commercially compatible; thus, they can be used interchangeably in products (U.S. CPSC 2010c). According to the U.S. CPSC (2010c), some manufacturers add small amounts of DIDP or bisphenol A as a stabiliser to their DINP. As the least expensive option, DINP is used as a direct substitute for DEHP, and sometimes together with DIDP and DIOP (Høibye et al. 2011).

DINP is considered a probable developmental toxicant in humans and 'possibly toxic' in humans with regard to endocrine and carcinogenic effects (U.S. CPSC 2010c, ECHA 2013). Differences in toxicity between the forms of DINP appear to be minor (U.S. CPSC 2010c). The inadequate evidence for DINP's acute toxicological effects in humans does not satisfy the regulatory definition of 'toxic'. Sufficient evidence for developmental effects of DINP in animals is based on the observation of malformations of the kidneys, male reproductive organs, skeletons in multiple studies in rats, and chronic toxicity in the liver (Lington et al. 1997, Moore 1998, Gray et al. 2000, U.S. CPSC 2010c). Research data on the toxicological effects of DINP has increased since the last evaluations (e.g. Boberg et al. 2011, Lee et al. 2019, Chiang et al. 2020, Liang & Yan 2020).

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[29] For the purpose of this entry 'childcare article' shall mean any product intended to facilitate sleep, relaxation, hygiene, the feeding of children or sucking on the part of children.

At the EU level, DINP does not have a harmonised classification in Annex VI of the CLP Regulation, does not fulfil the criteria for PBT/vPvB substances according to REACH, and does not show endocrine-disrupting effects (Groß et al. 2008). Still, companies have self-classified DINP as acutely very toxic to the aquatic environment, harmful if inhaled, and as a reproductive toxicant[30].

Usage

Approximately 95% of DINP is used in PVC applications, and the remaining 5% is used in non-PVC applications such as adhesives, sealants, rubbers, paints, printing inks, lacquers and lubricants (ECPI 2011). Other polymers to which DINP may be added are polymers such as PU or PE (Høibye et al. 2011). DINP is used as a plasticiser of PVC, which is utilised in vinyl flooring, wire and cable insulation, sheets, films, carpet backing, laminations, tubing, garden hoses, stationery, toys, coated fabrics, gloves, artificial leather, footwear, automotive products and roofing (NICNAS 2008e, ECHA 2013). Other polymers to which DINP may be added are PU and PE (Høibye et al. 2011).

Because DINP is used as a plasticiser of PVC, it is very likely that DINP can be found in a diverse group of plastic parts of electronic products and components, especially those made of PVC. DINP is also used as an alternative plasticiser to DEHP in cable and wire insulations (Høibye et al. 2011).

Restrictions

Entry 52 of Annex XVII of REACH, as amended by Commission Regulation (EC) No 552/2009, contains restrictions on the manufacture, placing on the market and use of DINP in mixtures and articles. According to the annex,

- DINP shall not be used as a substance or in mixtures, in concentrations greater than 0.1% by weight of the plasticised material, in toys and childcare articles31 which can be placed in the mouth by children.
- Such toys and childcare articles containing these phthalates in a concentration greater than 0.1% by weight of the plasticised material shall not be placed on the market.

5.1.17 Di-n-octyl phthalate (DNOP)

Description

DNOP is a colourless and odourless organic liquid (NICNAS 2008f). Its structure possesses two linear ester side chains, each with a backbone of eight carbons (C8) linked to a benzene dicarboxylic acid ring (U.S. CPSC 2010d). DNOP is the straight chain analogue to DEHP, but it is distinct from DEHP in both hazard and exposure potential.

DNOP is primarily used as a plasticiser in plastic production and found in a variety of consumer products (NICNAS 2008f, U.S. CPSC 2010d). Its use occurs in conjunction with two other PAEs, DHP (CAS 84-75-3) and di-n-decyl phthalate (DnDP, CAS 84-77-5) (U.S. CPSC 2010d).

The U.S. CPSC (2010d) concluded that DNOP can be considered 'toxic' due to its probable acute and subchronic toxicity based on the sufficient evidence in animals of DNOP-induced toxicity to the liver, kidney, thyroid and immune system. In addition, NICNAS (2008f) highlighted that the liver appears to be the primary target organ of DNOP causing dose-related statistically significant increases in relative liver weights, loss of centrilobular glycogen, and changes in fat accumulation and necrosis in the liver. In addition to effects on the liver, longer multiple dose studies show effects on the kidneys,

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[30] Summary of Classification and Labelling: https://echa.europa.eu/fi/information-on-chemicals/cl-inventory-database/-/discli/details/74139.

[31] For the purpose of this entry 'childcare article' shall mean any product intended to facilitate sleep, relaxation, hygiene, the feeding of children or sucking on the part of children.

thyroid and, possibly, immune function (NICNAS 2008f, U.S. CPSC 2010d). At the time, a full set of toxicity data was not available for all health endpoints; therefore, reproductive, developmental and carcinogenic effects have not been conclusively determined for DNOP (U.S. CPSC 2010d).

At the EU level, DNOP does not have a harmonised classification in Annex VI of the CLP Regulation, does not fulfil the criteria for PBT/vPvB substances according to REACH, and does not show endocrine-disrupting effects (Groß et al. 2008).

Usage

DNOP is primarily used as a plasticiser in plastic production to impart flexibility and other mechanical properties to various types of plastics, such as PVC, PS resins and cellulose ester resins (U.S. CSPC 2010d). PVC is utilised in the manufacturing of a variety of products including flooring and carpet tiles, pool liners, canvas tarps, traffic cones, vinyl furniture upholstery, shower curtains, gloves, garden hoses, weather stripping, notebook covers, toys, flea collars and shoes (NICNAS 2008f). DNOP-containing PVC is also used in food applications, such as bottle cap liners, seam cements and conveyor belts. Other uses as a plasticiser are, for example, automotive and industrial hoses, insulation materials and PU surface coatings.

Non-PVC uses include as a dye carrier in plastics production; as an active pesticide ingredient; in the manufacturing of adhesives, plastisols and nitrocellulose lacquer coatings; and in cosmetics and colourants (ATSDR 1997). It is also used as a fluid in electrical capacitors.

Confirmed information on the presence of DNOP in WEEE plastics was not found. Because DNOP is used as a plasticiser of PVC, it is possible that DNOP can be found in a diverse group of plastic parts of electronic products and components, especially those made of PVC.

Restrictions

Entry 52 of Annex XVII of REACH, as amended by Commission Regulation (EC) No 552/2009, contains restrictions on the manufacture, placing on the market and use of DNOP in mixtures and articles. According to the annex,

- DNOP shall not be used as a substance or in mixtures, in concentrations greater than 0.1% by weight of the plasticised material, in toys and childcare articles[32] which can be placed in the mouth by children.
- Such toys and childcare articles containing these phthalates in a concentration greater than 0.1% by weight of the plasticised material shall not be placed on the market.

5.1.18 Bis(2-methoxyethyl) phthalate (DMEP)

Description

DMEP is a practically colourless, oily liquid with a very slight odour (NICNAS 2008g, Annex XV report 2011). The general use of DMEP is as a plasticiser in polymeric materials to impart good light resistance, as well as improved durability and toughness (Annex XV report 2011).

Toxicity data for DMEP is not available for all health endpoints, but from available studies, it is assumed that DMEP may cause fertility and developmental effects (NICNAS 2008g). The metabolites of DMEP, 2-methoxyethanol (2-ME) and methoxyacetic acid (MAA), have been found to induce malformations, principally skeletal, and a decrease in testes and thymus weight in developmental studies of rodents. There is still no carcinogenicity data and insufficient data of the genotoxic potential of DMEP.

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[32] For the purpose of this entry 'childcare article' shall mean any product intended to facilitate sleep, relaxation, hygiene, the feeding of children or sucking on the part of children.

Usage

DMEP is used as a plasticiser in the production of PVC, PVA, nitrocellulose, acetyl cellulose and PVDC intended for contact with food or drink (Annex XV report 2011).

Furthermore, DMEP is used as a solvent and can be used in enamelled wire, film, high-strength varnish, adhesive, floor covers, leather care products, pesticide products, and as an additive to printer inks. NINCAS (2008) has found DMEP in balls for playing and exercise, hoppers and children's toys (NICNAS 2008g, Annex XV report 2011).

Confirmed information on the presence of DMEP in WEEE plastics was not found. Because DMEP is used as a plasticiser in polymeric materials, especially in PVC, it is possible that DMEP can be found in a diverse group of plastic parts of electronic products and components.

Restrictions

DMEP is classified as toxic for reproduction, category 1B, in the CLP Regulation ((EC) No 1272/2008).

DMEP is an SVHC and requires authorisation before it is used. Annex XIV of Regulation (EC) No 1907/2006 (Entry 37) classifies it as toxic for reproduction, category 1B, H360D (Article 57c).

DMEP is listed in Annex XVII, Group 30, of the REACH Regulation. It shall not be placed on the market or used for supply to the general public as a substance or in mixtures in concentrations equal to or greater than the generic concentration limit for reproduction toxicants (≥ 0.3%).

According to the Toy Safety Directive (2009/48/EY), the concentration of substances classified as toxic for reproduction, category 1B, shall not exceed 0.3% in toys or their parts.

5.2 **Phosphorus flame retardants (PFRs)**

5.2.1 PFRs in general

Various PFRs have been used for over 150 years. They have been considered suitable alternatives to halogenated FRs such as those containing bromine (Van Deer Veen 2012). These chemicals can be divided into three main groups: inorganic, organic and halogenated PFRs (Van Deer Veen 2012, Zhang et al. 2019).

In this report, only organic and halogenated PFRs are considered. In this group of PFRs, there are both reactive FRs, which means they are chemically bound to a polymer, and additive ones that are mixed into the polymer (Van Deer Veen 2012).

Organic PFRs can be divided into three categories based on their structure: organo-phosphate esters (OPEs), phosphonates and phosphinates (Van Deer Veen 2012). Organic non-halogenated phosphorus compounds are often used as plasticisers as well (Van Deer Veen 2012).

The group of halogenated PFRs has been widely used. In this group, the properties of both the halogen and the phosphorus components are combined. The halogen group also increases the lifetime of the FR in the end product by decreasing its mobility in the polymer (Van Deer Veen 2012). There might also be a need to substitute those halogenated PFRs because of their unwanted environmental properties (e.g. persistence, bioaccumulation potential and toxicity, Van Deer Veen 2012). According to present knowledge, only the chlorine-containing PFRs are carcinogenic (Van Deer Veen 2012). It has also been noted that non-halogen PFRs with higher molecular masses are more likely to be found in the environment than those with lower molecular masses (Van Deer Veen 2012).

In this chapter, only two PFRs are presented Table 5 because they are considered SVHCs. Other emerging PFRs are presented in Chapter 7.

Table 5. Phosphorus flame retardants reviewed in the project that are SVHC.

Name	Abbreviation	CAS
Tris (2-chloroethyl) phosphate	TCEP	115-96-8
Trixylyl phosphate	TXP	25155-23-1

5.2.2 Tris(2-chloroethyl)phosphate (TCEP)

Description

OFRs include organophosphate esters (OPEs), whose basic chemical structure contains a phosphate ester and, for some, such as TCEP, also halogen atoms. OFRs are of significant environmental concern because of their properties such as persistence, bioaccumulation and toxicity, but also because of their considerable market share. OPEs show significant reproductive, development and inhalation toxicity to the human body and are suspected to be carcinogenic and to cause birth defects, chromosomal abnormalities and other illnesses (Föllmann & Wober 2006, van der Veen & de Boer 2012). In the aquatic environment, TCEP is toxic to aquatic organisms and may cause long-term adverse effects (European Communities 2008).

TCEP is used primarily as an additive plasticiser and viscosity regulator in plastics with flame-retarding properties in applications such as coatings and adhesives (European Communities 2008, Andersson et al. 2019). As an FR plasticiser, it is used in the furniture, textile and building industries, as well as in flame-resistant paints and varnishes (European Communities 2008). Therefore, TCEP will be released from sources that have been treated with FRs, such as timber, carpet, upholstery, foam rubber, glues and plastic materials such as electronic devices, TVs and car interiors. However, TCEP is a non-volatile substance and does not appear in its gaseous form under normal conditions, which is why release might be expected during service life by abrasion, becoming part of the dust fraction, or during disposal of products containing TCEP.

Usage

TCEP is used as a plasticiser and viscosity regulator with flame-retarding properties in PU, polyester, PVC and other polymers, such as when the main use is in the production of unsaturated polyester resins. The use of TCEP in PUFs has declined and has been limited to specific products. The total concentration of TCEP in end products is assumed to be ≤ 25% (European Communities 2008).

TCEP is typically used in EEE devices as cable insulation, plastic housings, LCD panels and circuit boards (Kajiwara et al., 2011). Although TCEP usage is restricted by REACH, it is still a particular challenge that TCEP is transferred into new products by recycling of end-of-life electronic products. In addition, especially in the case of WEEE plastics, part of the plastic waste generated in Europe comes from products produced outside of Europe, where the lack of full enforcement of the applicable European regulations is possible (Hahladakis et al. 2018).

Restrictions

TCEP is regulated in Annex XIV of REACH entry no. 13 as an SVHC requiring authorisation by the European Commission before it is used.

The Toy Safety Directive (2009/48/EY) sets a limit value of 5 mg/kg (content limit) for TCEP in toys intended for use by children under 36 months or in other toys intended to be placed in the mouth. TCEP is classified as toxic for reproduction, category 1B, in the CLP Regulation. The concentration of such substances shall not exceed 0.3% in other toys or their parts.

5.2.3 Trixylyl phosphate (TXP)

Description

TXP is produced through the reaction of phosphorus oxytrochloride and xylenols. The xylenols, also called dimethyl phenols, are a distillation fraction of naturally occurring coal tar derivatives that also contain different ethyl phenols. Reaction of the different xylenols and ethyl phenols generates alkylated triphenyl phosphates as well as numerous possible isomers that cannot be easily analysed. Therefore, the composition of TXP is unknown, and it is classified as a UVCB substance containing over 50 different constituents and no additives (ECHA 2013a).

TXP in general can be used for many applications; one use of TXP is as a functional fluid, such as a fire-resistant, hydraulic or metal working fluid, and as a lubricant, lubricant additive or grease product (ECHA 2013b). It is also used as a plasticiser and fire retardant of PU, PVC and TPE, for coatings and textiles, and as a plasticiser of vinylite, cellulosic resin and rubber (Papazoglou 2004). It can be used for anti-mildew cable and as a plasticiser and fire retardant for artificial leather and flooring materials. Users involve a wide range of industrial and professional sectors.

The information gathered from companies for the REACH registration process identifies that TXP may damage fertility or the unborn child and may cause damage to organs through prolonged or repeated exposure (ECHA 2013a).

Usage

TXP is registered as an FR used during the manufacturing of plastic products, including compounding and conversion, whose use is claimed to be only industrial (ECHA 2013a). Furthermore, there are indications that TXP may be used in consumer products such as wire/cable insulation and as a fire retardant in furniture made of artificial leather (PVC or PU) available to consumers. TXP and other xylenols are used in applications where low volatility, high and long-term resistance, and high-temperature performance products are essential, such as agricultural (greenhouse) film or automobile seating (Harper 2003, Weil & Levchik 2009).

According to the substance information of TXP provided by the ECHA, TXP can be found in complex articles, with no release intended, such as vehicles, machinery and other transport equipment (lubricants and metal working fluids with TXP); mechanical appliances and electrical/electronic products (e.g. computers, cameras, lamps, refrigerators, washing machines); and cooling liquids in refrigerators and oil-based electric heaters (ECHA 2013a). Furthermore, hardcopy devices could be a source of exposure to TXP according to a survey of ultrafine particle release (Wensing 2008). Additionally, a computer store with PVC and carpet flooring, numerous computer displays, and cables and wires has been reported as a possible source of exposure (Kademoglou et al. 2017).

Restrictions

TXP is identified as a substance meeting the criteria of Article 57 (c) of Regulation (EC) 1907/2006 (REACH) owing to its classification as toxic for reproduction, category 1B, and is regulated in Annex XIV of REACH as an SVHC requiring authorisation by the European Commission before it is used.

TXP is classified as toxic for reproduction, category 1B, in the CLP Regulation. According to the Toy Safety Directive (2009/48/EY), the concentration of such substances shall not exceed 0.3% in toys or their parts.

TXP is included in the CoRAP under assessment as PBT.

5.3 Chlorinated flame retardants (CFRs)

5.3.1 CFRs in general

Chlorinated flame retardants (CFRs) are not as common as their brominated counterparts, but some products have gained commercial importance (Beard 2013). Chlorinated paraffins are the most frequently used group of CFRs and used in applications related to plastics, adhesives, coatings, rubber and textiles. Commercially, the most significant is Dechlorane Plus (DP) (CAS 13560-89-9), which has been used in various engineering plastics and thermosets, as well as polymer products such as electrical wires and cables, plastic roofing materials, and connectors in computers and televisions (Sverko et al. 2011, Beard 2013).

CFRs have been detected increasingly in biota samples worldwide (Sverko et al. 2011, Xian et al. 2011, Feo et al. 2012). DP and its breakdown products and structurally related CFRs have been reported in biota and other environmental matrices (Sverko et al. 2011, Shen et al. 2012, Suebring et al. 2013), as well as in human blood, dolphins and sediments (Sverko et al. 2008, de la Torre et al. 2012, Yan et al. 2012). Two possible reasons for the increase are an increase in both production and use (Wang et al. 2015) and CFRs' physical-chemical properties and persistence in the environment (Wu et al., 2010). Only one CFR representing SVHC substances was reviewed in the project (Table 6).

Table 6. Dechlorane Plus was the only chlorinated SVHC substance reviewed in the project.

Name	Abbreviation	CAS
Dechlorane Plus	DP	13560-89-9

5.3.2 Dechlorane plus, DP

Description

DP (Table 6) is a synthetic substance mainly used since the 1960s as a polychlorinated FR that is added to a polymer matrix during the manufacturing process (ECHA 2021a). In other applications, DP is used as an extreme pressure additive in greases for motor vehicles, aircraft, EEE including consumer electronics, and industrial gear lubricants. In addition, DP is used to a small extent in fireworks, building materials, adhesives and paints. DP can also be used in electrical batteries and accumulators, fabrics, textiles and apparels, and plastic articles (ECHA 2020a). Samples of wallpaper (non-woven, PVC, paper), latex paint, boards, glue, sealant, PVC line pipes and sound-absorbing foam and EPS panels have been detected to contain DP (Hou et al. 2018).

DP is released into the environment from human activities, and it is encountered in humans, wildlife and environmental samples worldwide, including the Arctic and Antarctic (Guo et al. 2017, Abdel Malak et al. 2018, Kurt-Karakus et al. 2019, Wang et al. 2020, ECHA 2021a). The main releases to the environment occur near production sites and urban areas via dust, sludge and wastewater through waste containing DP. Recent studies have presented e-waste recycling sites as a source of DP release into the environment (Iqbal et al. 2017, Ge et al. 2020).

Usage

DP is used as an additive FR in many polymeric systems which are typically either thermoplastics or thermosets, such as nylon, polyester, ABS, natural rubber, PBT, PP and styrene butadiene rubber (SBR) (Weil & Levchik 2009, ECHA 2021a). It can be used in thermosets such as epoxy and polyester resins, neoprene, PUF, PE or EPDM, PU and silicone rubber.

DP is used in polyolefins applied in electrical wire and cable coatings, nylon-incorporated connectors in TVs and computer monitors, printed circuit board housing, and other plastic and rubber parts

(Zhang et al. 2015, Wang et al. 2016, ECHA 2021a). Stakeholders have reported that wire coatings, housing, plastics and rubber parts contain DP in a concentration between 13% and 20% (ECHA 2021a).

Restrictions

DP is identified as an SVHC and included in the candidate list for authorisation under assessment as PBT and potentially a POP. The potential adverse effects and toxicity of DP are also currently discussed under the Stockholm Convention (POPRC 2021b).

Note that DP is still under assessment of the ECHA. Still, the ECHA proposes the following restrictions[33] to DP (covering any of its individual anti- and syn-isomers or any combination thereof):

DP shall not be manufactured or placed on the market as a substance on its own.

DP shall not be used in the production of, or placed on the market in,

- (a) another substance, as a constituent;
- (b) a mixture; or
- (c) an article in a concentration equal to or above 0.1% by weight.

[33] ECHA Proposes Restriction on the Manufacture and Placing on the Market of Dechlorane Plus, Including in Articles (e.g. Electrical and Electronic Equipment). Available: https://echa.europa.eu/documents/10162/52a2d8b3-a9da-577e-3ced-01be35554b1e.

6 Heavy metals

Metals that have high density and atomic weight and have toxic properties are defined as heavy metals. Lead (Pb), chromium (Cr) and cadmium (Cd), as well as zinc (Zn) are typical heavy metals existing in WEEE plastics. Heavy metals can be present in WEEE as components or as additives. Intentionally added metals, as well as selenium (Se), antimony (Sb) and copper (Cu), could also remain as residues or trace contaminants from the manufacturing process and have shown an environmental burden from WEEE recycling in soil and surroundings near recycling facilities.

Heavy metals can be released to the environment during the manufacturing, use or disposal of products (Wagner & Schlummer 2020). Additionally, evidence of arsenic (As), Cd, cobalt (Co), Cr, copper, mercury (Hg), manganese (Mn), nickel (Ni), lead, tin (Sn) and Zn have been detected in energy use of WEEE (Buekens &Yang 2014), and enrichment of heavy metal concentrations has been observed in both bottom and fly ashes of incineration residues of WEEE (Cesaro et al. 2017). Along with plastics, metals represent the most abundant materials WEEE components (Cesaro et al. 2017). They are also used as additives such as stabilisers, plasticisers, colourants or catalysts in plastics (Dimitrakakis et al. 2009a, Wäger et al. 2011, Buekens & Yang 2014, Stenmarck et al. 2017, Mao et al. 2020). Heavy metals are usually added to plastics for functionality reasons, such as stabilisers to protect the polymers from thermal degradation (Wagner & Schlummer 2020). High concentrations of different heavy metals have been found in small household appliances (Cd), ICT equipment (Pb) and consumer equipment (Pb) (Wäger et al. 2011). Furthermore, the actual amount of heavy metals in WEEE may reach up to 65% of total weight (Cesaro et al. 2017).

Despite subsequent restrictions, heavy metals added in plastics remain in circulation in society because of the long lifespan of many products and the more general contamination of recycled goods (Turner & Filella 2021). Migration of heavy metals from plastics has been observed in WEEE recycling, caused by aging of materials during product use. Aging can also cause leaching of Ni, Cu, Zn, Sb and Pb in WEEE (Mao et al. 2020). Concentrations of heavy metals in scientific studies were gathered in a study by Dimitrikakis et al. (2009a). The study also pointed out that there is wide variation of additives in EEE, and therefore precise deductions of hazardous substances in WEEE plastics cannot be made.

The RoHS Directive restricts the use of certain hazardous substances in EEE and applies to whole appliances, their cables and spare parts – including plastics. Restrictions concern to Cd, Pb, Hg and hexavalent chromium (Cr[VI]), which all have toxicological relevance (Dimitrakakis et al. 2009b). The maximum concentration limits – 0.01% by weight (100 mg/kg) for Cd and 0.1% by weight (1,000 mg/kg) for all other heavy metals – refer to the maximum permissible concentrations of the heavy metals in homogenous materials. These limit values had to be implemented in the Member States in 2006. Alassali et al. (2020) showed that appliances produced prior to 1990 have significantly higher heavy metal concentrations in comparison with appliances produced after 1990. It was also seen that other elements, such as halogenated compounds and bromine (Br) concentrations, drastically decreased in WEEE items produced from 2005 onwards.

Heavy metals restricted under the RoHS Directive (Cd, Pb, Hg and Cr[VI]) were viewed as relevant for review in this report (table 7). One potential substance to be included in this review would have also been Sb, which is a semi-metallic element (which oxides mainly Sb_2O_3) commonly used in plastics in combination with halogenated FRs (Alassali et al. 2020). Antimony oxides are not FRs on their own but are used as synergetic co-additives to facilitate the reduction in total FRs needed to achieve a desired level of functionality (Alassali et al. 2019). Relating to WEEE plastics, TV and PC housings have been found to contain Sb together with Br, forming specific Sb/Br ratios (Morf et al. 2005). Further information and restrictions (e.g. RoHS, REACH, Toy Safety Directive 2009/48/EY) related to the heavy metals of interest are provided under each substance below. However Sb was excluded because some selection of the substances needed to be done.

Table 7. Reviewed heavy metals in the project that are relevant for WEEE.

Name	Abbreviation	CAS
Cadmium	Cd	7440-43-9
Lead	Pb	7439-92-1
Mercury	Hg	7439-97-6
Hexavalent Chromium/ Chromium(VI)/ Chromium(VI) trioxide, Cr(VI)	Cr(VI)	18540-29-9

6.1 Cadmium (Cd)

Description

Cadmium is a silver-white blue-tinged heavy metal that is a natural element in the earth's crust (NTP 1992). As a mineral, cadmium is usually combined with other elements such as sulphur (cadmium sulphate or sulphide), oxygen (cadmium oxide) or chlorine (cadmium chloride). Compared with other heavy metals, cadmium and cadmium compounds are relatively water soluble (European Commission 2002). Solubility makes cadmium more mobile in the environment (soil, water etc.) and generally more bioavailable, and it also tends to bioaccumulate. As a cumulative toxin, cadmium accumulates in the human body, especially in the kidneys; it is proven to be carcinogenic to humans and associated with effects on the skeletal and respiratory systems (IARC 1993, Järup et al. 1998, Larsson & Wolk 2015).

Cadmium has been used in rechargeable nickel cadmium batteries, jewellery, toys and other plastic consumer products, and other uses are, for example, as coatings, pigments and stabilisers (Turner 2019, Turner & Filella 2021). In particular, cadmium pigments have several useful features, such as heat stability, tinting strength, high opacity and chemical resistance, which is why they are widely used in industry (Jansen & Letschert 2000, Faulkner & Schwartz 2009, Turner 2019). Despite the restrictions for usage of cadmium and cadmium compounds, many products containing cadmium will still be used in society due to their long service lifetime (e.g. Lego building bricks, PVC doors and windows, buttons and casings made of PA or ABS). The high concentrations of pigmented cadmium (up to 2% by weight) in old products is a matter of concern (Turner 2019). These old products that remain in circulation as trace pollutants delay the final disposal of the cadmium for several years.

Usage

Cadmium sulphide and cadmium selenide have been used in all types of plastics coloured with the primary colours yellow and red. They could be modified or mixed with other pigments to expand the colour range to greens and browns (MST 1980, Hansen et al. 2005, EU 2007). Cadmium stearate and cadmium dodecanoate have been used as heat and light stabilisers in PVC, especially in outdoor plastics such as window frames and wiring insulation (Turner 2019, Turner & Filella 2021).

Because EEE plastics contain numerous different resins, from styrenics and polyolefins to engineering plastics and thermosets, cadmium and its compounds have been used at least in pigment form in various plastic applications in electronics.

Cadmium is still encountered in plastic products due to its historical use in consumer products. The market demand for black plastic appears to be met by the recycling of black WEEE plastic into new plastic components and products (Haarman & Gasser 2016, Turner 2018). Because cadmium is found most frequently among black office and garden equipment, inefficiently sorted WEEE plastic has the potential to introduce cadmium into the recyclate and cause widespread contamination of black consumer goods (Turner 2018).

In addition, voluntary pledges have been made to phase out cadmium. The Institute of Electrical and Electronics Engineers (IEEE) Standard 1680 states that the amount of cadmium shall not exceed 50 mg/kg in homogeneous materials in personal computer products unless demonstrably present through recyclate (IEEE 2006).

Restrictions

Use of cadmium pigments and stabilisers in plastics was strongly limited by the cadmium ban in Sweden in 1982, followed by Denmark in 1983 and the EU in 1991 (OECD 1994). The EU restricted the use of cadmium further with Regulation 494/2011 by including entry 23 in Annex XVII of the REACH Regulation.

According to Regulation 494/2011, cadmium and its compounds shall not be used in mixtures and articles produced from the following synthetic organic polymers (hereafter referred to as plastic material):

- polymers or copolymers of vinyl chloride (PVC) [3904 10] [3904 21]
- polyurethane (PU) [3909 50]
- low-density polyethylene (LDPE), with the exception of LDPE used for the production of coloured masterbatch [3901 10]
- cellulose acetate (CA) [3912 11]
- cellulose acetate butyrate (CAB) [3912 11]
- epoxy resins [3907 30]
- melamine-formaldehyde (MF) resins [3909 20]
- urea-formaldehyde (UF) resins [3909 10]
- unsaturated polyester (UP) [3907 91]
- polyethylene terephthalate (PET) [3907 60]
- polybutylene terephthalate (PBT)
- transparent/general-purpose polystyrene [3903 11]
- acrylonitrile methylmethacrylate (AMMA)
- cross-linked polyethylene (VPE)
- high-impact polystyrene (HIPS)
- polypropylene (PP) [3902 10]

Mixtures and articles produced from plastic material as listed above shall not be placed on the market if the concentration of cadmium (expressed as Cd metal) is equal to or greater than 0.01% by weight of the plastic material.

Furthermore, cadmium has been characterised as an SVHC and included in the candidate list for authorisation. Cadmium and the following cadmium compounds are included in the candidate list for authorisation in Annex XIV of REACH:

- Cadmium (CAS no. 7440-43-9)
- Cadmium oxide (CAS no. 7440-43-9)
- Cadmium sulphide (CAS no. 1306-23-6)
- Cadmium chloride (CAS no. 10108-64-2)
- Cadmium fluoride (CAS no. 7790-79-6)
- Cadmium sulphate (CAS no. 10124-36-4, 31119-53-6)
- Cadmium carbonate (CAS no. 513-78-0)
- Cadmium hydroxide (CAS no. 21041-95-2)
- Cadmium nitrate (CAS no. 10325-94-7)

The RoHS Directive has limited the use of cadmium in EEE since 2006 (original RoHS Directive 2002/95/EC). Currently, the RoHS Directive (recast 2011/65/EC as latest amended by EU 2021/1980) sets a maximum concentration limit of 100 mg/kg for cadmium in homogeneous EEE materials. There are exemptions from this restriction for specific applications.

Directive 94/62/EC on packaging and packaging waste sets a maximum concentration limit for heavy metals in packaging. The sum of concentration levels of lead, cadmium, mercury and hexavalent chromium present in packaging or packaging components shall not exceed 100 ppm by weight. Plastic crates and plastic pallets are exempted from the limit provided they are used in closed and controlled product loops (Commission Decision 2009/292/EC).

The directive on ELVs (2003/53/EC) stipulates that the materials and components of vehicles put on the market after 1 July 2003 may not contain more than 0.01% by weight of cadmium in homogeneous material unless a specific exemption is granted. Additionally, spare parts used for vehicles put on the market before 1 July 2003 are exempted from the provision.

Cadmium is classified in the CLP Regulation as carcinogenic, category 1B, with no substance-specific limit value. According to the Toy Safety Directive (2009/48/EY), the concentration of such substances shall not exceed 0.1% in toys or their parts. Additionally, the Toy Safety Directive sets specific limit values for migration of cadmium from toys, depending on the type of raw material (1.3 mg/kg in dry, brittle, powder-like or pliable toy material; 0.3 mg/kg in liquid or sticky toy material; and 17 mg/kg in scraped-off toy material).

6.2 **Lead (Pb)**

Description

Lead is a bluish-grey metal found naturally in small amounts in the environment but is not essential for plant or animal life (NTP 1992, European Commission 2002). Overall, lead is found in all parts of the environment due to human activities such as burning fossil fuels, battery production and manufacturing. Lead has many excellent properties in terms of its usability in manufacturing, such as malleability, low melting point, high density, ease of fabrication and casting, and chemical stability in water, air and earth (King et al. 2014). Lead has several different applications, from metal products, ammunition and devices to shield X-rays to the most common use in lead-acid batteries. Lead is not used in its pure state in the applications but rather as an alloy. Due to health concerns, the use of lead in gasoline, paints, ceramic products, pipe solder and caulking has been reduced remarkably.

Usage

Lead was commonly used in plastics as a series of chromate pigments such as chrome yellow ($PbCrO_4$), chrome green ($PbCrO_4$) and chrome orange-red ($PbCrO_4 \cdot PbO$) and in PVC as a heat and light stabiliser, such as tetralead trioxide sulphate ($3PbO \cdot PbSO_4$), trilead bis(carbonate) dihydroxide ($Pb_3(CO_3)_2(OH)_2$) and trilead dioxide phosphonate ($PbHPO_3 \cdot 2(PbO)$) (Oldring 2001, Hansen et al. 2013). The highest concentrations of lead (Pb > 1,000 mg/kg) generally arise from older plastic products coloured with chromate pigments, plastics associated with pre-RoHS electrical and electronic items, and articles of beached plastic litter. Still, recent studies imply that these pigments are still circulating as colourants in a limited number of contemporary products through mechanical material recycling (Turner & Filella 2021).

Lead and lead compound usage in plastic is limited by the current RoHS and REACH regulations. Thus, only older consumer and electronic plastics, plasticised PVC (such as electrical insulation) and a range of brightly coloured articles can have high concentrations of lead. However, lead and lead compounds are still encountered in plastic products, presumably reflecting the use of recycled plastics from EEE. It has been suggested that lead in electronic and electrical plastic could also be contaminated by additional sources other than lead chromate pigments (e.g. PVC and soldering residues). When plastics originating from WEEE are used in a broader array of plastic products, those new plastic products could be contaminated by residues of lead chromate pigments (Turner & Filella 2021).

Restrictions

The RoHS Directive has limited the use of lead in EEE since 2006 (original RoHS Directive 2002/95/EC). Currently, the RoHS Directive (recast 2011/65/EC as latest amended by EU 2021/1980) sets a maximum concentration limit of 1,000 mg/kg for lead in in homogeneous EEE materials. There are several exemptions from this restriction for specific applications.

Some lead compounds have been included in the list of substances subject to authorisation under the EU REACH Regulation. Therefore, the substance in question can only be used if the use has been authorised by the European Commission. The following lead compounds are included in the REACH Authorisation List in Annex XIV:

- Lead chromate (CAS no. 7758-97-6)
- Lead chromate molybdate sulphate red (CAS no. 12656-85-8)
- Lead sulfochromate yellow (CAS no. 1344-37-2)

Furthermore, in 2018, metallic lead was added to REACH's candidate list of SVHCs for authorisation based on its reproductive toxicity.

Directive 94/62/EC on packaging and packaging waste sets a maximum concentration limit for heavy metals in packaging. The sum of concentration levels of lead, cadmium, mercury and hexavalent chromium present in packaging or packaging components shall not exceed 100 ppm by weight. Plastic crates and plastic pallets are exempted from the limit provided they are used in closed and controlled product loops (Commission Decision 2009/292/EC).

The directive on ELVs (2003/53/EC) stipulates that materials and components of vehicles put on the market after 1 July 2003 may not contain more than 0.1% by weight of lead in homogeneous material unless a specific exemption is granted. Additionally, spare parts used for vehicles put on the market before 1 July 2003 are exempted from the provision.

Lead is classified in the CLP Regulation as toxic for reproduction, category 1B, with a substance-specific limit value of 0.03%. According to the Toy Safety Directive (2009/48/EY), the concentration of lead shall not exceed the substance-specific limit value of 0.03% in toys or their parts. Additionally, the Toy Safety Directive sets specific limit values for migration of lead from toys, depending on the type of raw material (2.0 mg/kg in dry, brittle, powder-like or pliable toy material; 0.5 mg/kg in liquid or sticky toy material; and 23 mg/kg in scraped-off toy material).

In addition, voluntary pledges have been made to phase out the use of lead. For example, in the PVC industry, lead compounds, including stearates and basic sulphate, have been replaced by safer calcium-based alternatives (Vinyl Plus 2014), and IEEE Standard 1680 regarding personal computer products has been adopted, in addition to the criteria set in RoHS regarding an optional limit for intentionally added lead in plastic computer components (IEEE 2006).

6.3 **Mercury (Hg)**

Description

Mercury is a dense liquid, and in solid form, it is a silver-white, metalloid element that is not essential for plant or animal life (Budavari 1996). It is exceedingly mobile as a liquid and vaporises easily at room temperature. Mercury can form inorganic mercury compounds with other elements, such as sulphur, chlorine or oxygen, which are usually white powders or crystals. It can also combine with carbon and be biologically transformed to methylmercury and dimethylmercury, of which both are bioaccumulative and the latter is also volatile (European Commission 2002). Volatility makes dimethylmercury mobile in the environment, and it can be transported over long distances by air.

Usage

Mercury has been used in plastic manufacturing processes as a stabiliser in PVC-based materials, catalyst in the PU manufacturing process and dye in various pigments; for example, mercury sulphide (HgS) has been used in PE and PP as red pigment (Hansen et al. 2013, Filella & Turner 2018).

Mercury has been used in various phenylmercury compounds in the production of PU, of which phenylmercury neodecanoate appears to have had the most widespread use in the EU and The European Free Trade Association (EFTA) countries. Phenylmercury neodecanoate ($C_{16}H_{24}HgO_2$) was used as a catalyst in production of PU coatings, adhesives, sealants and elastomers. Phenylmercury acetate ($C_8H_8HgO_2$) was widely used as a biocide (e.g. in paint manufacturing), as a plant protection product, as a catalyst in the production of polymers and as a catalyst for PU elastomers. Other phenylmercury compounds used were phenylmercury propionate (as a PU catalyst), phenylmercury 2-ethylhexanoate (biocide in the production of paint) and phenylmercuric octanoate (pesticide) (ECHA 2010).

Mercury has been found in several plastic items, even in new commercial plastics made of PE, PP, PS, PU and PVC, confirming the use of phenylmercury compounds as a stabiliser, catalyst or pigment (Santos-Echeandía et al. 2020). Still, it is not considered likely that mercury pigments are widely used in plastics alone (Hansen et al. 2013) but in combination with cadmium as Hg-Cd pigments, which could explain why mercury is found in red, brown or black plastic objects (Filella & Turner 2018, Santos-Echeandía et al. 2020). In particular, black plastics tend to accumulate higher concentrations of mercury, followed by brown, reddish, grey and green-coloured plastics (Santos-Echeandía et al. 2020). It has been pointed out that black plastics are preferentially made of plastic recycled from WEEE (Haarman & Gasser, 2016), which might be one reason for the significant levels of mercury concentration (Turner 2018).

Restrictions

Use of mercury and mercury compounds has been widely restricted for example by the EU regulation (EU) 2017/852 on Mercury and REACH. Both RoHS directive and Directive on end-of-life vehicles (2000/53/EY) still allow certain exemptions for the use of mercury in specified types of lamps.

Annex II of the EU Regulation on Mercury contains a list of mercury-added products[34] whose export, import and manufacturing in the EU is prohibited. Additionally, the mercury regulation prohibits manufacturing or placing on the market new types of mercury-added products that were not being manufactured prior to 1 January 2018 unless authorised by the Commission. There are certain exceptions to this prohibition (such as products still allowed by the RoHS Directive and the directive on ELVs).

Additionally, in Annex XVII of REACH, entry 62 restricts uses of some phenylmercury.

Restrictions apply to the following:

- Phenylmercury acetate (CAS No. 62-38-4)
- Phenylmercury propionate (CAS No. 103-27-5)
- Phenylmercury 2-ethylhexanoate (CAS No. 13302-00-6)
- Phenylmercuric octanoate (CAS No. 13864-38-5)
- Phenylmercury neodecanoate (CAS No. 26545-49-3)
    - These phenylmercury compounds shall not be manufactured, placed on the market or used as substances or in mixtures after 10 October 2017 if the concentration of mercury in the mixtures is equal to or greater than 0.01% by weight.
    - Articles or any parts thereof containing one or more of these substances shall not be placed on the market after 10 October 2017 if the concentration of mercury in the articles or any part thereof is equal to or greater than 0.01% by weight.

[34] 'Mercury-added product' means a product or product component that contains mercury or a mercury compound that was intentionally added; where 'mercury' means metallic mercury (Hg, CAS 7439-97-6), and 'mercury compound' means any substance consisting of atoms of mercury and one or more atoms of other chemical elements that can be separated into different components only by chemical reactions.

The RoHS Directive has limited the use of mercury in EEE since 2006 (original RoHS Directive 2002/95/EC). Currently, the RoHS Directive (recast 2011/65/EC as latest amended by EU 2021/1980) sets a maximum concentration limit of 1,000 mg/kg for mercury in homogeneous EEE materials. There are exemptions from this restriction for specific applications.

Directive 94/62/EC on packaging and packaging waste sets a maximum concentration limit for heavy metals in packaging. The sum of concentration levels of lead, cadmium, mercury and hexavalent chromium present in packaging or packaging components shall not exceed 100 ppm by weight. Plastic crates and plastic pallets are exempted from the limit provided they are used in closed and controlled product loops (Commission Decision 2009/292/EC).

The directive on ELVs (2003/53/EC) stipulates that materials and components of vehicles put on the market after 1 July 2003 may not contain more than 0.1% by weight of mercury in homogeneous material unless a specific exemption is granted. Additionally, spare parts used for vehicles put on the market before 1 July 2003 are exempted from the provision.

Mercury is classified in CLP regulation as toxic for reproduction, category 1B, with no substance specific limit value. According to the Toy Safety Directive (2009/48/EY) the concentration of such substances shall not exceed 0,3% in toys or their parts. Additionally, the Toy Safety Directive sets specific limit values for migration of mercury from toys, depending on the type of raw material (7.5 mg/kg in dry, brittle, powder-like or pliable toy material; 1.9 mg/kg in liquid or sticky toy material; and 94 mg/kg in scraped-off toy material).

6.4 Chromium (Cr)

Description

Chromium is the seventh most abundant element on earth and occurs in several oxidation states; in ground water and soil, it normally exists as the relatively immobile chromium(III) under reducing conditions and under oxidising conditions as the highly mobile and toxic chromium(VI). Chromium(VI) can be reduced to chromium(III) by several means, but chromium(III) will not easily re-oxidise to hexavalent chromium. Chromium(VI) is known to be more toxic and mobile in ground water than the sparingly soluble chromium(III). Still, both can cause acute and chronic exposure because of their water solubility and mobility, along with the tendency of chromium(VI) towards easy reduction (Saha et al. 2011).

Chromium(VI) is used in several industrial applications including chrome plating on plastic or metal products, tanning, industrial water cooling, paper pulp production and petroleum refining. Furthermore, chromium compounds are used in paint pigments forming chromates of barium, lead and zinc to provide the pigments of chromium yellow, chromium red, chromium orange, zinc yellow and zinc green glass (Saha et al. 2011).

Chromium(VI) is a widely recognised environmental pollutant with potential for carcinogenic, neurological, teratogenic and mutagenic effects (Holmes et al. 2008, DesMarias & Costa 2019, Wise Jr. et al. 2022). In ground water, chromium(VI) has generally been assumed to be an anthropogenic contaminant because it is used widely in industrial applications (Saha et al. 2011). It enters the food chain because it is accumulated in aquatic species and plants (European commission 2002, Saha et al. 2011).

Usage

Chromium(VI), in the form of chromium(VI) trioxide(CrO_3), is used in the production of polyethylene as a catalyst; in colours and pigments based on compounds of cadmium, mercury and lead used for corrosion-resistant coatings and paints for plastics and ceramics; and in etchants in plastic metallisation processes (European commission 2002, Cusack & Perrett 2006). Commonly, chromium(VI) is associated with chrome plating (electroplating) observed on plastic or metal products such as car bumpers or shower heads and a host of consumer and industrial products. In general, chromium(VI) and chromium compounds are found in the plastics of PP, PE, PVC and ABS (Jahrman et al. 2018)

Chromium(VI) is used to apply a hard, smooth surface to machine parts, such as crankshafts and printer rollers (Saha et al. 2011). Metallisation of plastics is normally undertaken for either decorative or functional purposes, which are usually associated with metals, such as light weight, design flexibility and low cost of manufacturing. In particular, ABS is the most usually plated plastic (GE Corp. 1997).

Because chromium(VI) has had a wide variety of uses in non-plastic electronic equipment, imperfect sorting of WEEE materials could result in contamination of the plastic recyclate (Wäger et al. 2012).

Restrictions

The RoHS Directive has limited the use of chromium(VI) in EEE since 2006 (original RoHS Directive 2002/95/EC). Currently, the RoHS Directive (recast 2011/65/EC as latest amended by EU 2021/1980) sets a maximum concentration limit of 1,000 mg/kg for chromium(VI) in homogeneous EEE materials. There are exemptions from this restriction for specific applications.

According to Annex XVII of REACH, entry 28, substances classified as carcinogen category 1A or 1B in Part 3 of Annex VI of the CLP Regulation ((EC) No 1272/2008) and listed in Appendix 1 or Appendix 2 of Annex XVII of REACH shall not be placed on the market or used, as substances, as constituents of other substances, or in mixtures, for supply to the general public when the individual concentration in the substance or mixture is equal to or greater than

- the substance-specific concentration limit specified in Part 3 of Annex VI of the CLP Regulation, or
- the relevant generic concentration limit of 0.1% specified in the CLP Regulation for substances classified as carcinogen category 1A or 1B.

Chromium(VI), called here chromium trioxide, and the most relevant for plastics chromium(VI) compounds classified as carcinogen category 1A or 1B are

- Chromium trioxide (CAS No. 1333-82-0)
- Lead chromate (CAS No. 7758-97-6)
- Lead sulfochromate yellow (CAS No. 1344-37-2)
- Lead chromate molybdate sulphate red (CAS No. 12656-85-8)
- Potassium chromate (CAS No. 7789-00-6)
- Potassium dichromate (CAS No. 7778-50-9)
- Sodium chromate (CAS No. 7775-11-3)
- Sodium dichromate (CAS No. 10588-01-9, 7789-12-0)
- Zinc chromate (CAS No. 13530-65-9)

Because none of the above chromium(VI) compounds has a substance-specific limit value for carcinogenicity in Annex VI of the CLP Regulation, the generic concentration limit of 0.1% (set in Table 3.6.2 in Part 3 of Annex I of CLP) is applied to them.

With the exception of zinc chromate (CAS No. 13530-65-9), chromium(VI) and all the previous chromium(VI) compounds have been included on the list of substances subject to authorisation under Annex XIV of the REACH Regulation. Therefore, they can only be used if the use has been authorised by the European Commission.

Other chromium(VI) compounds that are potentially used in plastics but not included in Annex XIV of the REACH Authorisation List, and whose properties are likely to meet criteria for category 1A or 1B carcinogenicity, mutagenicity or reproductive toxicity and therefore should be given special attention, are

- Barium chromate (CAS No. 10294-40-3)
- Calcium chromate (CAS No. 13765-19-0)

Directive 94/62/EC on packaging and packaging waste sets a maximum concentration limit for heavy metals in packaging. The sum of concentration levels of lead, cadmium, mercury and hexavalent chromium present in packaging or packaging components shall not exceed 100 ppm by weight. Plastic crates and plastic pallets are exempted from the limit provided they are used in closed and controlled product loops (Commission Decision 2009/292/EC).

The directive on ELVs (2003/53/EC) stipulates that materials and components of vehicles put on the market after 1 July 2003 may not contain more than 0.1% by weight of hexavalent chromium in homogeneous material unless a specific exemption is granted. Additionally, spare parts used for vehicles put on the market before 1 July 2003 are exempted from the provision.

Chromium(VI) trioxide and several other cadmium compounds are classified in the CLP Regulation as carcinogenic, category 1A or 1B, with no substance-specific limit values. According to the Toy Safety Directive (2009/48/EY), the concentration of such substances shall not exceed 0.1% in toys or their parts. Additionally, the Toy Safety Directive sets specific limit values for migration of chromium(VI) from toys, depending on the type of raw material (0.02 mg/kg in dry, brittle, powder-like or pliable toy material; 0.005 mg/kg in liquid or sticky toy material; and 0.053 mg/kg in scraped-off toy material).

7 Emerging chemicals

Emerging substances represent chemicals present in WEEE plastics that are used to substitute already phased out or restricted chemicals, have not been paid that much attention concerning their possible environmental or health risks, and have no imposed restrictions to their production or use so far. The term ‘emerging’ is sometimes a little bit confusing because some of these chemicals might have already been in use for years or even decades. Some of these emerging chemicals are now being noticed and given more attention because they are detected in rather large concentrations from the environmental samples according to screening studies. Certain substances are found in various environmental compartments as well because of either their persistence or their extensive and wide use.

In this project, literature concerning emerging substances especially relevant for WEEE plastics were reviewed. Altogether, 72 emerging substances out of a total of 95 substances were identified and reviewed. Of those identified substances, 17 were chosen based on their possible future status when considering legislation. None of them has any restrictions yet, but almost all of them are now under assessment for possible risks they might cause. Community rolling action plan (CoRAP) process in EU prioritizes the evaluation of substances in the EU/EEA over a three-year period. The aim of the evaluation is to investigate the risk posed by a chemical to human health or the environment. Priority is given to substances suspected of being of highest risk. There are also a few substances that were included in the report because they were analysed from WEEE plastic samples within this project. These results are presented in Chapter 8 of this report.

7.1 Phosphorus Flame Retardants (PFRs)

7.1.1 PFRs in general

PFRs are one larger group of chemicals that include certain compounds suitable to substitute BFRs that have already been phased out or restricted. PFRs can be divided into non-halogen PFRs and halogenated PFRs. A more detailed description can be found in Section 5.2. The most relevant and emerging PFRs selected for this report are presented in Table 8.

Table 8. Selected emerging PFRs that are relevant for WEEE.

Name	Abbreviation	CAS
Triphenyl phosphate	TPP/TPhP	115-86-6
Tricresyl phosphate	TMPP	1330-78-5
Tris (1,3-dichloro-2-propyl) phosphate	TDCPP	13674-87-8
Tetrekis(2-chloroethyl)-dichloroisopentyldiphosphate	BCMP-BCEP	38051-10-4
Isopropylated triphenyl phosphate	IPTP	68937-41-7

7.2 **Non-halogen PFRs**

7.2.1 Triphenyl phosphate (TPP/TPhP)

Description

TPP is an additive FR that is only reactive in the gas phase (Van deer Veen 2012). TPhP forms phosphoric acid during the burning process, which further reacts and forms pyro phosphoric acid. This in turn acts as a heat transfer barrier in the condensed phase (Van Deer Veen 2012).

Usage

TPhP is suitable for various polymers (Van Deer Veen 2012). It has been used in PVC, cellulosic polymers, thermoplastics and synthetic rubber (Rauert et al. 2014). Several commercial uses have been identified, such as paints and coatings and plastic and rubber products. Several consumer uses have been reported, including foam seating and bedding products. There are some uses in electronic equipment as well. The existing information indicates that TPP is also used in the manufacturing and use of nail polish and in flea and tick collars.

Restrictions

TPP is under assessment as endocrine disrupting in the CoRAP, France.

7.2.2 Tricresyl phosphate (TMPP)

Description

TMPP is used as a plasticiser, and it also has good flame retardancy. TMPP also has other properties such as wear and mildew resistance and low volatility. TMPP has a good electrical property, and it is easy to process. Due to TMPP's toxicity, it cannot be used for food and medicine packaging materials.

TMPP is soluble only in organic solvents such as benzene, alcohols, ethers, vegetable oils and mineral oils.

Usage

TMPP has been used in PVC, cellulosic polymers, thermoplastics, polyester, polyolefin and synthetic rubber (Rauert et al. 2014). TMPP is used as a plasticiser for vinyl resins and nitrocellulose and as an FR for PUF. It has also been used in paints to increase the flexibility of paint films. Usage of TMPP has been common for PVC cable materials, artificial leather, moving belts, thin plates, floor materials and more. It can also be used for neoprene and as a preservative in viscose fibre. Other uses of TMPP are as an additive in gasoline, lubricant and hydraulic oil.

Restrictions

TMPP is under assessment as PBT in the CoRAP, Netherlands.

7.3 **Halogen containing PFR**

7.3.1 Tris (1,3-dichloro-2-propyl) phosphate (TDCPP)

Description

TDCPP is a halogen-containing organophosphorus chemical, which has been extensively used as a primary alternative for PBDEs (Chen et al. 2020). TDCPP and tris(chloropropyl)phosphate (TCPP) have both been used as additive FRs. TCPP is by volume the most important PFR in Europe, representing approximately 80% of all chlorinated PFRs (Van Deer Veen 2012). TCPP, however, was not included in this report because there are no restrictions or risk assessments available. TDCPP is used in similar products as TCPP. Because TDCPP is more expensive than TCPP, it is only used in applications in which more effective FRs are required (Van Deer Veen 2012). According to certain studies, TDCPP has been found frequently in measured foams with concentrations of 1–5% (w/w) (Van Deer Veen 2012).

TDCPP has two mechanisms in the case of fire. It acts in a solid phase where phosphorus is active, as well as in a gas phase where, on the other hand, chlorine is active. TDCPP appears to be a less bioaccumulative and toxic alternative to PBDEs. TDCPP is more hydrophilic, and its accumulation in the environment or organisms is probably much lower than that of PBDEs. Although TDCPP is rapidly metabolised with a short half-life and lower overall persistence in the environment compared with PBDEs, in the actual environment, TDCPP is fairly universally distributed in air, water, soil, sediment, sludge and biotic samples (Chen et al. 2020). Because TDCPP is a persistent and mobile organic chemical (PMOC), it possibly undergoes long-range transport via waterborne routes (Chen et al. 2020). With the high detection of TDCPP in various environmental media, there is concern regarding the potential human health effects from exposure to this chemical (Chen et al. 2020).

Usage

TDCPP is widely used as an FR in various consumer products with a high production volume. TDCPP is extensively utilised as an additive to PUFs, used in furniture and moulded automotive parts such as seat cushions, headrests and fabric linings. TDCPP has also been used in a variety of other sectors and applications such as construction materials, resins, latexes, varnishes/paints/coatings, mattresses/bedding products, textiles/fabrics/leather products, baby products and electronic equipment (Chen et al. 2020, Stapleton et al. 2012, Van & De 2012).

Restrictions

TDCPP is suspected to be carcinogenic in the CoRAP, Germany.

According to the EU risk assessment process under the Existing Substances Regulation (EEC 793/93), TDCPP is classified as a persistent substance in the aquatic environment (ECHA 2008, Regnery et al. 2011, Verbruggen et al. 2006). It is also classified as a category 2 carcinogen with hazard statement H351 ‘suspected of causing cancer’ under CLP Regulation EC 1272/2008.

The Toy Safety Directive (2009/48/EY) sets a limit value of 5 mg/kg (content limit) for both TDCPP and TCPP in toys intended for use by children under 36 months or in other toys intended to be placed in the mouth. TCPP is classified as toxic for reproduction, category 1B, in the CLP Regulation. The concentration of such substances shall not exceed 0.3% in other toys or their parts. TDCPP is classified as carcinogenic, category 2, and its applicable limit value in toys and their parts is 1%.

7.3.2 Tetrekis(2-chloroethyl)-dichloroisopentyldiphosphate (BCMP-BCEP)

Description

BCMP-BCEP, also known as V6, is an additive FR. It has been produced in Europe by only one producer (Van Deer Veen 2012). V6 also contained TCEP (4.5–7.5% w/w), even though its purity was < 90% (Van Deer Veen 2012). Later, V6 became available without any TCEP impurities. V6 was used only together with TCPP and TDCPP in certain applications for which more specific and effective FRs were required.

Usage

BCMP-BCEP has mainly been used in PUF in the automotive and furniture industries. Some uses could include electronic equipment as well.

Restrictions

BCMP-BCEP is included in the EC Inventory and is in the pre-registration process.

7.3.3 Isopropylated triphenyl phosphate (IPTP)

Description

IPTP is one of the chemicals used to substitute PBDEs, yet all the possible risks related to the use are not known (Wade et al. 2019). The technical IPTP is actually a mixture of aryl phosphate ester congeners with varying numbers of phenyl moieties containing the isopropyl group (Wade et al. 2019).

Usage

IPTP has been used as an additive FR, for example, in PVCs and flexible PUFs (Wade et al. 2019). IPTP has also been a major component of a product known as Firemaster 550. This product has been used as a direct replacement for pentabromodiphenyl ether mixtures, and thus, its use has increased (Wade et al. 2019). IPTP has been used in various materials and applications. One of the uses has been in electronic equipment such as computers, cameras, lamps, refrigerators and washing machines.

Restrictions

IPTP is under assessment as PBT in the CoRAP, Netherlands.

7.4 Brominated flame retardants (BFRs) and Bisphenol-A (BPA)

7.4.1 Brominated flame retardants (BFRs) and Bisphenol-A (BPA) in general

BFRs are various group of organobromine compounds that have an inhibitory effect on combustion chemistry and tend to reduce the flammability of products containing them. BFRs usually occur in mixtures of synthetic chemicals that are added to a wide variety of products, including for industrial use. They are used commonly in plastics, textiles and electrical/electronic equipment. Altogether, 11 BFRs and BPA were reviewed in the project (Table 9).

BPA is an organic compound with two aromatic rings joined together via a short carbon chain. BPA is used as a building material in PC and epoxy resins and is found in several plastic consumables. BPA is also a derivate for some FRs reviewed in this project.

Table 9. Selected emerging BFRs and BPA that are relevant for WEEE.

Name	Abbreviation	CAS
Polybrominated biphenyls	PBB	
Bisphenol-A	BPA	80-05-7
Tetrabromobisphenol-A	TBBPA	79-94-7
Tetrabromobisphenol-bis(2,3-dibromopropylether)	TBBPA-DBPE	21850-44-2
Decabromodiphenyl ethane	DBDPE	84852-53-9
1,2-bis(2,4,6-tribromophenoxyethan)	BTBPE	37853-59-1
Bis (2-ethylhexyl) tetrabromophthalate	BEH-TEBP	26040-51-7
Ethylene bis(tetrabromophthalimide)	EBTBP	1663-45-2
2-ethylhexyl-2,3,4,5-tetrabromobenzoate	EHTBB	183658-27-7
Pentabromotoluene	PBT	87-83-2
Hexabromobenzene	HxBB	87-82-1
Pentabromobenzene	PeB /PBBz	608-90-2

7.4.2 Polybrominated biphenyls (PBB)

Description

Brominated biphenyls or polybromobiphenyls are a group of chemicals that consists theoretically of 209 different congeners of PBBs (de Boer et al. 2000). Together with PBDEs, PBBs are also called brominated diphenyl oxides (de Boer et al. 2000). PBBs are synthetic chemicals with chlorine analogues to PCBs. These substances cannot actually be called emerging substances because they are, in fact, more of legacy substances. They are considered in this report because they are part of those BFRs that might still end up in the recycling processes in some cases from items with a long life cycle.

PBBs are produced by substituting hydrogen with bromine in biphenyl (Di Carlo et al. 1978). Commercial PBB products were mixtures. A product called Firemaster BP-6® contained HBB but also PBBs. It was accidentally added to cattle feed in 1973, which led to the ban of these HBB FRs in the USA in 1974 (Luross et al. 2002). HBB was listed under the Stockholm Convention in Annex A in 2009 (see Section 4.4). However, the production and use of octabromobiphenyl- and decabromobiphenyl-containing FRs continued until 1979 in the USA, whereas the production of technical grade decabromobiphenyl was phased out in Europe in 2000 (Luross et al. 2002).

Usage

Previously, PBBs were widely used in ABS. The main uses were in construct housings for business machines and in electronic products where PBBs were incorporated into thermoplastics (Di Carlo et al. 1978). To a lesser extent, PBBs were used in automotive coatings, varnishes and PUF.

Restrictions

The use of PBBs is prohibited in textile articles intended to come into contact with the skin under Annex XVII of REACH.

All uses of HBB are prohibited in Annex I of the EU POP Regulation.

7.4.3 Bisphenol-A (BPA)

Description

The main functions of BPA in plastics have been, for example, as a monomer in production of PC, epoxy resin and unsaturated polyester resin. BPA has also been used as an antioxidant and an ingredient in PVC additive packaging and as a crosslinking agent in ridged PUF (Hansen et al. 2013).

Usage

BPA has been used for various purposes in plastic. Some of the most relevant materials are PC, epoxy resins, phenoplast cast resin, PVC, rigid PUF, modified PA and unsaturated polyester resin (Hansen et al. 2013). It should be noted that use in PVC manufacturing has been phased out (Hansen et al. 2013). The main article groups in which BPA might exist are all PC plastics and many epoxy resins, some phenoplasts (e.g. phenoplast high-pressure laminate compact panels), and PVC articles (Hansen et al. 2013).

Restrictions

The use of BPA in thermal paper is restricted in REACH XVII.

BPA is classified in the CLP Regulation as toxic for reproduction, category 1B. According to the Toy Safety Directive (2009/48/EY), the concentration of such substances shall not exceed the limit value of 0.03% in toys or their parts. The Toy Safety Directive also sets a specific limit value of 0.04 mg/l for migration of BPA from toys intended for use by children under 36 months or in other toys that could be placed in the mouth.

7.4.4 Tetrabromobisphenol-A (TBBPA)

Description

TBBPA is one of the most widely used and produced FRs substituting PBDEs in electronic equipment, plastics, furniture and textiles (Groß et al. 2007, Zhou 2020). It has been produced from BPA by bromination (Covaci et al. 2019). TBBPA has been reported to have the highest production volume, covering around 60% of the total market for BFRs in 2001 (Law et al. 2006, Covaci et al 2019).

Usage

TBBPA has been used as both a reactive FR, in epoxy and PC resins for printed circuit boards and electronic equipment (58% of usage), and an additive FR (18% of usage) in HIPS or ABS resins (Rauert ym. 2014, Law et al. 2006). The rest (18%) is used to produce TBBPA derivatives and oligomers (Law et al. 2006). Commercial epoxy resins, in which TBBPA has been used as a reactive FR, are known to contain up to approximately 20% bromine (Covaci et al. 2019). Concentration of TBBPA as an additive FR is commonly between 10% and 20% (by weight), depending on the polymer (Law et al. 2006). It has also been used in furniture (Covaci et al. 2019).

ABS resins containing TBBPA are used, for example, in automotive parts, pipes, refrigerators, business machines and telephones (Law et al. 2006). HIPS resins, on the other hand, are used in packaging, consumer products and EEE such as television casings; PC monitor casings; components in printers, fax machines and photocopiers; vacuum cleaners; coffee machines; and plugs/sockets. Other uses are in furniture and building and construction materials (Law et al. 2006).

Restrictions

TBBPA is under assessment as PBT and as endocrine disrupting in the CoRAP, Denmark.

TBBPA was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

7.4.5 Tetrabromobisphenol-bis(2,3-dibromopropylether) (TBBPA-DBPE)

Description

TBBPA-DBPE, which is one of the derivates of TBBPA, is used as a substitute for the FR decabromodiphenyl oxide (DBDPO) (Masten et al. 2002).

Usage

TBBPA-DBPE is used as an additive FR in polyolefins and polymers, including PP, high-density polyethylene (HDPE), and LDPE and in PS (Masten et al. 2002, Harju et al. 2008). The substance is also used in plastic materials for parts of electrical cabinets. TBBPA-DBPE has also been an ingredient in Saytex® HP-800A FR. This product has been used in textiles, paints and hot melts. Additionally, especially its granular form HP-800AG is used in PP and HIPS applications such as pipes, water barriers, kitchen hoods and households appliances and in TVs, Hi-Fi audio equipment and electronics (Masten et al. 2002).

Restrictions

TBBPA-DBPE is under assessment as PBT and as endocrine disrupting in the CoRAP, Germany.

7.4.6 Decabromodiphenyl ethane (DBDPE)

Description

DBDPE is one of the most dominant alternatives for substituting decabrominated diphenyl ether (decaBDE). Globally DBDPE has also become one of the most widely used BFRs in recent years (Chen et al. 2019). DBDPE has a similar structure to PBDEs and is also persistent in the environment (Chen et al. 2019).

Usage

DBDPE has been used as a replacement for PBDEs in HIPS, ABS copolymers (ABS/PS) and HIPS/PPO polymers (Harju et al. 2008, Rauert et al. 2014). DBDPE has similar uses to decaBDE and has been widely used in various applications such as electronic products, furniture, and children's toys and textiles (Rauert et al. 2014).

Restrictions

DBDPE is under assessment as PBT in the CoRAP, Sweden.

DBDPE was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

7.4.7 1,2-bis(2,4,6-tribromophenoxyethan) (BTBPE)

Description

BTBPE has been used as an alternative for PBDEs because it has a similar electronic structure to PBDEs. BTBPE has been used especially in the production of plastic materials that require high manufacturing temperatures (Hakk & Letcher 2003). Because it is highly hydrophobic, BTBPE is also expected to be persistent in the environment (Hakk & Letcher 2003).

Usage

BTBPE has been used in thermoplastics, thermoset resins, PC and coatings (Rauert et al. 2014).

Restrictions

BTBPE is under assessment as PBT.

BTBPE was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

7.4.8 Bis (2-ethylhexyl) tetrabromophthalate (BEH-TEBP)

Description

BEH-TEBP is one of the brominated phthalates that are used as FRs (KEMI 2020). BEH-TEBP has been one of the components in the product Firemaster 550 (Rauert et al. 2014).

Usage

BEH-TEBP has been one of the primary replacements for pentaBDE in PUF and PUF products. BEH-TEBP has also been used as an FR and as a plasticiser for flexible polyvinylchloride and in wire and cable insulation, film and sheeting, carpet backing, coated fabrics, wall coverings and adhesives. It has also been used in neoprene (Harju et al. 2008). Some uses also cover electrical/electronic products such as computers, cameras, lamps, refrigerators and washing machines (KEMI 2020).

Restrictions

BEH-TEBP is under assessment as PBT in the CoRAP, Sweden.

7.4.9 Ethylene bis(tetrabromophthalimide) (EBTBP)

Description

EBTBP is identified as another bromine-containing FR that can replace c-decaBDE in many of its applications. According to some estimations, EBTBP seems to be rather expensive.

Usage

EBTBP has been used as an FR in plastic and rubber materials. It has also been used in textiles and in electronic applications and components (Government of Canada 2019).

Restrictions

EBTBP is under assessment as PBT.

7.4.10 2-ethylhexyl-2,3,4,5-tetrabromobenzoate (EHTBB)

Description

EHTBB has been used as one of the replacements for pentaBDEs (Niu et al. 2019).

Usage

EHTBB exists in commercial mixtures such as Firemaster 550 and BZ-54. These products are mostly used in PUF applications (Niu et al. 2019). EHTBB is suspected to be derived from indoor dust and from other sources such as household electric products and building materials (Niu et al. 2019).

Restrictions

There are no EHTBB restrictions at the moment.

EHTBB was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

7.4.11 Pentabromotoluene (PBT)

Description

PBT is one of the novel BFRs.

Usage

PBT has been used mainly in unsaturated polyesters, polyethylene, PP, PS, SBR latex, textile, rubbers and ABS (terpolymer) (Covaci et al. 2011).

Restrictions

There are no PBT restrictions at the moment.

PBT was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

7.4.12 Hexabromobenzene, HxBB

Description

Previously HBB has been used especially in Japan as an additive flame retardant. Nowadays it is usage is presumed to be much lower volumes (Covaci et al. 2011).

Usage

HxBB has been used as an FR in paper, woods, textiles, electronics and plastic goods (Covaci et al. 2011).

Restrictions

There are no HxBB restrictions at the moment.

HxBB was one of the substances that were analyzed from WEEE plastics in this project (see chapter 8).

7.4.13 Pentabromobenzene (PeBB/PBBz)

Description

PeBB is a metabolite of HxBB (Covaci et al. 2011).

Usage

No data on PeBB usage was found.

Restrictions

There are no PeBB restrictions at the moment.

PeBB was one of the substances analysed from WEEE plastics in this project (see Chapter 8).

8 Chemical analyses

In this project certain BFRs were also analysed from the WEEE plastic material. Measured concentrations were used to verify detection methods for identifying restricted BFRs from waste streams developed. There were altogether 16 substances and congeners measured.

X-ray fluorescence spectroscopy (XRF) was used to quantify the amount of elemental bromine in the individual WEEE plastic pieces. These results, as well as the XRF measurements of other elements, are shown in Appendix 1. X-ray fluorescence spectroscopy results of waste plastics. The used analyser was Thermo Fisher Scientific Niton XL3t 900S. In addition, the samples were measured with time-gated Raman spectroscopy along with pure polymers (HDPE, LDPE, PLA, PP, PET, PA, ABS, PS, PC, PVC, SAN). Thus, using the Raman spectra of the pure polymers as the reference, the samples' polymers could be identified. These measurements were compared to the results of chemical analyses and performed in the laboratory of the Finnish Institute for Health and Welfare. Chemical analyses were ordered by VTT Technical Research Centre of Finland.

8.1 Brominated flame retardants

Plastic materials were received from Kuusakoski and represented small electronic devices belonging to category 5 according to Annexes III and IV of the WEEE Directive. Several tonnes of WEEE plastics (already pre-sorted, crushed, magnetised, screened and unit processed for the removal of residual metals) were directed for identification and separation of bromine. Separation was performed on an industrial scale XRF line. When measured with XRF, the limit value for elemental bromine was 750 ppm. If the XRF detects elemental bromine, it blows a piece of material onto its own conveyor. Raw samples (from Br and non-Br streams) were collected from the moving material streams. In the lab, pieces of different colours were separated from the raw sample bags by hand. These samples represent individual plastic pieces, and their results are presented in Table 10. The crushed composite samples were taken from non-Br streams, and their results are presented in Table 11. These composite samples from crushed non-Br streams were selected for phthalate and metal analyses as well, and the results are presented in Sections 8.2 and 8.3.

The results are presented in Tables 10 and 11. TBBPA and DBDPE were the most dominant chemicals identified from various plastic materials in individual plastic pieces (Table 10). HBCDD was also found in a few samples of ABS/PS plastic, although its use in HIPS has been suggested to be marginal. HBCDD was also found in PP, which was surprising because no use of HBCDD in PP plastics has been reported (Table 10). DecaBDE was also detected in a few samples of various plastic materials (table 10). BDE-209 was found in very high concentration in one sample PK257 (Table 10). Only 0.05% of this kind of plastic would be enough to contaminate a batch of recycled plastic compared to UTC -value. Samples with high levels of DBDPE in particular and some BDE-209 often also contained some bromobenzenes, which are natural degradation products in these substances.

Concentrations of brominated compounds in the samples taken from crushed non-Br streams were all below the detection limit (Table 11).

Table 10. Analysed BFRs in WEEE plastics (mg/kg). Two samples (PK001 and PK007) were from the non-bromine and all the other from the bromine-rich fraction. Unknown polymers are marked with a white background. These samples represent individual plastic pieces. PBEB and EHTBB, as well as BDE congeners BDE-47, BDE-100 and BDE-154, were also analysed, but their results are not presented because their concentrations were below the detection limit in all samples.

Sample		PeBB	PBT	HxBB	HBCDD	TBBPA	BTBPE	DBDPE	BDE-99	BDE-153	BDE-183	BDE-209
PK064	PA	<0.5[a]	<0.5	<0.5	<15	7,371	<2.5	39	<0.5	<0.5	<0.5	<20
PK184		<0.5	<0.5	<0.5	<15	6,483	<2.5	<10	<0.5	<0.5	<0.5	<20
PK263		<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK384		<0.5	<0.5	<0.5	<15	9,063	<2.5	<10	<0.5	<0.5	<0.5	103
PK296	PET	<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK009		<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK075	PP	<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK309		<0.5	<0.5	<0.5	5,367	31	<2.5	<10	<0.5	<0.5	<0.5	<20
PK151		<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK257		0.8	<0.5	0.9	<15	<25	107	160	1	4	19	89,327
PK001	ABS/PS	<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK007		<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK012		<0.5	<0.5	<0.5	<15	9,345	<2.5	<10	<0.5	<0.5	<0.5	<20
PK013		<0.5	<0.5	<0.5	<15	32	<2.5	<10	<0.5	<0.5	<0.5	<20
PK014		<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK015		<0.5	1.1	<0.5	<15	6,775	<2.5	3,025	<0.5	<0.5	<0.5	129
PK053		0.8	3.7	8.8	<15	<25	<2.5	39,233	<0.5	<0.5	<0.5	<20
PK067		<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK071		<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK079		<0.5	<0.5	<0.5	4,671	<25	<2.5	74	<0.5	<0.5	2	<20
PK172		<0.5	0.6	7.1	<15	44	<2.5	43,269	<0.5	<0.5	<0.5	<20
PK277		0.5	1.2	4.4	<15	<25	<2.5	57,874	<0.5	<0.5	<0.5	<20
PK298		<0.5	<0.5	<0.5	4,806	51	<2.5	20	<0.5	<0.5	<0.5	<20
PK305		<0.5	<0.5	<0.5	<15	<25	<2.5	<10	<0.5	<0.5	<0.5	<20
PK371		<0.5	<0.5	<0.5	<15	38	<2.5	<10	<0.5	<0.5	<0.5	188

[a]Unit is mg/kg.

Table 11. Analysed BFRs in WEEE plastics (mg/kg). These samples represent crushed composite samples from non-Br streams. There were two parallel samples, but because all analysed concentrations were below the detection limit, results are shown only once here.

Sample	PC/ABS	PS	PP	ABS
PeBB	<0,5[a]	<0.5	<0.5	<0.5
PBT	<0.5	<0.5	<0.5	<0.5
PBEB	<0.5	<0.5	<0.5	<0.5
HxBB	<0.5	<0.5	<0.5	<0.5
EH-TBB	<0.5	<0.5	<0.5	<0.5
HBCDD	<1	<1	<1	<1
TBBPA	<25	<25	<25	<25
BTBPE	<2.5	<2.5	<2.5	<2.5
DBDPE	<10	<10	<10	<10
BDE-47	<0.5	<0.5	<0.5	<0.5
BDE-99	<0.5	<0.5	<0.5	<0.5
BDE-100	<0.5	<0.5	<0.5	<0.5
BDE-153	<0.5	<0.5	<0.5	<0.5
BDE-154	<0.5	<0.5	<0.5	<0.5
BDE-183	<0.5	<0.5	<0.5	<0.5
BDE-209	<12.5	<12.5	<12.5	<12.5

[a] Unit is mg/kg.

8.2 Phthalates

Plastic materials were received from the same sampling as for BFR analyses from Kuusakoski, and they represented small electronic devices belonging to category 5 according to Annexes III and IV of the WEEE Directive. Composite samples from crushed non-Br streams were selected for these phthalate analyses as well.

Results are shown in Table 12. Altogether seven out of fifteen studied phthalates were detected from these different composite samples. The concentrations seem to be rather low when considering the actual amounts of phthalates added to the plastics when they are used. Therefore, these concentrations detected refer to the residual concentrations in these studied materials. Phthalates are also usually added to different plastic materials than the four studied in this project.

Concentrations were also below the limit values set in the RoHS Directive. The applicable limit value is 0.1% (1,000 mg/kg) for DEHP, BBP, DBP and DIBP calculated by weight in homogeneous materials.

Table 12. Analysed (µg/kg) phthalates from crushed (2 mm) non-Br streams. Results marked with **red** mean that the concentrations of these samples were no longer in the linear measuring range, and n.d. = not detected

	PC/ABS			ABS			PS			PP		
	A	B	C	A	B	C	A	B	C	A	B	C
DEHP	1,700[a]	4,900	2,000	**8,700**	**14,000**	9,400	7,800	5,800	5,500	**12,500**	**12,500**	**19,300**
BMPP	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
BBP	3,300	300	55	7,600	3,200	5,900	830	280	340	520	580	810
DEHT	100	140	160	530	390	480	450	470	330	570	1,370	1,950
DBP	1,170	1,400	1,400	**11,400**	**12,400**	10,700	**17,800**	10,300	9,800	4,050	4,100	3,700
DEP	250	260	290	460	580	540	550	350	330	330	330	370
DHP	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
DIBP	150	210	300	10,600	**13,500**	9,100	7,890	540	540	1,150	1,200	1,300
DINP	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
DISP	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
DMP	110	140	120	120	170	150	410	145	140	100	125	150
DNOP	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
DPP	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
DCHP	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
HEHP	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

[a] Unit is mg/kg.

8.3 Heavy Metals

Plastic materials were received from the same sampling as for BFR analyses from Kuusakoski, and they represented small electronic devices belonging to category 5 according to Annexes III and IV of the WEEE Directive. Composite samples from crushed non-Br streams were selected for these metal analyses as well.

Results are shown in Table 13. Concentrations were all rather low for chromium, mercury and lead, and they were well below the limit value of 0.1% (1,000 mg/kg, calculated by weight in homogeneous materials) set in the RoHS Directive for these substances. However, the concentrations of cadmium (82–309 mg/kg) in most ABS samples were above the applicable limit value of 0.01% (100 mg/kg) in the RoHS Directive. The concentrations of cadmium were also high in all PP samples (69–87 mg/kg).

Table 13. Heavy metal concentrations (mg/kg) measured from crushed (2 mm) non-Br plastic streams

	PC/ABS				ABS				PS				PP			
Cr	6,9[a]	6.5	4.5	5.8	2.7	2.2	2.4	1.9	8.0	9.4	17	16	3.7	3.6	3.5	3.2
Cd	0.21	0.28	0.21	0.20	309	189	182	82	6.4	4.8	4.9	4.4	87	69	77	74
Hg	0.09	0.09	0.09	0.09	0.08	0.08	0.07	0.08	0.05	0.05	0.06	0.06	0.13	0.11	0.11	0.10
Pb	14	14	13	24	17	17	14	16	12	13	13	16	24	25	21	19

[a] Unit is mg/kg.

9. Summary and conclusions

The existing waste legislation and WEEE Directive put pressure on increasing the recycling of both WEEE and WEEE plastics. Plastics from this waste stream have great recycling potential when considering material volumes entering the waste handling phase at the end of their life cycle. In particular, small electronic devices belonging to category 5 according to Annex III of the WEEE Directive seem to have a rather short life cycle. This also means large amounts of plastic waste are generated. According to circular economy targets, it would be necessary to keep different materials and substances in economically valuable circulation as much as possible. This would reduce the use of raw materials and energy, harmful emissions to the environment and, overall, the amount of waste generated.

Properties of plastic materials in specific applications such as electrical and electronic devices need to be improved using several chemical additives. In addition, safety issues often necessitate setting certain requirements for the materials. For these reasons, plastic parts of electrical and electronic devices contain various chemical additives such as FRs, plasticisers and stabilisers. The possible presence of certain chemical substances can restrict recycling or the use of the recycled material.

The WEEE Directive sets rules on selective treatment for WEEE materials and components. It sets out a list of the substances, mixtures and components (e.g. plastic-containing BFRs) that must be removed from any separately collected WEEE. However, these rules do not effectively account for the wide variety of possible harmful additives in WEEE plastics.

In general, the regulatory framework of harmful chemicals in the interface of wastes and products is complex. Consideration of this interface is particularly relevant when waste materials are turned into products in recycling processes. According to the chemicals legislation, most importantly the REACH and POP regulations and RoHS Directive, recycled materials must fulfill the same requirements on the content of harmful substances as virgin raw materials. It has to be noted, that all the time new harmful substances fall under the restrictions. Thus, already banned or restricted legacy chemicals could cause problems in recycled materials because these substances can still be found in waste streams destined for recycling.

Tracking the chemical content of waste-based materials is often difficult and expensive in practice. To reduce the costs and effort needed, it is of utmost importance to define those chemicals that are necessary to identify from WEEE plastics to ensure that the material fulfils the legal requirements set in legislation on chemicals and other products.

Among the most important chemicals that should be identified from WEEE plastics are POP substances because the EU POP Regulation prohibits the recycling of POP waste. Recycled waste-based materials may only contain POP substances as UTCs below the limit values set in Annex I of the regulation. POP substances that are relevant for WEEE plastics are PBDEs, HBCDD, HBB, SCCP and PFOA, as well as PFHxS, which will most likely be named a POP substance under the Stockholm Convention in 2022.

Besides POP substances, identification of chemicals listed under the RoHS Directive and chemicals identified as SVHCs under REACH is necessary. Of these substances, phthalates in particular are relevant for recycling due to their high content in materials when used as additives (range 40–70% of total weight). Some phthalates are already subject to authorisation. If recycled material contains them, its use in any manufacturing process requires authorisation from the Commission. In addition, restrictions have been set for the use of several other phthalates that are classified as SVHCs. Some of these phthalates will be included in Annex XIV of REACH and subject to authorisation in the future. Phthalates were also detected from the analysed samples. Samples were taken from crushed and separated non-Br streams (XRF limit value for Br 750 ppm) that represented small electronic devices belonging to category 5 according to Annexes III and IV of the WEEE Directive. The concentrations seemed to be rather low when considering the actual amounts of phthalates added to the plastics. Therefore, these concentrations detected refer to the residual concentrations or impurities of phthalates in these studied materials.

According to this project, heavy metals such as cadmium should be given more attention in these WEEE plastics. In this project, heavy metals were analysed from crushed and separated (XRF limit value for Br 750 ppm) non-Br streams that represented small electronic devices belonging to category 5 according to Annexes III and IV of the WEEE Directive. The results revealed that the concentrations of cadmium in most ABS samples were above the applicable limit value of 0.01% (100 mg/kg) in the RoHS Directive.

Other additives might be seen as less important when considering recycling because their concentrations in materials when used as additives are much lower. The amount of stabilisers, antioxidants, UV stabilisers (0.05–3% in wet weight), heat stabilisers (0.05–3% in wet weight), slip agents (0.1–3% in wet weight), lubricants (0.1–3% in wet weight), antistatics (0.1–1% in wet weight), biocides (0.001–1% in wet weight), and colourants added to the material depends on the chemical structure of the additive and of the plastic polymer (Hansen et al. 2013).

However, the existing detection methods suitable for industrial scales are only available for halogenated compounds and more specifically for brominated compounds. Hence, these methods are only suitable for identifying BFRs. Besides restricted POP substances, these methods also capture other brominated substances that have been identified as SVHCs under REACH or other emerging BFRs. The major shortcoming in these existing detection methods is that they are designed to measure total bromine only and not the specific individual substances. As seen in this study, the concentrations of selected brominated compounds detected from these waste plastic streams mainly represented substances substituting these already restricted chemicals. This means that when using these identification methods based on detection of total bromine, some potentially recyclable materials might also be lost. Regarding other compounds (even other halogenated compounds), identification still needs to be done through traditional chemical analyses. These are rather expensive, the representativeness of the samples might cause some difficulties, and they are usually too time-consuming for recycling on an industrial scale. On top of this, development of reliable standardised analytical methods is needed for the substances mentioned above in different matrices.

There are various chemical additives that have been considered as suitable alternatives for already restricted or phased out harmful chemicals in WEEE plastics. These are called emerging chemicals, even though some of them have already been used for years or even decades. In this report, special attention has been paid to FRs and certain plasticisers. These selected and identified suitable alternatives for already phased out or restricted substances belong to larger groups of chemicals such as BFRs and chlorine- or phosphorus-containing FRs. The latter group is further divided into non-halogenated PFRs and halogenated PFRs. The most relevant emerging chemicals to keep in mind according to this study are TBBPA, DBDPE, BTBPE, BEH-TEBP and PBT. They are widely used to substitute the already restricted or phased out FRs, and their concentrations in plastic materials when used as additives are rather high (12–18% as total weight) (Hansen et al. 2013). In addition to halogenated FRs, all the selected emerging PFRs (TPP/TPhP, TMPP, TDCPP, BCMP-BCEP, IPTP) are also relevant to keep in mind, even though they are considered less persistent and less toxic in the environment than halogenated FRs. They are all currently under EU risk assessments, which means that they are identified to be potentially harmful to either the environment or human health. However, this does not automatically mean that they would be restricted in the future.

As a key part of the Commission's 2022 Sustainable Product Policy Initiative,[35] the Commission published its proposal for a new Ecodesign Regulation,[36] repealing the existing Ecodesign Directive (2009/125/EC)[37]. The proposed regulation aims to reduce the overall environmental and climate impacts of products. The current ecodesign framework mostly regulates energy-related products. The proposed regulation would apply to a broader range of products and set product-level requirements that promote, for example, product durability, reusability, resource use, minimum recycled content, easy disassembly, and carbon and environmental footprints. The proposal recognises chemical safety as an element of product sustainability and aims to address the chemical management of products. The proposal would allow, under certain conditions, for the restriction, primarily for reasons other than chemical or food safety, of substances present in products or used in their manufacturing processes that negatively affect products' sustainability.[38] The proposal also includes measures for the creation of a digital passport for products that would enable products to be tagged, identified and connected with relevant data on their sustainability. This could include data on substances of concern and, in this way, help track chemicals throughout the product life cycle[39].

However, it should be highlighted that the possible regulation is a proposal at this point, and the final regulation might differ from the proposed one.

More cost-efficient measures are needed to ensure that the recycled material fulfils the requirements set in the legislation on chemicals and other products. Both direct methods for identifying chemicals on site at an industrial scale and the development of laboratory analytics are needed. These measures are also needed to achieve a safe and sustainable circular economy (Kauppi et al. 2019). In the future, other solutions, such as the ECHA's SCIP database, might help track SVHCs within the WEEE streams. The SCIP database contains information on articles that contain SVHCs and are placed on the EU market. One possible option could also be the Safe and Sustainable-by-Design (SSbD) concept, which is part of the EU's chemical strategy. The SSbD concept includes the integration of risk assessment and safety-based considerations, along with life cycle (and circular economy) based considerations (Caldeira et al. 2022). Finally, the OECD report 'A Chemicals Perspective on Designing with Sustainable Plastics' (2021) contributes the industry perspective on chemicals in the design phase, such as plastic material selection processes.

[35] COM (2022) 140 final. Communication from the Commission to the European Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: On making sustainable products the norm.
[36] COM (2022) 142 final. Proposal for a Regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC.
[37] Directive 2009/125/EC of the European Parliament and of the Council establishing a framework for the setting of ecodesign requirements for energy-related products (OJ L 285, 31.10.2009, p. 10–35).
[38] Recital 22 of the Proposed Regulation.
[39] A problem that was identified the Commission's interface communication. COM (2018) 32 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions on the implementation of the circular economy package: options to address the interface between chemicals, product and waste legislation.

Lexicon

ABS	Acrylonitrile butadiene styrene is a common thermoplastic polymer
ABS/PS	Acrylonitrile butadiene styrene/polystyrene
AMMA	Acrylonitrile methyl methacrylate
As	Arsenic
BBP	Benzyl butyl phthalate
BCMP-BCEP	2,2-Bis(chloromethyl)-1,3-propandiol bis[bis(2-chloroethyl) phosphate]
BDE	Brominated diphenyl ether
BEH-TEBP	Bis(2-ethylhexyl) tetrabromophthalate
BFRs	Brominated flame retardants
BPA	Bisphenol-A
Br	Bromine
BTBPE	1,2-Bis(2,4,6-tribromophenoxy)ethane
c-pentaBDE	Commercial mixture of tetrabromodiphenyl ether and pentabromodiphenyl ether
c-octaBDE	Commercial mixture of hexabromodiphenyl ether and heptabromodiphenyl ether
c-decaBDE	Commercial mixture decabromodiphenyl ether
CA	Cellulose acetate
CAB	Cellulose acetate butyrate
Cd	Cadmium
CFRs	Chlorinated flame retardants
CLP	Classification, labelling and packaging (of substances and mixtures; Regulation [EC] 1272/2008)
CMR	Carcinogenic, mutagenic and reprotoxic
Co	Cobalt
CoRAP	Community rolling action plan (prioritises the evaluation of substances in the EU/EEA over a three-year period; the aim is to investigate the risk posed by a chemical to human health or the environment)
Cr	Chromium
Cr(VI)	Hexavalent chromium
Cu	Copper
DBDPE	Decabromodiphenyl ethane
DBDPO	Decabromodiphenyl oxide
DBP	Dibutyl phthalate
DCHP	Dicyclohexyl phthalate
decaBDE	Decabromodiphenyl ether

DEHP	Di(2-ethylhexyl) phthalate
DEHT	Dioctyl terephthalate
DEP	Diethyl phthalate
DHP	Dihexyl phthalate
DIB	Diisobutene
DIBP	Diisobutyl phthalate
DIDP	Diisodecyl phthalate
DIHP	Diisohexyl phthalate
DINP	Diisononyl phthalate
DIOP	Diisooctyl phthalate
DIPP	Diisopentyl phthalate
DMEP	Bis(2-methoxyethyl) phthalate
DMP	Dimethyl phthalate
DNA	Deoxyribonucleic acid (the molecule that carries genetic information for the development and functioning of an organism)
DNOP	Di-n-octyl phthalate
DP	Dechlorane plus
DBDPE	Decabromodiphenyl ethane
DPIPP	n-Pentyl-isopentylphthalate
DPP	Dipentyl phthalate
EBTBP	Ethylene bis(tetrabromophthalimide)
ECHA	European Chemicals Agency
EDCs	Endocrine disrupting chemicals
EEE	Electrical and electronic equipment
EH-TBB	2-Ethylhexyl-2,3,4,5-tetrabromobenzoate
EP resin	Epoxy resins
ELV	End-of-life vehicle
EPDM	Ethylene propylene diene monomer
EPS	Expanded polystyrene
EVA	Ethylene-vinyl acetate
FRs	Flame retardants
GF-EVA	Copolymer made of greenhouse polyethylene crystal film and ethylene-vinyl acetate
HBB	Hexabromobiphenyl
HBCDD	Hexabromocyclododecane
hexaBDE	Hexabromodiphenyl ether

heptaBDE	Heptabromodiphenyl ether
Hg	Mercury
HIPS	High impact polystyrene
HIPS/PPO	High impact polystyrene and polyphenylene oxide
HxBB	Hexabromobenzene
IPTP	Isopropylated triphenyl phosphate
LCD	Liquid-crystal display
LDPE	Low-density polyethylene
MF	Melamine-formaldehyde
MIBP	Monoisobutyl phthalate
Mn	Manganese
Ni	Nickel
nonaBDE	Nonabromodiphenyl ether
nPIPP	n-Pentyl-isopentylphthalate
octaBDE	Octabromodiphenyl ether
OFRs	Organic flame retardants
OPEs	Organo-phosphate esters
PA	Polyamide
PAEs	Phthalate esters
Pb	Lead
PBBs	Polybrominated biphenyls
PBDEs	Polybrominated diphenylethers
PBEB	Pentabromoethylbenzene
PBT	Persistent bioaccumulative and toxic (note: same abbreviation for pentabromotoluene and polybuhtylene terephthalate)
PBT	Pentabromotoluene (note: same abbreviation for persistent bioaccumulative and toxic and polybuhtylene terephthalate)
PBT	Polybutylene terephthalate (note: same abbreviation for pentabromotoluene and persistent bioaccumulative and toxic)
PC	Polycarbonate
PCBs	Polychlorinated biphenyls
PCDDs	Polychlorinated dibenzodioxins
PCDFs	Polychlorinated dibenzofurans
PE	Polyethylene or polythene
PeBB / PBBz	Pentabromobenzene

PET	Polyethylene terephthalate
pentaBDE	Pentabromodiphenyl ether
PFAS	Perfluoroalkyl substance
PFHxS	Perfluorohexane sulfonate
PFOA	Perfluorooctanoic acid
PFRs	Phosphorus flame retardants
POM	Polyoxymethylene
POPs	Persistent organic pollutants
POP-BDEs	Brominated diphenyl ethers that are classified as persistent organic pollutants
PP	Polypropylene
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PU	Polyurethane
PU resins	Polyurethane resins
PUF	Polyurethane foam
PVA	Polyvinyl acetate
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
PVC/PVA	Polyvinyl chloride/polyvinyl acetate
PVDC	Polyvinylidene dichloride
REACH	Registration, evaluation, authorisation and restriction of chemicals
RoHS	Restriction of hazardous substances
Sb	Antimony
SBR	Styrene butadiene rubber
SCCPs	Short-chain chlorinated paraffins
SCIP	Substances of concern in articles as such or in complex objects (products)
Se	Selenium
Sn	Tin
SVHC	Substances of very high concern
TBBPA	Tetrabromobisphenol-A
TBBPA-DBPE	Tetrabromobisphenol-bis(2,3-dibromopropylether)
TCEP	Tris(2-chloroethyl)phosphate
TCPP	Tris(chloropropyl)phosphate
TDCPP	Tris (1,3-dichloro-2-propyl) phosphate
tetraBDE	Tetrabromodiphenyl ether

TMPP	Tricresyl phosphate
TPE	Thermoplastic elastomers
TPhP (TPP)	Triphenyl phosphate
TXP	Trixylyl phosphate
UF	Urea-formaldehyde
UP resin	Unsaturated polyester resin
UTC	Unintentional trace contaminants
UVCB	Unknown or variable composition, complex reaction product or biological material
V6	Tetrekis(2-chlorethyl)dichloroisopentyldiphosphate
VPE	Cross-linked polyethylene
vPvB	Very Persistent and very Bio-accumulative
WEEE	Waste electrical and electronic equipment
WFD	Waste Framework Directive
XPS	Extruded polystyrene foam
XRF	X-ray fluorescence spectroscopy
Zn	Zinc

References

Abdel Malak, A. I., Cariou, R., Vénisseau, A., Dervilly-Pinel, G., Jaber, F., Babut, M. & Le Bizec, B. 2018. Occurrence of Dechlorane Plus and related compounds in catfish (Silurus spp.) from rivers in France. Chemosphere 207: 413–420.

Alaranta, J., Turunen, T. 2021. How to Reach a Safe Circular Economy? – Perspectives on Reconciling the Waste, Product and Chemicals Regulation. Journal of Environmental Law 33: 113–136.

Alassali, A., Picuno, C., Samara, H., Diedler, S., Fiore, S. & Kuchta, K. 2019. Antimony mining from PET bottles and E-Waste plastic fractions. Sustainability 11: 4021.

Alassali, A., Barouta, D., Tirion, H., Moldt, Y. & Kuchta, K. 2020. Towards a high quality recycling of plastics from waste electrical and electronic equipment through separation of contaminated fractions. Journal of Hazardous Materials 387: 121741.

Andersson, M., Oxfall, H. & Nilsson, C. 2019. Mapping and evaluation of some restricted chemical substances in recycled plastics originating from ELV and WEEE collected in Europe. Swedish Environmental Protection Agency.

Annex XV report 2011. Proposal for identification of a substance as a CMR Cat 1A or 1B, PBT, vPvB or a substance of an equivalent level of concern. Bis(2-methoxy) phthalate, Submitted by Germany, September 2011. Available: http://echa.europa.eu/documents/10162/38458518-7e1d-49ff-b53d-d07963c1bceb.

Annex XV report 2012. Proposal for identification of a substance as a CMR Cat 1A or 1B, PBT, vPvB or a substance of an equivalent level of concern. N-Pentyl-isopentyl phthalate, Submitted by Federal Office for Chemicals, Germany, August 2012. Available: https://echa.europa.eu/documents/10162/48f63323-2ed7-453b-b1ca-c42987d0453f

Annex XV report 2013a. Proposal for identification of a substance as a CMR Cat 1A or 1B, PBT, vPvB or a substance of an equivalent level of concern. Dihexyl phthalate. Submitted by the German Competent Authorities, November 2013. Available: https://echa.europa.eu/documents/10162/9a8b4fa6-c852-48bd-b561-c727b8d197ff

Annex XV report 2013b. Proposal for identification of a substance as a CMR Cat 1A or 1B, PBT, vPvB or a substance of an equivalent level of concern. Dipentyl phthalate, Submitted by Bureau for Chemical Substances, Poland, February 2013. Available: http://echa.europa.eu/documents/10162/d55c182b-f063-4955-969d-5684584d17b2

Api, A. M. 2001. Toxicological profile of diethyl phthalate: a vehicle for fragrance and cosmetic ingredients. Food and Chemical Toxicology 39(2): 97–108.

ATSDR 1997. Toxicological profile for di-n-octylphthalate. U.S. Department of Health and Human Services. Agency for Toxic Substances and Disease Registry. 117pp.

ATSDR 2001. Toxicological profile for di-n-butyl phthalate. Agency for Toxic Substances and Disease Registry. Available: http://www.atsdr.cdc.gov/toxprofiles/tp135.pdf [accessed 03/2022]

ATSDR 2022. Agency for Toxic Substances and Disease Registry: Toxicological profile for di(2-ethylhexyl)phthalate (DEHP). U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA. Available: http://www.atsdr.cdc.gov/toxprofiles/tp9.pdf [accessed 03/2022]

Beard, A. 2013. European initiatives for selecting sustainable flame retardants. Chemical Alternatives Assessments. The Royal Society of Chemistry, London, UK, 44–66.

Berenstein, G., Hughes, E. A., Zalts, A., Basack, S., Bonesi, S. M., & Montserrat, J. M. 2022. Environmental fate of dibutylphthalate in agricultural plastics: Photodegradation, migration and ecotoxicological impact on soil. Chemosphere 290: 133-221.

Birnbaum, L. And Staskal, D.F. 2004. Brominated flame retardants: cause for concern? Environ. Health Perspectives. 112: 9-17.

Boberg, J., Christiansen, S., Axelstad, M., Kledal, T. S., Vinggaard, A. M., Dalgaard, M., Nellemann, C. & Hass, U. 2011. Reproductive and behavioral effects of diisononyl phthalate (DINP) in perinatally exposed rats. Reproductive Toxicology 31(2): 200–209.

de Boer, J., de Boer, K., Boon, J.P. (2000). Polybrominated Biphenyls and Diphenylethers. In: Hutzinger, O., Paasivirta, J. (eds) Volume 3 Anthropogenic Compounds Part K. The Handbook of Environmental Chemistry, vol 3K. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-48915-0_4

Braekevelt E., Tittlemier S.A., Tomy G.T. 2003. Direct measure of octanol-water partition coefficients of some environmentally relevant brominated diphenyl ether congeners. Chemosphere, 51(7): 563-567

Budavari, S. (Ed.) 1996. The Merck Index: An Encyclopedia of Chemicals, Drugs, and Biologicals (12th ed.). Merck & Co Inc., New Jersey. p. 308

Buekens, A., & Yang, J. 2014. Recycling of WEEE plastics: a review. Journal of Material Cycles and Waste Management 16(3): 415–434.

BSEF (Bromine Science and Environmental Forum). About Hexabromocyclododecane (HBCD). 2006. http://www.bsef.com/our-substances/hbcd/about-hbcd/ (accessed January 2008).

BSEF (Bromine Science and Environmental Forum). About Hexabromocyclododecane (HBCD). 2010. http://www.bsef.com/our-substances/hbcd/about-hbcd/ (accessed June 2010)

Cadogan D. F., Howick C. J. 2012. Plasticizers. Ullman's Encyclopedia Of Industrial Chemistry.

Patinha Caldeira, C., Farcal, R., Moretti, C., Mancini, L., Rauscher, H., Rasmussen, K., Riego Sintes, J. and Sala, S., Safe and Sustainable by Design chemicals and materials Review of safety and sustainability dimensions, aspects, methods, indicators, and tools, EUR 30991 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47609-2, doi:10.2760/68587, JRC127109.

CalEPA, 2015. TSCA Work Plan Chemical Problem Formulation and Initial Assessment Chlorinated Phosphate Ester Cluster Flame Retardants.

Cartwright, C. D., Thompson, I. P., & Burns, R. G. 2000. Degradation and impact of phthalate plasticizers on soil microbial communities. Environmental Toxicology and Chemistry: An International Journal 19(5): 1253–1261.

Cesaro A., Marra A., Belgiorno V., Guid M., 2017. Effectiveness of WEEE mechanical treatment: Separation yields and recovered material toxicity. Journal of cleaner production 142: 2656-2662

Chaine C., Hursthouse A., McLellan B., McLellan I., McMahon B., McNulty J., Millerr J., Viza E. 2021. Recycling Plastics from WEEE: A Review of the Environmental and Human Health Challenges Associated with Brominated Flame Retardants. International Journal of Environmental Research and Public Health.

Chen W., Haibo C., Hui L., Jun Y., Xiaoli W., Yongdi L. 2020.. Environment International Vol 143.

Chiang, C., Lewis, L. R., Borkowski, G., & Flaws, J. A. 2020. Exposure to di (2-ethylhexyl) phthalate and diisononyl phthalate during adulthood disrupts hormones and ovarian folliculogenesis throughout the prime reproductive life of the mouse. Toxicology and Applied Pharmacology 393: 114952.

Clark, K. E., David, R. M., Guinn, R., Kramarz, K. W., Lampi, M. A. & Staples, C. A. 2011. Modeling human exposure to phthalate esters: A comparison of indirect and biomonitoring estimation methods. Human and Ecological Risk Assessment 17: 923–965.

COM (2018) 32 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions on the implementation of the circular economy package: options to address the interface between chemicals, product and waste legislation.

COM (2022) 140 final. Communication from the Commission to the European Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: On making sustainable products the norm.

COM (2022) 142 final. Proposal for a Regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC.

Covaci A., Voorspoels S., Abou-Elwafa Abdallah M., Geens T., Harrad S., Law R. J. 2019. Analytical and environmental aspects of the flame retardant tetrabromobisphenol-A and its derivatives. Journal of Chromatography A, 1216 (2009): 346–363.

COWI 2009. Data on manufacture, import, export, uses and releases of benzyl butyl phthalate (BBP) as well as information on potential alternatives to its use. COWI in cooperation with Entec and IOM for European Chemicals Agency (ECHA), Helsinki.

Cusack, P. and Perrett, T. 2006. The EU RoHS Directive and its implications for the plastics industry. Plastics Additives & Compounding May/June 2006.

Danish EPA (1999). Brominated flame retardants. Substance flow analysis and assessment of alternatives. www2.mst.dk/udgiv/Publications/1999/87-7909-416-3/html/kap04_eng.htm

Delgado C, Barruetabeña L, authors Salas O, Wolf O, editors. 2007 Assessment of the Environmental Advantages and Drawbacks of Existing and Emerging Polymers Recovery Processes. EUR 22939 EN. Luxembourg (Luxembourg): OPOCE; 2007. JRC37456

DesMarias, T. L. & Costa, M. 2019. Mechanisms of chromium-induced toxicity. Current Opinion in Toxicology 14: 1–7.

Deyo, J. A. 2008. Carcinogenicity and chronic toxicity of di-2-ethylhexyl terephthalate (DEHT) following a 2-year dietary exposure in Fischer 344 rats. Food and Chemical Toxicology 46(3): 990–1005.

Di Carlo F. J., Seifter J., DeCarlo V. J. 1978. Assessment of the Hazards of Polybrominated Biphenyls. Environmental Health Perspectives. Vol. 23: 351–365.

DIGITALEUROPE 2015. Comments on REACH PFOA Restriction Proposal. (https://www.digitaleurope.org/resources/digitaleurope-comments-on-reach-pfoa-restriction-proposal/) viitattu 07.04.2022

Dimitrakakis, E., Janz, A., Bilitewski, B., & Gidarakos, E. 2009a. Determination of heavy metals and halogens in plastics from electric and electronic waste. Waste Management 29(10): 2700–2706.

Dimitrakakis, E., Janz, A., Bilitewski, B., & Gidarakos, E. 2009b. Small WEEE: determining recyclables and hazardous substances in plastics. Journal of hazardous materials 161(2–3): 913–919.

ECHA 2009. Member state committee support document for identification of diisobutyl phthalate as a substance of very high concern because of its CMR properties. European Chemicals Agency – November 2009.

ECHA 2010. Annex XV Restriction Report Proposal for a Restriction (Phenylmercury Compounds). European Chemicals Agency, Helsinki.

ECHA 2013a. Annex XV report (2013): Proposal for identification of a substance as a CMR Cat 1A or 1B, PBT, vPvB or a substance of an equivalent level of concern. Trixylyl phosphate. Submitted by Environment Agency Austria, August 2013. Available: http://echa.europa.eu/documents/10162/e887aa86-ff8a-44be-9a31-ade0c8856a92 [accessed 02/2022]

ECHA 2013b. Annex XV — Identification of trixylylphosphate (TXP) CAS 25155-23-1 AS SVHC [WWW document]. URL. https://echa.europa.eu/documents/10162/953524f2- 7965-430c-be61-0bb02f08f83c [accessed 02/2022]

ECHA 2013c. Evaluation of the New Scientific Evidence Concerning DINP and DIDP in Relation to Entry 52 of Annex XVII to Regulation (EC) No 1907/2006 (REACH) - Final Review Report. European Chemicals Agency, Helsinki, Finland (2013). Available: https://echa.europa.eu/documents/10162/31b4067e-de40-4044-93e8-9c9ff1960715.

ECHA 2015. Substance evaluation report – DEP. Available: https://echa.europa.eu/fi/information-on-chemicals/evaluation/community-rolling-action-plan/corap-table/-/dislist/details/0b0236e18071b6bc [accessed 03/2022]

ECHA 2020a. Registration dossier/Disseminated website for 1,6,7,8,9,14,15,16,17,17,18,18 dodecachloropentacyclo[12.2.1.16,9.02,13.05,10]octadeca-7,15-diene. CAS number:13560-89-9. [Online]. Available: https://echa.europa.eu/da/registrationdossier/-/registered-dossier/11906/3/1/4 [accessed 03/2022]

ECHA 2021a. ANNEX XV Restriction Report; Proposal for a restriction of 1,6,7,8,9,14,15,16,17,17,18,18-Dodecachloropentacyclo[12.2.1.16,9.02,13.05,10]octadeca-7,15-diene (“Dechlorane Plus”TM) [covering any of its individual anti- and syn-isomers or any combination thereof]. [Online]. Available: https://echa.europa.eu/documents/10162/e226337f-0f0d-de37-b1bc-0687817f2615 [accessed 03/2022]

ECHA 2021b. Assessment of regulatory needs – Ortho-phthalates. European Chemicals Agency (ECHA). Available: https://echa.europa.eu/documents/10162/fe1067a7-c400-a8af-f23f-b5530aad9cbf [accessed 03/2022]

ECHA 2021c. Background document for dicyclohexyl phthalate (DCHP). European Chemicals Agency (ECHA). https://echa.europa.eu/documents/10162/7caae357-c28b-053b-1640-4dc16044e419 [accessed 04/2022]

ECHA (European Chemicals Agency). Data on manufacture, import, export, uses and releases of HBCDD as well as information on potential alternatives to its use. 2008a

ECHA (European Chemicals Agency). Member state committee support document for identification of

hexabromocyclododecane and all major diastereoisomers as a substance of very high concern. 2008b, 43 pp.

ECHA (European Chemicals Agency). Guidance on waste and recovered substances. 05/2010.

ECHA (European Chemicals Agency). Guidance for monomers and polymers. Version 2.0, 2012.

ECPI 2011. DIDP Information Centre, DINP Information Centre and DPHP Information Centre. The European Council for Plasticisers and Intermediates (ECPI). Available: http://www.didp-facts.com/ , http://www.dinp-facts.com/ [accessed 04/2022]

Engel, A., Buhrke, T., Imber, F., Jessel, S., Seidel, A., Völkel, W., & Lampen, A. 2017. Agonistic and antagonistic effects of phthalates and their urinary metabolites on the steroid hormone receptors ERα, ERβ, and AR. Toxicology Letters 277: 54–63.

EPA 2009. Phthalates Action Plan. U. S. Environmental Protection Agency. Available: http://www.epa.gov/oppt/existingchemicals/pubs/phthalates_ap_2009_1230_final.pdf [accessed 03/2022]

EPA 2019. Proposed Designation of Di-isobutyl Phthalate (DIBP) (CASRN 84-69-5) as High-Priority Substance for Risk Evaluation. U. S. Environmental Protection Agency. Available: https://www.epa.gov/sites/default/files/2019-08/documents/diisobutylphthalate_84-69-5_high-priority_proposeddesignation_082319_0.pdf [accessed 03/2022]

EPA 2020. Final Scope of the Risk Evaluation for Dibutyl Phthalate (1,2-Benzenedicarboxylic acid, 1,2-dibutyl ester). The United States Environmental Protection Agency (U.S. EPA). August 2020.

Erythropel, H. C., Maric, M., Nicell, J. A., Leask, R. L., & Yargeau, V. 2014. Leaching of the plasticizer di (2-ethylhexyl) phthalate (DEHP) from plastic containers and the question of human exposure. Applied Microbiology and Biotechnology 98(24): 9967–9981.

EU 2007. European Union Risk Assessment Report. CADMIUM METAL. Part I – Environment. Part II – Human Health. Available: https://echa.europa.eu/documents/10162/4ea8883d-bd43-45fb-86a3-14fa6fa9e6f3 [accessed 03/2022]

EEA 2021. Waste recycling in Europe. https://www.eea.europa.eu/ims/waste-recycling-in-europe referenced on 25.5.2022)

European Commission 2002. Heavy Metals in Waste – Final Report. Project ENV.E.3/ETU/2000/0058, COWI A/S, Denmark 2002.

European Commission 2003. European Union Risk Assessment Report dibutyl phthalate, Volume 29. Luxembourg: Office for Official Publications of the European Communities 2003 – VIII pp. 142 pp.

European Commission. Risk assessment hexabromocyclododecane, CAS-No.: 25637-99-4, EINECS No.: 247-148-4, Final Report May 2008

European Communities 2008. Tris(2-chloroethyl)phosphate, TCEP – Summary risk assessment report. Final report 26.05 2008. Germany.

Faber, W. D., Deyo, J. A., Stump, D. G., Navarro, L., Ruble, K. & Knapp, J. 2007a: Developmental toxicity and uterotrophic studies with di-2-ethylhexyl therephthalate. Birth Defects Research (Part B) 80(5): 396–405.

Faber, W. D., Deyo, J. A., Stump, D. G. & Ruble, K. 2007b.Two-generation reproduction study of di-2-ethylhexyl terephthalate in Crl:CD rats. Birth Defects Research (Part B): Developmental and Reproductive Toxicology 80: 69–81.

Faulkner, E. B. & Schwartz, R. J. 2009. High Performance Pigments. John Wiley & Sons, New York, USA.

Feo, M. L., Baron, E., Eljarrat, E. & Barcelo, D. 2012. Dechlorane plus and related compounds in aquatic and terrestrial biota: a review Analytical and Bioanalytical Chemistry 404: 2625–2637.

Filella, M. & Turner, T. 2018. Observational study unveils the extensive presence of hazardous elements in beached plastics from Lake Geneva. Frontiers of Environmental Science & Engineering 6(1): 1–8.

Foster, P. M., Thomas, L. V., Cook, M. W. & Gangolli, S. D. 1980. Study of the testicular effects and changes in zinc excretion produced by some n-alkyl phthalates in the rat. Toxicology and Applied Pharmacology 54(3): 392–8.

Foster, P. M., Foster, J. R., Cook, M. W., Thomas, L. V. & Gangolli, S. D. 1982. Changes in ultrastructure and cytochemical localization of zinc in rat testis following the administration of di-n-pentyl phthalate. Toxicology and Applied Pharmacology 63: 120–132.

Freire, M. T., Santana, I. A. & Reyes, F. G. 2006. Plasticizers in Brazilian food-packaging materials acquired on the retail market. Food Additives & Contaminants 23(1): 93–99.

Fromme, H., Küchler, T., Otto, T., Pilz, K., Müller, J. & Wenzel, A. 2002. Occurrence of phthalates and bisphenol A and F in the environment. Water Research 36(6): 1429–1438.

Föllmann, W. & Wober, J. 2006. Investigation of cytotoxic, genotoxic, mutagenic, and estrogenic effects of the flame retardants tris-(2-chloroethyl)-phosphate (TCEP) and tris-(2-chloropropyl)-phosphate (TCPP) in vitro. Toxicology Letters 161(2): 124–134.

Ge, S., Yan, B., Huang, J., Chen, Y., Chen, M., Yang, X., Yang, W., Dingwen, S. & Ma, P. 2019. Diisodecyl phthalate aggravates the formaldehyde-exposure-induced learning and memory impairment in mice. Food and Chemical Toxicology 126: 152–161.

Ge, X., Ma, S., Zhang, X., Yang, Y., Li, G. & Yu, Y. 2020. Halogenated and organophosphorous flame retardants in surface soils from an e-waste dismantling park and its surrounding area: Distributions, sources, and human health risks. Environment International 139: 105741.

GE Corp. 1997. Metallization Guide. General Electric Company, GE Plastics, 1995. GUIDE, PRODUCT. GE Plastics. CYC-300D (3/99) CA.

Granholm, T., Creasy, D. M., Pöllänen, P. & Söder, O. 1992. Di-n-pentyl phthalate-induced inflammatory changes in the rat testis are accompanied by local production of a novel lymphocyte activating factor. Journal of Reproductive Immunology 21(1):1–14.

Gray, L. E., Ostby, J., Furr, J., Price, M., Veeramachaneni, D. N. R. & Parks, L. 2000. Perinatal exposure to phthalates DEHP, BBP, and DINP, but not DEP, DMP, or DOTP, alters sexual differentiation of the male rat. Toxicological Sciences 58: 350–365.

Groß, R., Bunke, D., Gensch, C. O., Zangl, S., & Manhart, A. 2008. Study on hazardous substances in electrical and electronic equipment, not regulated by the RoHS Directive. Study made at the Öko-Institut eV (Head Office Freiburg).

Guo, J., Venier, M., Salamova, A. & Hites, R. A. 2017. Bioaccumulation of Dechloranes, organophosphate esters, and other flame retardants in Great Lakes fish. Science of the Total Environment 583: 1–9.

Government of Canada 2019. Ethylene bis(tetrabromophthalimide) (EBTBP) (https://www.canada.ca/en/health-canada/services/chemical-substances/fact-sheets/chemicals-glance/ethylene-bis-tetrabromophthalimide.html) Date modified: 2019-05-10 (cited 5.4.2022)

Haarman, A. & Gasser, M. 2016. Managing hazardous additives in WEEE plastic from the Indian informal sector. In: A Study on Applicable Identification & Separation Methods. Sustainable Recycling Industries, St. Gallen, Switzerland (66 pp.).

Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., & Purnell, P. 2018. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. Journal of hazardous materials 344: 179–199.

Hakk H., Letcher R. J. 2003. Metabolism in the toxicokinetics and fate of brominated flame retardants—a review. Environment International Volume 29, Issue 6, September, pp. 801-828

Hannas, B. R., Furr, J., Lambright, C. S., Wilson, V. S., Foster, P. M., & Gray Jr, L. E. (2011). Dipentyl phthalate dosing during sexual differentiation disrupts fetal testis function and postnatal development of the male Sprague-Dawley rat with greater relative potency than other phthalates. Toxicological Sciences 120(1): 184–193.

Hansen, E., Lassen, C. & Maxson, P. 2005. RoHS substances (Hg, Pb, Cr(VI), Cd, PBB and PBDE) in electronic equipment in Belgium. Directorate-General Environment. Federal Public Service Health, Food Chain Safety and Environment. Belgium.

Hansen, E., Nilsson, N. H., Lithner, D. & Lassen, C. 2013. Hazardous Substances in Plastic Materials. COWI and the Danish Technological Institute on behalf of The Norwegian Climate and Pollution Agency, Oslo, p. 150.

Harju M., Heimstad E. S., Herzke D., Sandanger T., Posner S., Wania F. 2008. Current State of Knowledge and Monitoring requirements. Emerging "new" Brominated flame retardants in flame retarded products and the environment. Statens forurensningstilsyn Norwegian Pollution Control Authority 2462/2009.

Harper, C. A. 2003. Handbook of Building Materials for Fire Protection. McGraw Hill Professional. Available: https://www.academia.edu/8173979/850_Handbook_of_Building_Materials_for_Fire_Protection [accessed 02/2022]

Hill, R. J. & Ive, F. A. 1993. Allergic contact dermatitis from diisodecyl phthalate in a polyvinyl chloride identity band. Contact Dermatitis: 29: 94–95.

Høibye, L., Maag, J. & Hansen, E. 2011. Background data for Annex XV dossier - DEHP, BBP, DBP and DIBP. Environmental Projevt No. 1362. Danish Environmental protection Agency, Copenhagen.

Holmes, A. L., Wise, S. S. & Wise Sr., J. P. 2008. Carcinogenicity of hexavalent chromium. Indian Journal of Medical Research 128: 353–372.

Horn, O., Nalli, S., Cooper, D. & Nicell, J. 2004. Plasticizer metabolites in the environment. Water Research 38(17): 3693–3698.

Hoshino, N., Iwai, M. & Okazaki, Y. 2005. A two-generation reproductive toxicity study of dicyclohexyl phthalate in rats. Journal of Toxicological Sciences 30: 79–96.

Hou, M., Wang, Y., Zhao, H., Zhang, Q., Xie, Q., Zhang, X., Chen, R. & Chen, J. 2018. Halogenated flame retardants in building and decoration materials in China: Implications for human exposure via inhalation and dust ingestion. Chemosphere 203: 291–299.

Howarth, J. A., Price, S. C., Dobrota, M., Kentish, P. A., & Hinton, R. H. 2001. Effects on male rats of di-(2-ethylhexyl) phthalate and di-n-hexylphthalate administered alone or in combination. Toxicology Letters 121(1): 35–43.

Howdeshell, K. L., Wilson, V. S., Furr, J., Lambright, C. R., Rider, C. V., Blystone, C. R., Hotchkiss, A. K. & Gray, L. E. Jr. 2008. A mixture of five phthalate esters inhibits fetal testicular testosterone production in the sprague-dawley rat in a cumulative, dose-additive manner. Toxicological Sciences 105: 153–165.

IARC 1993. Cadmium and cadmium compounds (Group1). IARC monographs Vol. 58:1993. International Agency for Research on Cancer, Lyon.

IEEE 2006. Standard for Environmental Assessment of Personal Computer Products, Including Laptop Personal Computers, Desktop Personal Computers, and Personal Computer Monitors. The Institute of Electrical and Electronics Engineers Inc, New York (32 pp.).

IPCS/WHO 1997. Di-n-butylphthalate. Environmental Health Criteria 189. Available: https://inchem.org/documents/ehc/ehc/ehc189.htm [accessed 03/2022]

Iqbal, M., Syed, J. H., Breivik, K., Chaudhry, M. J. I., Li, J., Zhang, G. & Malik, R. N. 2017. E-Waste Driven Pollution in Pakistan: The First Evidence of Environmental and Human Exposure to Flame Retardants (FRs) in Karachi City. Environmental Science & Technology 51: 13895–13905.

IVM (2013) POP Stream, POP-BDE waste streams in the Netherlands: analysis and inventory (R13-16). Institute for Environmental Studies, The Netherlands.

Jahrman, E. P., Seidler, G. T. & Sieber,J. R. 2018. Determination of Hexavalent Chromium Fractions in Plastics Using Laboratory-Based, High-Resolution X-ray Emission Spectroscopy. Analytical Chemistry 90(11): 6587–6593.

Jansen, M. & Letschert, H. P. 2000. Inorganic yellow-red pigments without toxic metals. Nature 27(404): 980–982.

Järup, L., M. Berglund, C. G. Elinder, G. Nordberg & M. Vahter. 1998. Health effects of cadmium exposure – a review of the literature and a risk estimate. Scandinavian Journal of Work, Environment & Health 24: 1–52.

Kademoglou, K., Xu, F., Padilla-Sanchez, J. A., Haug, L. S., Covaci, A., & Collins, C. D. 2017. Legacy and alternative flame retardants in Norwegian and UK indoor environment: implications of human exposure via dust ingestion. Environment International: 102: 48–56.

Kajiwara N, Sueoka M, Ohiwa T, Takigami H. Determination of flame-retardant hexabromocyclododecane diastereomers in textiles. Chemosphere. 2009;74(11):1485-9.

Kajiwara, N., Noma, Y. & Takigami, H. 2011. Brominated and organophosphate flame retardants in selected consumer products on the Japanese market in 2008. Journal of Hazardous Materials 192: 1250–1259.

Kastner. J., Cooper, D. G., Maric, M., Dodd, P. & Yargeau, V. 2012. Aqueous leaching of di-2-ethylhexyl phthalate and "green" plasticizers from poly(vinyl chloride). Science of The Total Environment 432: 357–364.

Kauppi, S., Bachér, J., Laitinen, S., Kiviranta, H., Suomalainen, K., Turunen, T., Kautto, P., Mannio, J., Räisänen, M., Laitala, K., Porras, S., Rantio, T., Salminen, J., Santonen, T., Seppälä, T., Teittinen, T. & Wahlström, M. 2019. Kestävä ja turvallinen kiertotalous – Selvitys POP-yhdisteiden ja SVHC-aineiden hallinnasta kiertotaloudessa. (Safe and sustainable circular economy. Report on the control of POPs and SVHCs in circular economy). Valtioneuvoston kanslia, Helsinki. Valtioneuvoston selvitys- ja tutkimustoiminnan julkaisusarja 2019:58. http://urn.fi/URN:ISBN:978-952-287-787-1

KEMI 2020. Substance Evaluation Conclusion as required by REACH Article 48 and EVALUATION REPORT for Bis(2-ethylhexyl) tetrabromophthalate EC No 247-426-5 CAS No 26040-51-7 Evaluating Member State: Sweden.

King, M., Ramachandran, V., Prengaman, R. D., DeVito, S. C. & Been, J. 2014. Lead and Lead Alloys. Kirk-Othmer Encyclopedia of Chemical Technology (1999-2016). John Wiley & Sons, Inc. Online Posting Date: 28 Apr 2014.

Kurt-Karakus, P. B., Muir, D. C., De Jourdan, B., Teixeira, C., Epp Martindale, J., Embers, H., Wang, X., Keir, M. & Backus, S. 2019. Bioaccumulation of selected halogenated organic flame retardants in Lake Ontario. Environmental Toxicology and Chemistry 38: 1198–1210.

Lake, B. G., Foster, J. R., Collins, M. A., Stubberfield, C. R., Gangolli, S. D. & Srivastava, S. P. 1982. Studies on the effects of orally administered dicyclohexyl phthalate in the rat. Acta pharmacologica et toxicologica 51: 217–26.

Lamb IV, J. C., Chapin, R. E., Teague, J., Lawton, A. D., & Reel, J. R. 1987. Reproductive effects of four phthalic acid esters in the mouse. Toxicology and Applied Pharmacology 88(2): 255–269.

Larsson, S. C. & Wolk, A. 2015. Urinary cadmium and mortality from all causes, cancer and cardiovascular disease in the general population: systematic review and meta-analysis of cohort studies. International Journal of Epidemiology 45: 782–791.

Larsson, L., Ohlsson, S., Derving, J., Diedrich, B., Sandgren, P., Larsson, S., & Uhlin, M. 2022. DEHT is a suitable plasticizer option for phthalate-free storage of irradiated red blood cells. Vox Sanguinis 117(2): 193–200.

Latini, G. 2005. Monitoring phthalate exposure in humans. Clinica Chimica Acta 361: 20–29.

Law R. J., Allchin C. R., de Boer J. Covaci A., Herzke D., Lepom P., Morris S., Tronczynski J., de Wit C. A. 2006. Levels and trends of brominated flame retardants in the European environment. Chemosphere 64 (2006): 187–208.

Lee, H., Lee, J., Choi, K., & Kim, K. T. 2019. Comparative analysis of endocrine disrupting effects of major phthalates in employed two cell lines (MVLN and H295R) and embryonic zebrafish assay. Environmental Research 172: 319–325.

Liang, F., & Yan, B. 2020. Oxidative damage in the liver and kidney induced by dermal exposure to diisononyl phthalate in Balb/c mice. Toxicology and Industrial Health 36(1): 30–40.

Li, H. H., Chen, L. J., Yang, Z. B., Xu, X. X., Xian, J. R., Zhao, L. L., & Yang, S. 2022. Pollution Characteristics and Health Risk Assessment of Phthalate Esters in Household Dust in Chengdu, China. DOI: 10.21203/rs.3.rs-1186935/v1.

Lington, A. W., Bird, M. G., Plutnick, R. T., Stubblefield, W. A. & Scala, R. A. 1997. Chronic toxicity and carcinogenic evaluation of diisononyl phthalate in rats. Fundamental and Applied Toxicology 36: 79–89.

Liu, J., Hernandez, R., Li, X., Meng, Z., Chen, H., & Zhou, C. 2022. Pregnane X Receptor Mediates Atherosclerosis Induced by Dicyclohexyl Phthalate in LDL Receptor-Deficient Mice. Cells 11(7): 1125.

Liu, W. L., Shen, C. F., Zhang, Z., & Zhang, C. B. 2009. Distribution of phthalate esters in soil of e-waste recycling sites from Taizhou city in China. Bulletin of Environmental Contamination and Toxicology 82(6): 665–667.

Maag, J., Brandt, U. K., Mikkelsen, S. H., & Lassen, C. 2010. Inclusion of HBCDD, DEHP, BBP, DBP and additive use of TBBPA in annex IV of the Commission's recast proposal of the RoHS Directive. Danish Environmental Protection Agency.

Malarvannan, G., Onghena, M., Verstraete, S., van Puffelen, E., Jacobs, A., Vanhorebeek, I., Verbruggen, S. C. A. T., Joosten, K. F. M., Van den Berghe, G., Jorens, P. G. & Covaci, A. 2019. Phthalate and alternative plasticizers in indwelling medical devices in pediatric intensive care units. Journal of Hazardous Materials 363: 64–72.

Managaki S, Miyake Y, Yokoyama Y, Hondo H, Masunaga S, Nakai S, Kobayashi T, Kameya T, Kimura A, Nakarai T, Oka Y, Otani H and Miyake A. Emission load of hexabromocyclododecane in Japan based on the substance flow analysis. 2009

Mao, S. H., Gu, W. H., Bai, J. F., Dong, B., Huang, Q., Zhao, J., Zhuang, X. N., Zhang, C. L., Yuan, W. Y. & Wang, J. W. 2020. Migration of heavy metal in electronic waste plastics during simulated recycling on a laboratory scale. Chemosphere 245: 125645.

Masten S., Karen E., Haneke M. S. 2002. Tetrabromobisphenol A bis(2,3-dibromopropyl ether) [21850-44-2] Review of Toxicological Literature.

Mersiowsky, I. 2002. Long-term fate of PVC products and their additives in landfills. Progress in Polymer Science 27(10): 2227–2277.

Ministry of the Environment, 2016. Requirements for the management of waste containing persistent organic pollutants - Rules concerning waste in the POP Regulation and their application to waste electrical and electronic equipment and end-of-life vehicles. Environmental Administration Guidelines 4en/2016. Ministry of the Environment, Environmental Protection Department. Helsinki, December 2016.

Moore, M. R. 1998. Oncogenicity Study in Mice with Di(isononyl)phthalate Including Ancillary Hepatocellular Proliferation and Biochemical Analyses. Covance Laboratories 144 Inc., Vienna, VA 22182. For Aristech Chemical Corporation, Pittsburgh, PA 15230. January 29, 1998. Covance 2598-105.

Morf, L. S., Tremp, J., Gloor, R., Huber, Y., Stengele, M. & Zennegg, M. 2005. Brominated flame retardants in waste electrical and electronic equipment: substance flows in a recycling plant. Environmental Science & Technology 39: 8691–8699.

Morf L, Buser A, Taverna R, Bader HP, Scheidegger R. Dynamic substance flow analysis as a valuable tool - a case study for brominated flame retardants as an example of potential endocrine disruptors. 2008: 62(5):424-431

MST (1980). Cadmiumforurening. En redegørelse om anvendelse, forekomst og skadevirkninger af cadmium i Danmark. Miljøstyrelsen, København.

Murphy, J. 2001. The additives for plastics handbook. 2nd edition. ISBN 1 85617 370 4. Elsevier, New York.

Nagorka, R., Conrad, A., Scheller, C., Süßenbach, B., & Moriske, H. J. 2011. Diisononyl 1, 2-cyclohexanedicarboxylic acid (DINCH) and Di (2-ethylhexyl) terephthalate (DEHT) in indoor dust samples: Concentration and analytical problems. International Journal of Hygiene and Environmental Health 214(1): 26–35.

Nalli, S, Cooper, D. G. & Nicell, J. A. 2006a. Interaction of metabolites with R. rhodochrous during the biodegradation of di-ester plasticizers. Chemosphere 65(9): 1510–1517.

Nalli, S., Cooper, D. G. & Nicell, J. A. 2006b. Metabolites from the biodegradation of di-ester plasticizers by Rhodococcus rhodochrous. Science of The Total Environment 366(1): 286–294.

Nalli, S., Horn, O. J., Grochowalski, A. R., Cooper, D. G. & Nicell, J. A. 2006c. Origin of 2-ethylhexanol as a VOC. Environmental Pollution 140(1): 181–185.

NICNAS 2008a. Diisobutly phthalate. Existing chemical hazard assessment report. National Industrial Chemicals Notification and Assessment Scheme. Australian Government.

NICNAS 2008b. Dimethyl phthalate. Existing chemical hazard assessment report. National Industrial Chemicals Notification and Assessment Scheme. Australian Government.

NICNAS 2008c. Dihexyl phthalate. Existing chemical hazard assessment report. National Industrial Chemicals Notification and Assessment Scheme. Australian Government.

NICNAS 2008d. Phthalates hazard compendium; a summary of physiochemical and human health hazard data for Diisodecyl Phthalate. Sydney, National Industrial Chemicals Notification and Assessment Scheme. Australian Government.

NICNAS 2008e. Phthalates hazard compendium; a summary of physiochemical and human health hazard data for Diisononyl Phthalate. Sydney, National Industrial Chemicals Notification and Assessment Scheme. Australian Government.

NICNAS 2008f. Phthalates hazard compendium; a summary of physiochemical and human health hazard data for Di-n-octyl phthalate (DnOP). Sydney, National Industrial Chemicals Notification and Assessment Scheme. Australian Government.

NICNAS 2008g. Existing Chemical Hazard Report, Bis(2-methoxyethyl) Phthalate. Sydney, National Industrial Chemicals Notification and Assessment Scheme. Australian Government.

Niu D., Qiu Y., Du X., Li L., Zhou Y., Yin D., Lin Z., Chen L., Zhu Z., Zhao J., Bergman Å. 2019. Novel brominated flame retardants in house dust from Shanghai, China: levels, temporal variation, and human exposure. Environmental Sciences Europe volume 31: 6.

NTP 1992. National Toxicology Program Chemical Repository Database. Institute of Environmental Health Sciences, National Institutes of Health. Research Triangle Park, North Carolina.

OECD 1994. Risk Reduction Monograph No. 5: Cadmium. OECD Environment Monograph Series No. 104. OECD Environment Directorate, Paris, France.

OECD 2018. Considerations for Assessing the Risks of Combined Exposure to Multiple Chemicals, Series on Testing and Assessment No. 296, Environment, Health and Safety Division, Environment Directorate. OECD Series on Testing Assessment OECD Series on Testing Assessment.

Okita, R. T. & Okita, J. R. 1992. Effects of diethyl phthalate and other plasticizers on laurate hydroxylation in rat. Pharmaceutical Research 9: 1648–1653.

Oldring, P. K. T. 2001. Coatings, colorants, and paints. In: Meyers, R.A. (Ed.), Encyclopedia of Physical Science and Technology, third edition. Elsevier, London, pp. 175–190.

OECD (2021), A Chemicals Perspective on Designing with Sustainable Plastics : Goals, Considerations and Trade-offs, OECD Publishing, Paris, https://doi.org/10.1787/f2ba8ff3-en

Otake, T., Yoshinaga, J. & Yanagisawa, Y. 2004. Exposure to phthalate esters from indoor environment. Journal of Exposure Analysis and Environmental Epidemiology 14: 524–528.

Papazoglou, E. S. 2004. Chapter 4 Flame retardants for plastics. Out of: Harper C. A. Handbook of building materials for fire protection. Available: https://www.academia.edu/8173979/850_Handbook_of_Building_Materials_for_Fire_Protection [accessed 02/2022]

Pirkanmaa Centre for Economic Development, Transport and the Environment, 2022. Sähkö- ja elektroniikkalaitetilastot. https://www.ymparisto.fi/fi-FI/Kartat_ja_tilastot/Jatetilastot/Tuottajavastuun_tilastot/Sahko_ja_elektroniikkalaitetilastot. referenced on 24.5.2022

Plastics Europe (2018). Plastics – the Facts 2018 - An analysis of European plastics production, demand and waste data https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf

POPRC 2021b. Persistent Organic Pollutants Review Committee (POPRC). Dechlorane Plus and its syn- and anti-isomers. Draft Risk Profile of 11 May (in preparation). Revised version of UNEP/POPS/POPRC.16/INF/19 from 8 February 2021. Available: http://chm.pops.int/TheConvention/POPsReviewCommittee/Meetings/POPRC16/POPRC16Followup/tabid/8748/Default.aspx [accessed 03/2022]

Rahman F., Langford K. H., Scrimshaw M. D., Lester J. N. 2001. Polybrominated diphenyl ether (PBDE) flame retardants, Science of The Total Environment, Volume 275, Issues 1–3, 2001, Pages 1-17, ISSN 0048-9697

Rahman, M. & Brazel, C. S. 2004. The plasticizer market: an assessment of traditional plasticizers and research trends to meet new challenges. Progress in Polymer Science 29(12): 1223–1248.

Rakkestad, K. E., Dye, C. J., Yttri, K. E., Holme, J. A., Hongslo, J. K., Schwarze, P. E. & Becher, R. 2007. Phthalate levels in Norwegian indoor air related to particle size fraction. Journal of Environmental Monitorin 9: 1419–1425.

Rauert C., Lazarov B., Harrad S., Covaci A., Stranger M. 2014. A review of chamber experiments for determining specific emission rates and investigating migration pathways of flame retardants. Atmospheric Environment Vol. 82: 44-55

Reel, J. R., Lawton, A. D. & Myers, C. B. 1985. Di-n-hexyl phthalate: Reproduction and fertility assessment in CD-1 mice when administered in the feed. NTP-85-187. NTIS#PB85- 249332. National Toxicology Program, National Institute of Environmental Health Sciences.

Reemtsma T., Berger U., Arp H.P.H., Gallard H., Knepper T.P., Neumann M., Quintana J.B., Voogt P.D. 2016. Mind the gap: persistent and mobile organic compounds—water contaminants that slip through. Environ. Sci. Technol., 50(19):10308-10315

Saha, R., Nandi, R. & Saha, B. 2011. Sources and toxicity of hexavalent chromium – Review. Journal of Coordination Chemistry 64(10): 1782–1806.

Salaudeen, T., Okoh, O., Agunbiade, F. & Okoh, A. 2018. Fate and impact of phthalates in activated sludge treated municipal wastewater on the water bodies in the Eastern Cape. South Africa Chemosphere,203: 336–344.

Santos-Echeandía, J., Rivera-Hernándeza, J. R., Rodriguesa, J. P. & Moltó, V. 2020. Interaction of mercury with beached plastics with special attention to zonation, degradation status and polymer type. Marine Chemistry 222: 103788.

SCA (Swedish Chemicals Agency) 2014. CLH Report for Dicyclohexyl phthalate. Available: https://www.echa.europa.eu/documents/10162/50aed41f-b445-9262-c22c-0ba774dce8d1 [accessed 03/2022]

SCA (Swedish Chemical Agency) 2016. CLH Report for Diisohexyl Phthalate – 71850-09-4. CLH report Proposal for Harmonised Classification and Labelling Substance Name: 1,2-Benzenedicarboxylic acid, diisohexyl ester. Available: https://echa.europa.eu/documents/10162/f7a4d5fe-c6b1-c507-2c42-f58ee5f7324a [accessed 03/2022]

SCENIHR (Scientific Committee on Emerging and Newly-Identified Health Risks) 2015. Opinion on the safety of medical devices containing DEHP-plasticized PVC or other plasticizers on neonates and other groups possibly at risk. European Commission, Directorate-General for Health and Food Safety. Available: https://data.europa.eu/doi/10.2875/969692 [accessed 03/2022]

Schlummer, M., Gruber, L., Maurer, A., Wolz, G. & van Eldik, R. 2007. Characterisation of polymer fractions from waste electrical and electronic equipment (WEEE) and implications for waste management. Chemosphere 67:1866–1876.

Shen, L., Jobst, K. J., Helm, P. A., Reiner, E. J., McCrindle, R., Tomy, G. T., Backus, S., Brindle, I. D. & Marvin, C. H. 2012. Identification and determination of the dechlorination products of dechlorane 602 in Great Lakes fish and Arctic beluga whales by gas chromatography-high resolution mass spectrometry. Analytical and Bioanalytical Chemistry 404: 2737–2748.

Singh N., Duan H., Tang Y. 2020. Toxicity evaluation of E-waste plastics and potential repercussions for human health. Environment International 137 (2020).

Staples, C. A., Peterson, D. R., Parkerton, T. F. & Adams, W. J. 1997. The environmental fate of phthalate esters: A literature review. Chemosphere 35: 67–749.

Stapleton H.M., Sharma S., Getzinger G., Ferguson P.L., Gabriel M., Webster T.F., Blum A. 2012. Novel and high volume use flame retardants in US couches reflective of the 2005 PentaBDE phase out. Environ. Sci. Technol., 24: 13432-13439

Stenmarck, Å., Belleza, E. L., Fråne, A., & Busch, N. 2017. Hazardous substances in plastics – ways to increase recycling. Nordic Council of Ministers.

Suebring, R., Moeller, A., Freese, M., Pohlmann, J.-D., Wolschke, H., Sturm, R., Xie, Z., Hanel, R. & Ebinghaus, R.2013. Brominated flame retardants and dechloranes in eels from German Rivers Chemosphere 90: 118–124.

Sverko, E., Tomy, G. T., Marvin, C. H., Zaruk, D., Reiner, E., Helm, P. A., Hill, B. & McCarry, B. E. 2008. Dechlorane plus levels in sediment of the lower Great Lakes. Environmental Science & Technology 42: 361–366.

Sverko, C. E., Tomy, G. T., Reiner, E. J., Li, Y. F., McCarry, B. E., Arnot, J. A., Law, R. J. & Hites, R. A. 2011. Dechlorane plus and related compounds in the environment: a review. Environmental Science & Technology 45: 5088–5098.

Swerea. Exploration of management options for HBCDD. Report. Authors: Posner S, Roos S, Olsson E. 2010.

Takeuchi, S., Kojima, H., Saito, I., Jin, K., Kobayashi, S., Tanaka-Kagawa, T., & Jinno, H. 2014. Detection of 34 plasticizers and 25 flame retardants in indoor air from houses in Sapporo, Japan. Science of The Total Environment 491: 28–33.

de la Torre, A., Alonso, M. B., Martínez, M. A., Sanz, P., Shen, L., Reiner, E. J., Lailson-Brito, J., Torres, J. P. M., Bertozzi, C., Marigo, J., Barbosa, L., Cremer, M., Secchi, E., Malm, O., Eljarrat, E. & Barceló D. 2012. Dechlorane-related compounds in Franciscana Dolphin (Pontoporia blainvillei) from Southeastern and Southern Coast of Brazil. Environmental Science & Technology 46: 12364–12372.

Tran, H. T., Lin, C., Bui, X. T., Nguyen, M. K., Cao, N. D. T., Mukhtar, H., Hoang, H. G., Varjani, S., Ngo, H. H. & Nghiem, L. D. 2022. Phthalates in the environment: characteristics, fate and transport, and advanced wastewater treatment technologies. Bioresource Technology 344: 126249.

Turner, A. 2018. Black plastics: linear and circular economies, hazardous additives and marine pollution. Environment International 117: 308–318.

Turner, A. 2019. Cadmium pigments in consumer products and their health risks. Science of The Total Environment 657: 1409–1418.

Turner, A. & Filella, M. 2021. Hazardous metal additives in plastics and their environmental impacts. Environment International: 156: 106622.

Van der Veen I., De Boer J. 2012. Phosphorus flame retardants: properties, production, environmental occurrence, toxicity and analysis Chemosphere, 88(10): 1119-1153

Ullman, F. 2012. Ullmann´s Encyclopedia of Industrial Chemistry. 7th edition. Wiley-VCH Verlag GmbH & Co KGaA. DOI: 10.1002/14356007

U.S. CPSC 2001. Chronic hazard advisory panel on diisononyl phthalate (DINP). U.S. Consumer Product Safety Commission, Bethesda, MD 20814, June 2001. Available: https://www.cpsc.gov/s3fs-public/pdfs/dinp.pdf.

U.S. CPSC 2010a. Toxicity Review for di(2-ethylhexyl) phthalate (DEHP). United States Consumer Product Safety Commission. Available: https://www.cpsc.gov/s3fs-public/ToxicityReviewOfDEHP.pdf [accessed 03/2022]

U.S. CPSC 2010b. Toxicity Review of Di(isodecyl) Phthalate. United States Consumer Product Safety Commission. Available: https://www.cpsc.gov/s3fs-public/toxicityDIDP.pdf [accessed 04/2022]

U.S. CPSC 2010c. Toxicity Review of Diisononyl phthalate. United States Consumer Product Safety Commission. Available: https://www.cpsc.gov/s3fs-public/ToxicityReviewOfDINP.pdf [accessed 04/2022]

U.S. CPSC 2010d. Toxicity Review of Di-n-octyl phthalate (DnOP). United States Consumer Product Safety Commission. Available: https://www.cpsc.gov/s3fs-public/toxicityDNOP.pdf [accessed 04/2022]

U.S. CPSC 2011a. Toxicity Review for Dimethyl Phthalate (DMP, CASRN 131-11-3). United States Consumer Product Safety Commission. Available: https://www.cpsc.gov/s3fs-public/dmp.pdf [accessed 03/2022]

U.S. CPSC 2011b. Toxicity Review for Dicyclohexyl Phthalate (DCHP, CASRN 84-61-7). United States Consumer Product Safety Commission. Available: https://www.cpsc.gov/s3fs-public/ToxicityReviewOfDCHP.pdf [accessed 04/2022]

UNEP 2006 Pentabromodiphenyl Ether Risk Profile. Stockholm Convention on Persistent Organic Pollutants Persistent Organic Pollutants Review Committee Second meeting Geneva, 6–10 November 2006. UNEP/POPS/POPRC.2/17/Add.1

UNEP 2007a Commercial Octabromodiphenyl Ether Risk Profile. Stockholm Convention on Persistent Organic Pollutants Persistent Organic Pollutants Review Committee Third meeting Geneva, 19–23 November 2007. UNEP/POPS/POPRC.3/20/Add.6

UNEP 2007b Hexabromobiphenyl Risk Management Evaluation. Stockholm Convention on Persistent Organic Pollutants Persistent Organic Pollutants Review Committee Third meeting Geneva, 19–23 November 2007. UNEP/POPS/POPRC.3/20/Add.3

UNEP 2010. Report of the Persistent Organic Pollutants Review Committee on the work of its sixth meeting Addendum Risk profile on hexabromocyclododecane. UNEP/POPS/POPRC.6/13/Add.2

UNEP 2014 Decabromodiphenyl Ether (commercial mixture, c-decaBDE) Risk Profile. Persistent Organic Pollutants Review Committee Tenth meeting Rome, 27–30 October 2014. UNEP/POPS/POPRC.10/10/Add.2

UNEP 2015 Short-Chained Chlorinated Paraffins Risk Profile. Persistent Organic Pollutants Review Committee Eleventh meeting Rome, 19–23 October 2015. UNEP/POPS/POPRC.11/10/Add.2

UNEP 2017. Proposal to list perfluorohexane sulfonic acid (CAS No: 355-46-4, PFHxS), its salts and PFHxS-related compounds in Annexes A, B and/or C to the Stockholm Convention on Persistent Organic Pollutants. UNEP/POPS/POPRC.13/4*.

UNEP 2018. Report of the Persistent Organic Pollutants Review Committee on the work of its fourteenth meeting Addendum Risk profile on perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS-related compounds. UNEP/POPS/POPRC.14/6/Add.1

UNEP 2019a. General technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants. Conference of the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, Fourteenth meeting Geneva, 29 April–10 May 2019. UNEP/CHW.14/7/Add.1/Rev.1.

UNEP 2019b. Report of the Persistent Organic Pollutants Review Committee on the work of its fifteenth meeting Addendum Risk management evaluation on perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS-related compounds. UNEP/POPS/POPRC.15/7/Add.1

Van der Veen, I., & de Boer, J. 2012. Phosphorus flame retardants: properties, production, environmental occurrence, toxicity and analysis. Chemosphere 88(10): 1119–1153.

VinylPlus 2014. The European PVC industry's experience in replacing lead and cadmium-based stabilisers. Available: https://docplayer.net/5403858-The-european-pvc-industry-s-experience-in-replacing-lead-and-cadmium-based-stabilisers.html [accessed 02/2022]

Wade M.G., Kawata A., Rigden M., Caldwell D., Holloway A. C. 2019. Toxicity of Flame Retardant Isopropylated Triphenyl Phosphate: Liver, Adrenal, and Metabolic Effects. International Journal of Toxicology Vol. 38(4): 279-290.

Wagner, S. & Schlummer, M. 2020. Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures. Resources, Conservation & Recycling 158: 104800.

Wams, T. J. 1987. Diethylhexylphthalate as an environmental contaminant — a review. Science of The Total Environment 66: 1–16.

Wang, D.-G., Guo, M.-X., Pei, W., Byer, J. D. & Wang, Z. 2015. Trophic magnification of chlorinated flame retardants and their dechlorinated analogs in a fresh water food web. Chemosphere 118: 293–300.

Wang, P., Zhang, Q., Zhang, H., Wang, T., Sun, H., Zheng, S., Li, Y., Liang, Y. & Jiang, G. 2016. Sources and environmental behaviors of Dechlorane Plus and related compounds — A review. Environment International 2016: 206–220.

Wang, Y., Peris, A., Rifat, M. R., Ahmed, S. I., Aich, N., Nguyen, L. V., Urík, J., Eljarrat, E., Vrana, B., Jantunen, L. M. & Diamond, M. L. 2020. Measuring exposure of e-waste dismantlers in Dhaka Bangladesh to organophosphate esters and halogenated flame retardants using silicone wristbands and T-shirts. Science of The Total Environment 720: 137480.

Wang, Z., Deng, D. Y., & Yang, L. L. 2014. Degradation of dimethyl phthalate in solutions and soil slurries by persulfate at ambient temperature. Journal of Hazardous Materials 271: 202–209.

Weaver, J. A., Beverly, B. E., Keshava, N., Mudipalli, A., Arzuaga, X., Cai, C., Hotchkiss, A. K., Makris, S. L. & Yost, E. E. 2020. Hazards of diethyl phthalate (DEP) exposure: A systematic review of animal toxicology studies. Environment International 145: 105848.

Weil, E. D. & Levchik, S. V. 2009. Flame retardants for plastic and textiles: practical applications. Carl Hanser Verlag GmbH & Co. Munich. Available: https://www.hanser-elibrary.com/doi/10.3139/9781569905791.fm [accessed 02/2022]

Wensing, M., Schripp, T., Uhde, E., Salthammer, T. 2008. Ultra-fine particles release from hardcopy devices: Sources, real-room measurements and efficiency of filter accessories. Science of The Total Environment 407(1): 418–27.

Wise Jr., J. P., Young, J. L., Cai, J. & Cai, L. 2022. Current understanding of hexavalent chromium [Cr(VI)] neurotoxicity and new perspectives. Environment International 158: 106877.

Wormuth, M., Scheringer, M., Vollenweider, M. & Hungerbuhler, K. 2006. What are the sources of exposure to eight frequently used phthalic acid esters in Europeans? Risk Analysis 26: 803–824.

Wu, J. P., Zhang, Y., Luo, X. J., Wang, J., Chen, S. J., Guan, Y. T. & Mai, B. X. 2010. Isomer-specific bioaccumulation and trophic transfer of dechlorane plus in the freshwater food web from a highly contaminated site, South China. Environmental Science & Technology 44: 606–611.

Wäger, P., Schluep, M., Müller, E. (2010), RoHS substances in mixed plastics from Waste Electrical and Electronic Equipment, Final Report, Empa, Swiss Federal Laboratories for Materials Science and Technology. pp. 1-99 [Online] Available at:http://new.weeeforum.org/system/files/documents/rohs20in20mixed20plastics_empa_final_2010200920171.pdf [Accessed 6 July 2015].

Wäger, P. A., Schluep, M., Müller, E. & Gloor, R. 2012. RoHS regulated substances in mixed plastics from waste electrical and electronic equipment. Environmental Science & Technology 46(2): 628–635.

Xian, Q., Siddique, S., Li, T., Feng, Y. L., Takser, L. & Zhu, J. 2011: Sources and environmental behavior of dechlorane plus – a review Environment International 37: 1273–1284.

Yamasaki, K., Okuda, H., Takeuchi, T. & Minobe, Y. 2009. Effects of in utero through lactational exposure to dicyclohexyl phthalate and p,p'-DDE in Sprague-Dawley rats. Toxicology Letters 189: 14–20.

Yost, E. E., Euling, S. Y., Weaver, J. A., Beverly, B. E., Keshava, N., Mudipalli, A., Arzuaga, X., Blessinger, T. Dishaw, L., Hotchkiss, A. & Makris, S. L. 2019. Hazards of diisobutyl phthalate (DIBP) exposure: A systematic review of animal toxicology studies. Environment International 125: 579–594.

Zhang H., Kelly B.C. 2018. Sorption and bioaccumulation behavior of multi-class hydrophobic organic contaminants in a tropical marine food web. Chemosphere 199: 44-53

Zhang, S., Chen, X., Li, X., Wang, Y., Zhu, Q., Huang, T., & Ge, R. S. 2020. Effects of in utero exposure to diisodecyl phthalate on fetal testicular cells in rats. Toxicology Letters 330: 23–29.

Zhang X, Yang F, Luo C, Wen S, Zhang X, Xu Y. Bioaccumulative characteristics of hexabromocyclododecanes in freshwater species from an electronic waste recycling area in China. Chemosphere. 2009;76(11):1572-8.

Zhang, X. L., Luo, X. J., Liu, H. Y., Yu, L. H., Chen, S. J. & Mai, B. X. 2011. Bioaccumulation of several brominated flame retardants and dechlorane plus in waterbirds from an e-waste recycling region in south China: associated with trophic level and diet sources. Environmental Science & Technology 45: 400–405.

Zhang, Y., Su, H., Ya, M., Li, J., Ho, S. H., Zhao, L., Jian, K., Letcher, R. J., & Su, G. 2019. Distribution of flame retardants in smartphones and identification of current-use organic chemicals including three novel aryl organophosphate esters. Science of The Total Environment 693: 133654.

Zhou H., Yin N., Faiola F. 2020. Tetrabromobisphenol A (TBBPA): A controversial environmental pollutant. Journal of Environmental Sciences 97: 54–66.

Appendices

Appendix 1. X-ray fluorescence spectroscopy results of waste plastics

The concentration units in the below table are in parts per million (PPM). Symbol L marks that the concentration is below the limit of detection. The minimum and maximum errors for each element throughout the samples is shown below as well, for reference. The actual error is unique for each measurement.

Error	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
Min	2	102	2	4	25	20	16	4	2	1	2	2	3	3	3	4	4	8	1
Max	60	3471	1788	11284	2425	246	71	466	634	5788	71	605	75	119	448	85	116	240	126

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK001	L	L	4414	332	L	L	L	L	5	L	L	L	L	L	10	L	12	44	59
PK002	L	L	4394	716	3738	67	L	L	L	9414	L	L	L	L	7	L	L	65	50
PK003	L	L	47627	210	L	L	L	L	10	L	L	L	L	L	49	L	21	119	513
PK004	L	L	6384	191	L	L	L	L	L	L	L	L	L	L	L	L	10	21	88
PK005	L	L	3526	18872	38607	1748	L	L	90	91669	L	L	L	L	41	L	L	L	L
PK006	L	L	2321	143	L	L	124	L	6	L	L	L	L	L	44	10	9	53	35
PK007	L	292	5882	200	L	L	L	L	L	L	L	L	L	L	8	9	9	36	78
PK008	L	L	3932	816	8010	138	L	L	L	12164	L	L	L	L	8	L	L	250	44
PK009	L	705	570	278	29078	417	L	207	L	55233	L	L	L	L	376	L	33	633	L
PK010	L	264	24307	248	L	L	L	L	174	11	L	L	L	L	200	132	L	503	288
PK011	L	L	6448	237	L	L	L	L	L	L	L	L	L	L	11	L	10	34	90
PK012	L	L	11609	12845	46950	1697	L	L	81	90385	L	L	L	L	120	L	52	121	68
PK013	L	L	8993	222	35147	298	L	L	80	102527	L	L	L	L	185	L	L	L	L
PK014	L	L	13299	10485	35200	295	L	L	81	112362	L	L	L	L	87	L	L	229	83
PK015	L	L	10779	21575	35668	903	L	L	L	86137	L	L	L	L	109	L	45	162	47

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK016	L	L	716	39	46227	460	L	L	83	76205	L	L	L	L	1865	L	57	61	L
PK017	L	318	L	73	L	L	L	L	L	L	L	L	L	5	8	L	8	250	L
PK018	L	L	12511	335	L	L	35	L	21	L	L	L	L	L	77	14	11	453	151
PK019	L	L	9029	330	47524	447	L	L	84	95877	L	L	L	L	69	L	L	74	41
PK020	L	L	168	236	9516	121	L	L	28	18923	L	L	L	L	43	L	20	114	L
PK021	L	L	4390	83	L	L	L	L	16	L	L	L	L	L	7	L	L	21	61
PK022	L	114725	1988	970	76501	383	L	806	L	191611	L	L	L	L	159	L	L	896	L
PK023	L	402	7	69	L	L	L	L	56	4	L	L	L	L	41	L	7	213	L
PK024	L	L	5461	59	L	L	L	L	18	L	L	L	L	L	25	L	L	83	63
PK025	L	L	10925	382	L	L	L	L	17	L	L	L	L	L	43	L	25	151	142
PK026	L	L	10571	156	L	L	L	L	20	L	L	L	L	L	375	L	14	227	128
PK027	L	L	L	85	L	L	L	L	10	L	L	L	L	L	17	L	8	53	L
PK028	L	L	9784	102	L	L	L	L	24	1465	L	L	L	L	23	L	13	155	109
PK029	L	290	23	463	635	38	L	L	25	584	L	6	L	L	111	L	10	211	2
PK030	L	L	10054	231	L	L	L	L	10	L	L	L	L	L	24	L	11	77	124
PK031	L	L	4374	74	40749	493	L	L	183	36754	L	61	L	L	182	26	45	1458	L
PK032	L	242	10468	71	187	L	L	L	8	3	L	L	L	L	11	L	L	90	143
PK033	L	L	6448	105	L	39	L	L	123	12	L	L	L	L	950	22	22	476	90
PK034	L	L	2838	70	L	L	L	L	26	4	L	L	L	L	44	7	10	206	40
PK035	L	2080	160	166	L	L	L	L	27	11	L	9	L	L	12741	L	L	446	L
PK036	L	L	13224	158	L	L	L	L	11	6	L	L	L	L	36	L	L	164	160
PK037	L	L	14038	84	L	L	L	L	6	L	L	L	L	L	282	L	14	93	174
PK038	L	L	539	159	32175	358	L	L	68	61633	L	L	L	L	3174	L	L	893	L
PK039	L	L	9930	49	L	L	L	L	5	4	L	L	L	L	15	L	L	119	130
PK040	L	L	5110	54	L	L	L	L	L	2	L	L	L	L	96	L	L	85	66
PK041	L	L	1658	48	11134	327	30	L	28	18382	L	34	L	L	48	L	17	83	L
PK042	L	L	10208	169	96	L	L	L	11	L	L	L	L	L	38	L	23	158	134
PK043	L	L	20233	92	L	L	L	L	L	L	L	L	L	L	13	L	17	47	247

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK044	L	L	3566	91	L	L	L	L	L	L	L	L	L	L	17	L	9	85	49
PK045	L	L	3990	51	L	L	L	L	9	L	L	L	L	L	19	L	9	71	58
PK046	L	L	5181	140	12231	122	L	L	25	16249	L	11	L	L	31	L	19	617	40
PK047	L	L	2747	288	4553	69	L	L	18	8434	L	L	L	L	312	L	L	246	34
PK048	L	L	16676	99	149	L	L	L	L	L	L	L	L	L	789	L	13	60	190
PK049	L	L	6075	58	133	L	L	L	5	L	L	L	L	L	11	L	24	52	80
PK050	L	L	29	287	425	L	L	L	29	855	L	L	L	L	76	L	17	293	4
PK051	L	L	317	969	27329	230	448	L	1672	148023	L	21803	L	L	581	L	51	253	L
PK052	19	L	980	49	45495	328	L	L	126	70041	L	L	L	L	135	L	L	727	L
PK053	L	L	19598	109	25135	296	L	L	L	95117	L	L	L	L	1431	L	57	76	176
PK054	L	L	32164	176	67	L	L	L	7	L	L	L	L	L	22	L	22	150	345
PK055	L	L	1996	262	12911	180	L	L	23	19182	L	L	L	L	53	L	L	507	11
PK056	L	L	31783	5888	31395	790	L	L	L	104390	L	L	L	L	89	L	L	167	264
PK057	L	L	1843	77	L	L	L	L	5	L	L	L	L	L	19	L	11	94	27
PK058	L	L	1750	47	L	L	L	L	L	L	L	L	L	L	13	L	11	61	28
PK059	L	L	18568	123	213	L	L	L	L	L	L	L	L	L	1040	L	44	120	223
PK060	L	222	3460	305	L	L	L	L	L	L	L	L	L	L	6	L	11	44	48
PK061	L	L	219	94	13581	180	L	L	41	16520	L	10	L	L	170	23	18	446	L
PK062	L	L	3568	98	L	L	L	L	16	L	L	L	L	L	63	11	14	705	62
PK063	L	L	2841	305	17172	220	L	L	25	25453	L	L	L	L	27	L	20	602	13
PK064	L	L	6708	10389	54175	2027	L	405	137	144771	L	L	L	L	240	L	146	735	L
PK065	L	L	14224	17712	55155	1012	L	344	63	102907	L	L	L	L	72	40	61	216	89
PK066	L	L	47580	243	38345	396	L	L	L	89501	L	L	L	L	96	L	63	763	125
PK067	L	L	16763	181	65214	552	L	351	89	134462	L	L	L	L	118	L	58	252	121
PK068	L	14824	6578	41	L	L	L	L	23	L	L	L	L	L	90	L	L	164	35
PK069	L	315	12328	511025	45	8754	L	L	204	11	L	L	L	L	L	L	88	517	170
PK070	L	L	4072	94	L	L	L	L	68	5	L	L	L	L	36	L	10	208	53
PK071	L	L	11920	107	12082	175	L	L	39	34115	L	L	L	L	39	L	36	184	122

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK072	L	L	4197	789	7249	116	L	L	35	9808	L	L	L	L	77	L	15	625	50
PK073	L	L	3651	537	6517	93	L	L	18	8665	L	L	L	L	20	L	L	261	42
PK074	L	1892	17099	235	L	L	L	L	23	L	L	L	L	L	8	L	11	49	205
PK075	L	L	2729	51	2038	L	L	L	L	6734	L	L	L	L	16	L	10	58	35
PK076	L	L	13224	81	56	L	L	L	L	L	L	L	L	L	121	L	26	43	164
PK077	L	L	1023	101	60162	484	L	L	114	100974	L	L	L	L	139	L	L	717	L
PK078	L	L	3219	208	18100	281	L	L	23	16099	L	L	L	L	76	L	24	603	21
PK079	L	L	6022	68	57	2444	L	L	L	31896	L	L	L	L	122	L	13	56	75
PK080	L	1642	144	206	111	L	L	L	29	14	L	L	L	L	9893	L	14	70	L
PK081	L	240	3301	53	L	35	L	L	5	L	L	L	L	L	9	L	11	50	45
PK082	17	400	10357	49	127	L	L	L	L	L	L	L	L	L	L	L	L	L	124
PK083	L	1625	6151	540	L	L	L	L	12	L	L	L	L	L	30	L	15	130	81
PK084	L	L	1734	57	14910	183	L	L	32	15518	L	L	L	L	59	L	20	210	L
PK085	L	8102	5802	44	L	L	L	L	L	4	L	L	L	L	46	L	L	49	68
PK086	L	L	404	L	28666	323	L	L	54	73243	L	L	L	L	1705	L	L	180	L
PK087	L	L	5138	121	L	L	L	L	11	L	L	L	L	L	41	16	12	138	75
PK088	L	L	4098	37	L	L	L	L	L	L	L	L	L	L	12	L	17	50	58
PK089	L	650	16874	78	L	L	461	L	L	4	L	L	L	L	605	L	L	44	201
PK090	56	L	19417	11464	54710	2814	L	L	452	77104	L	L	L	L	141	L	L	439	83
PK091	L	L	6026	64	L	L	L	L	L	L	L	L	L	L	7	L	10	34	77
PK092	L	L	10329	6349	41491	2294	L	L	77	97003	L	L	L	L	115	L	49	355	55
PK093	L	L	5219	110	43	L	L	L	13	36	L	L	L	L	38	L	11	163	71
PK094	L	541	5601	123	L	L	L	L	126	L	L	L	L	L	7508	L	13	1271	77
PK095	L	L	14559	163	L	L	L	L	7	L	L	L	L	L	24	L	29	138	169
PK096	L	L	3536	73	45	L	L	L	7	8	L	L	L	L	22	L	L	116	45
PK097	L	L	9874	72	73	L	L	L	7	L	L	L	L	L	257	L	22	59	129
PK098	L	L	13398	77	L	L	L	L	L	L	L	L	L	L	7	L	14	43	173
PK099	L	L	766	128	54213	409	L	L	106	116996	L	L	L	L	109	L	L	234	L

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK100	L	L	4961	505	31038	349	L	L	58	23485	L	L	L	L	62	L	L	254	L
PK101	L	476	2034	77	L	L	L	L	5	L	L	L	L	L	18	L	11	52	30
PK102	L	L	7011	282	83198	7254	L	L	291	189182	L	199	L	L	248	56	93	3664	L
PK103	L	L	8348	14845	46268	2376	L	L	86	100181	L	L	L	L	776	L	48	625	L
PK104	L	L	15712	79	L	L	L	L	L	L	L	L	L	L	13	L	16	61	189
PK105	L	L	9011	71	L	L	L	L	L	L	L	L	L	L	17	L	20	81	119
PK106	L	L	14968	430	34895	376	L	L	94	103033	L	L	L	L	774	L	L	555	100
PK107	L	L	3910	87	L	L	L	L	5	L	L	L	L	L	295	L	9	52	45
PK108	L	2294	L	L	L	L	L	L	30	L	L	L	L	98	12005	L	30	269	8
PK109	L	302	1887	58	L	L	L	L	L	L	L	L	L	L	7	L	13	20	28
PK110	L	L	18695	109	L	L	L	L	6	L	L	L	L	L	17	L	13	66	219
PK111	L	L	13615	83	L	L	L	L	L	L	L	L	L	L	8	L	L	18	163
PK112	L	L	5122	302	L	L	L	L	7	26	L	L	L	L	866	L	15	84	70
PK113	L	L	8989	25823	57584	1984	L	L	116	127480	L	L	L	L	157	L	L	270	L
PK114	L	L	8593	66	L	L	L	L	7	2776	L	L	L	7	14	L	13	54	107
PK115	L	L	27188	120	L	L	L	L	6	L	L	L	L	L	55	L	15	676	311
PK116	L	L	11807	77	11585	186	L	L	28	35723	L	10	L	L	32	L	20	136	112
PK117	L	L	9184	53	L	L	L	L	4	L	L	L	L	L	12	L	11	43	120
PK118	L	L	9312	5642	47882	1799	L	L	115	114853	L	L	L	L	234	48	L	1158	52
PK119	L	L	4537	68	L	32	31	L	L	L	L	L	L	L	88	L	8	39	59
PK120	L	L	15213	250	43079	412	L	L	70	85849	L	L	L	L	185	39	L	532	87
PK121	L	1982	6799	606078	L	L	835	L	28940	211	L	L	L	L	177	398	L	1090	90
PK122	L	537	7572	67	L	L	L	L	8	L	L	L	L	L	375	L	L	122	102
PK123	L	786	7764	5519	38542	404	L	L	63	103313	L	103	L	L	272	L	L	419	32
PK124	L	L	2067	229	9675	161	L	L	42	15838	L	L	L	L	74	L	18	276	17
PK125	L	L	12977	1370	83196	567	L	L	118	151799	L	L	L	L	864	112	L	1015	L
PK126	20	L	14727	448	47764	457	L	L	80	111643	L	L	L	L	1649	L	L	289	58
PK127	53	L	7141	215	34803	320	L	L	51	87857	L	L	L	L	97	L	51	269	35

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK128	L	L	12	145	L	L	L	L	93	L	L	7	L	L	66	11	9	236	L
PK129	L	L	2827	39	L	L	L	L	10	4	L	L	L	8	21	L	12	170	40
PK130	L	L	4951	281	61359	293	L	L	88	166182	L	L	L	L	196	L	L	1510	L
PK131	L	L	7532	63	L	L	L	L	44	2418	L	L	L	L	14	L	12	77	100
PK132	L	L	305	106	3756	82	L	L	58	71389	L	L	L	L	184	L	25	376	16
PK133	L	L	10347	335	50130	417	L	L	98	135529	L	L	L	L	237	L	L	485	47
PK134	21	L	5189	83	76073	533	L	L	180	136693	L	71	L	L	263	L	L	104	L
PK135	L	L	5608	45	L	L	L	L	5	L	L	L	L	L	19	L	L	63	70
PK136	L	4033	9487	103	L	L	L	L	7	L	L	L	L	L	13	L	11	53	110
PK137	L	L	2368	215	L	L	L	L	136	66	L	L	L	L	272	20	L	895	36
PK138	L	320	3043	67	L	L	L	L	6	L	L	L	L	L	9	L	11	62	45
PK139	L	255	15927	100	43	L	L	L	8	7	L	L	L	L	669	L	L	84	189
PK140	20	L	9541	7404	26761	589	L	L	77	94390	L	L	L	L	69	L	L	219	76
PK141	L	L	40305	145	L	L	L	L	L	L	L	L	L	L	18	L	L	56	349
PK142	L	L	3984	72	70	L	L	L	40	11	L	L	L	L	84	9	14	290	47
PK143	L	L	37790	166	L	L	L	L	16	L	L	L	L	L	52	L	L	225	429
PK144	L	L	29	204	L	L	L	L	46	3	L	L	L	L	87	8	9	461	L
PK145	L	880	10924	46	L	L	L	L	L	L	L	L	L	L	13	L	65	2124	134
PK146	L	L	3511	95	L	L	L	L	6	L	L	L	L	L	18	L	13	52	49
PK147	L	L	3046	115	8288	114	L	L	14	10079	L	9	L	L	37	L	L	343	28
PK148	L	242	27467	193	279	L	L	L	8	3	L	L	L	L	22	L	50	93	292
PK149	L	L	14901	77	L	L	L	L	12	L	L	L	L	L	13	L	14	58	171
PK150	L	L	1085	212	80767	468	L	464	112	193453	L	L	L	L	200	L	L	1481	L
PK151	L	L	43125	285	31118	300	L	L	59	99300	L	L	L	L	127	L	86	1865	403
PK152	L	L	27863	162	L	L	L	L	5	L	L	L	L	L	18	L	L	191	50
PK153	L	L	7821	57	L	L	L	L	L	5	L	L	L	L	347	L	12	42	102
PK154	L	L	13271	68	77285	585	L	L	131	139402	L	251	L	L	310	L	L	108	L
PK155	L	591	5860	L	L	L	L	L	22	L	L	L	L	L	22	L	21	180	72

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK156	L	L	11704	231	9347	487	L	L	94	24560	L	15	L	L	189	25	19	1145	125
PK157	L	998	8726	1367	886	42	L	L	29	2144	L	L	L	L	554	14	15	176	114
PK158	L	L	406	107	26615	270	L	L	86	73593	L	L	L	L	1961	L	L	485	L
PK159	L	L	2509	L	L	L	L	L	9	L	L	L	L	L	27	L	19	153	38
PK160	L	L	7611	682	4912	78	L	L	47	8573	L	L	L	L	144	15	14	517	88
PK161	L	L	30993	395	169	L	L	L	28	L	L	L	L	L	34	L	13	124	350
PK162	L	L	2328	165	L	L	L	L	5	L	L	L	L	L	15	L	13	51	34
PK163	L	804	65	50	L	L	L	L	53	8	L	L	L	L	11786	L	15	343	L
PK164	L	L	822	903	60049	507	L	L	121	107384	L	L	L	L	5699	L	L	669	L
PK165	L	L	1589	92	26595	337	L	L	55	53325	L	L	L	L	200	L	48	158	L
PK166	L	L	1818	148	67	L	L	L	L	L	L	L	L	L	1724	L	10	22	23
PK167	L	L	7231	49	L	L	L	L	9	2435	L	L	L	L	22	L	10	120	95
PK168	L	L	10324	62	50	L	L	L	10	L	L	L	L	L	13	L	16	89	138
PK169	L	L	3157	126	L	L	L	L	13	L	L	L	L	L	153	11	14	132	44
PK170	L	L	8146	23859	61377	1691	L	L	L	120310	L	L	L	L	248	L	L	566	L
PK171	L	L	19639	92	L	L	L	L	L	L	L	L	L	L	13	L	L	36	234
PK172	L	10911	7240	145	15431	130	L	L	74	106078	L	L	L	L	795	L	42	105	66
PK173	L	L	632	L	41048	388	L	L	L	70173	L	92	L	L	4711	L	L	248	L
PK174	L	L	11637	12539	46554	1686	L	L	76	89432	L	L	L	L	95	L	L	115	85
PK175	L	3670	22908	149	L	L	L	L	L	L	L	L	L	L	9	L	13	57	159
PK176	L	L	7305	208	42884	408	L	L	103	93726	L	L	L	L	296	L	L	325	L
PK177	L	L	9030	42	197	L	L	L	10	L	L	L	L	L	11	L	11	151	115
PK178	26	L	3404	48	200	L	L	L	4	L	L	L	L	L	10	L	11	81	46
PK179	L	L	13642	100	L	L	L	8	14	L	L	L	L	L	183	L	22	194	173
PK180	L	L	103127	1325	L	109	L	L	53	78390	L	L	L	L	81	56	L	657	168
PK181	L	L	8	70	L	L	L	L	L	L	L	L	L	L	13	L	L	45	4
PK182	L	L	3897	86	L	L	L	L	14	L	L	L	L	L	108	L	L	194	54
PK183	L	L	9779	20020	31727	1000	L	L	83	102617	L	L	L	L	154	L	L	195	56

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK184	L	L	9821	21663	63965	2281	L	L	171	119727	L	L	L	L	261	43	L	1823	39
PK185	L	L	5162	56	L	L	L	L	L	L	L	L	L	L	8	L	13	31	75
PK186	L	L	3335	33	L	L	L	L	L	L	L	L	L	L	7	L	10	37	44
PK187	L	L	8449	6207	59231	1236	L	L	102	88558	L	L	L	L	91	L	48	227	L
PK188	L	L	4859	80	18856	250	L	L	28	13174	L	13	L	L	38	L	L	247	26
PK189	59	L	21137	7178	50730	1109	L	L	71	96905	L	L	L	L	165	L	59	604	130
PK190	L	L	25840	10497	56680	600	L	L	L	75933	L	L	L	L	523	L	510	531	132
PK191	L	L	6619	132	L	L	L	L	59	L	L	L	L	L	157	13	17	313	83
PK192	L	L	41892	5280	45803	1976	L	L	122	110964	L	L	L	L	624	L	76	578	171
PK193	L	L	637	68	44652	499	L	L	127	68985	L	94	L	L	8734	L	L	404	L
PK194	L	L	35847	235	195	L	L	L	12	L	L	L	L	L	134	L	L	164	396
PK195	21	L	8085	233	58134	529	L	L	109	95803	L	L	L	L	121	L	L	635	L
PK196	L	L	4680	80	L	L	L	L	L	L	L	L	L	L	L	L	10	225	68
PK197	L	962	23377	118	L	L	L	L	7	L	L	L	L	L	32	L	13	171	86
PK198	L	L	10041	121	L	L	L	L	7	L	L	L	L	L	408	L	14	115	127
PK199	L	L	21209	157	52788	392	L	L	L	135787	L	L	L	L	1823	L	L	L	98
PK200	L	L	5688	136	L	L	L	L	L	51867	L	L	L	L	34	L	13	214	79
PK201	L	L	9102	72	L	L	L	L	13	L	L	L	L	L	23	L	8	117	116
PK202	L	L	5603	267	29767	332	L	L	86	71907	L	L	L	L	252	39	38	757	25
PK203	L	L	5069	55	L	L	L	L	5	L	L	L	L	L	10	L	L	29	69
PK204	L	L	17071	81	120	L	L	L	44	23	L	L	L	L	82	L	12	1019	203
PK205	L	L	28492	133	L	L	L	L	17	9	L	5	L	11	120	L	31	172	321
PK206	L	L	6280	18273	2320	55	L	L	L	15429	L	3890	L	L	352	L	31	48	105
PK207	L	47241	860	194	50754	289	L	L	113	158547	L	L	L	L	271	L	L	883	L
PK208	L	L	6424	66	41	L	L	L	L	L	L	L	L	L	103	L	14	41	83
PK209	L	L	3307	56	L	L	43	L	9	L	L	L	L	L	71	L	10	96	47
PK210	L	L	5701	60	L	L	L	L	7	L	L	L	L	L	17	L	L	73	80
PK211	L	L	18768	17502	53023	995	L	L	64	103245	L	L	L	L	95	L	63	281	114

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK212	L	L	28309	120	L	L	L	L	9	L	L	L	L	L	25	14	L	405	320
PK213	L	916	4721	91	L	L	L	L	8	L	L	L	L	L	12	L	L	64	63
PK214	L	L	5062	596	7893	111	L	L	31	12412	L	L	L	L	74	L	15	467	55
PK215	21	L	3952	48	127	L	L	L	15	1374	L	L	L	L	17	L	22	125	46
PK216	34	8122	319	136	L	L	L	98	39	L	L	L	L	L	75	L	L	2545	20
PK217	L	L	941	198	31997	249	L	L	231	47455	L	25	L	L	681	L	39	1313	L
PK218	L	L	4932	143	32565	355	L	L	71	24164	L	L	L	L	54	L	L	273	L
PK219	L	L	14306	191	L	L	L	L	16	L	L	L	L	L	80	14	18	473	182
PK220	L	L	15359	220	L	L	L	L	L	L	L	L	L	L	19	L	L	563	196
PK221	L	L	14037	140	24482	275	L	L	67	72103	L	L	L	L	135	L	79	556	127
PK222	25	L	719	42	42404	391	L	L	39	59991	L	L	L	L	72	L	39	441	L
PK223	L	L	33775	5456	46774	1331	L	L	62	87731	L	L	L	L	91	L	L	251	267
PK224	L	L	17127	309	51070	473	L	L	L	108490	L	L	L	L	86	L	52	427	92
PK225	L	L	5484	49	L	L	L	L	L	L	L	L	L	L	240	L	8	63	77
PK226	L	6853	19788	373	L	L	L	L	21	L	L	L	L	L	22	11	L	75	144
PK227	L	L	1263	346	59930	451	L	506	157	131517	L	L	L	L	368	102	78	2372	L
PK228	L	L	3896	648	7902	102	L	L	L	12592	L	7	L	L	340	L	13	363	41
PK229	L	L	49815	207	77	L	L	L	7	L	L	L	L	L	29	L	23	152	555
PK230	L	L	3425	211	43450	464	L	L	74	96796	L	L	L	L	261	L	42	455	L
PK231	L	L	773	114	30238	299	L	L	42	57117	L	L	L	L	1316	L	L	721	L
PK232	L	L	1769	87	L	L	L	L	9	2	L	L	L	L	49	9	11	134	26
PK233	L	L	9	56	L	L	L	L	26	L	L	L	L	L	30	L	L	123	L
PK234	L	222	8500	91	50	L	L	L	6	L	L	L	L	L	386	L	13	62	109
PK235	L	L	8501	65	L	35	L	L	L	L	L	L	L	L	194	L	8	42	105
PK236	L	L	6479	282	70	L	39	L	9	640	L	L	L	L	19	L	10	42	90
PK237	L	L	2583	35	L	L	L	L	12	L	L	L	L	L	15	L	6	35	38
PK238	L	L	8373	39466	25854	233	L	L	72	73566	L	L	L	L	615	L	35	299	59
PK239	22	L	732	150	46560	490	L	328	60	74946	L	L	L	L	13266	L	L	807	L

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK240	L	L	15239	227	146	L	L	L	166	12	L	L	L	L	488	36	35	2013	205
PK241	L	L	31938	252	83	L	L	L	6	L	L	L	L	L	15	L	17	52	348
PK242	L	L	7482	142	50691	439	L	L	L	99326	L	L	L	L	105	L	L	316	L
PK243	L	L	5102	43	L	L	L	L	8	L	L	L	L	L	11	L	11	36	66
PK244	35	L	17079	8358	47905	1497	L	L	154	90341	L	L	L	L	247	39	44	1024	106
PK245	L	9641	5522	226	L	L	L	L	36	3	L	L	L	L	76	L	L	508	66
PK246	25	11899	1260	242	52383	489	L	391	108	84501	L	L	L	L	521	46	58	1672	L
PK247	L	2042	10309	5243	19450	380	L	L	58	76680	L	L	L	L	82	L	L	193	76
PK248	L	L	21948	129	44	L	L	L	6	L	L	L	L	L	58	L	L	469	271
PK249	L	866	1322	131	2279	72	L	L	50	1379	L	344	L	L	54	L	17	586	18
PK250	L	L	8162	53	L	L	L	L	5	L	L	L	L	L	17	L	10	56	102
PK251	L	L	19869	118	L	L	L	L	18	4	L	L	L	L	101	L	16	306	235
PK252	L	L	8244	151	3199	79	L	L	17	9727	L	6	L	L	51	L	21	209	88
PK253	L	L	2981	41	L	L	L	L	33	L	L	L	L	L	31	L	L	74	41
PK254	L	L	9882	119	L	L	L	L	7	L	L	L	L	L	26	13	13	96	116
PK255	L	L	13864	18232	45288	793	L	L	141	98391	L	L	L	L	283	L	72	1334	69
PK256	L	L	20406	331	741	44	L	L	L	22348	L	L	L	L	35	L	25	86	245
PK257	L	L	19236	500	832	44	L	L	96	38359	L	L	L	L	62	L	35	156	235
PK258	L	L	9454	73	L	L	L	L	6	L	L	L	L	L	18	L	12	46	128
PK259	L	204	706	141	L	L	L	L	16	L	L	L	L	L	50	9	10	215	10
PK260	L	L	14702	96	L	L	L	L	5	L	L	L	L	L	310	L	15	63	182
PK261	L	939	4668	5819	43877	423	L	L	66	105533	L	103	L	L	259	L	46	454	L
PK262	19	L	700	42	37351	320	L	L	73	75685	L	L	L	L	436	L	40	385	L
PK263	L	L	11038	138	31412	320	L	L	53	72620	L	L	L	L	148	L	32	61	81
PK264	L	L	7754	6693	45287	2283	L	L	114	102058	L	L	L	L	78	L	L	156	L
PK265	L	L	9059	25666	58422	2064	L	L	71	129157	L	L	L	L	131	L	L	391	L
PK266	L	L	13722	220	L	L	L	L	17	L	L	L	L	L	94	14	L	317	181
PK267	L	L	3032	178	L	L	L	L	10	L	L	L	L	L	155	L	12	78	41

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK268	43	L	1104	599	63589	524	L	L	388	81092	L	L	L	L	4374	397	61	8355	L
PK269	L	L	3015	354	4927	89	L	L	35	6674	L	L	L	L	208	20	L	422	37
PK270	L	L	2769	50	L	L	25	L	L	L	L	L	L	L	14	L	9	33	38
PK271	L	L	7753	170	L	L	L	L	120	11	L	L	L	L	306	59	23	1992	99
PK272	L	L	7429	63	L	L	L	L	9	5	L	L	L	L	13	L	8	74	95
PK273	L	L	3009	137	8855	371	L	L	24	18400	L	13	L	L	37	L	15	133	22
PK274	L	L	18035	222	L	L	L	L	26	L	L	L	L	L	99	L	19	426	217
PK275	L	L	6371	126	L	L	L	L	10	L	L	L	L	L	34	L	11	102	87
PK276	L	L	7484	210	L	L	L	L	10	L	L	L	L	L	560	L	9	104	98
PK277	L	L	12513	83	17683	524	L	L	58	59361	L	L	L	L	455	L	L	62	92
PK278	L	760	5512	64	L	L	L	9	15	L	L	L	L	L	37	L	20	432	54
PK279	L	3092	4470	78	L	L	L	L	8	L	L	L	L	L	22	L	12	61	56
PK280	L	L	6774	56	109	L	L	L	4	L	L	L	L	L	6	L	15	548	81
PK281	L	L	37123	5870	56221	3058	L	L	84	90602	L	L	L	L	140	L	69	383	266
PK282	L	L	28793	138	L	L	L	L	9	L	L	L	L	L	32	L	16	120	352
PK283	L	L	8205	71	L	L	L	L	4	L	L	L	L	L	628	L	13	99	110
PK284	L	263	5740	53	145	L	L	L	L	L	L	L	L	7	L	L	29	28	74
PK285	L	L	6605	53	L	L	L	L	L	48433	L	L	L	L	15	L	19	L	73
PK286	L	L	9216	115	19307	234	L	L	49	54838	L	L	L	L	31	L	23	64	83
PK287	32	L	1409	52	L	L	L	L	147	L	L	L	L	L	31	L	13	327	20
PK288	L	L	19358	92	L	L	L	L	6	L	L	L	L	L	64	L	L	59	238
PK289	L	38351	3038	90	4740	65	L	L	L	12957	L	L	L	L	377	L	L	L	L
PK290	L	L	19507	5961	54017	474	L	L	62	91610	L	L	L	L	85	L	L	135	112
PK291	L	L	23576	127	52	L	L	L	13	12	L	L	L	L	27	L	L	499	280
PK292	L	L	4497	58	L	L	L	L	15	L	L	L	L	L	32	L	13	105	61
PK293	L	2581	13878	99	L	L	L	L	9	L	L	L	L	L	99	L	L	105	172
PK294	L	L	8852	1110	60284	454	L	L	143	102648	L	L	L	L	7287	L	58	892	45
PK295	L	L	6625	L	74424	626	L	L	55	90821	L	L	L	L	102	L	L	378	L

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK296	L	L	747	113	65658	557	L	265	57	81567	L	122	L	L	21913	L	L	1245	L
PK297	L	L	176	48	12725	190	L	L	41	30235	L	L	L	L	326	L	L	77	L
PK298	L	L	11025	70	L	L	L	L	L	10696	L	L	L	L	23	L	17	42	141
PK299	L	L	5531	155	L	L	L	L	L	3	L	3	L	L	1783	12	9	54	72
PK300	L	L	10437	314	10480	189	L	L	169	33556	L	22	L	L	137	65	19	817	121
PK301	L	L	18104	119	L	L	L	L	12	L	L	L	L	L	48	L	19	635	218
PK302	L	1448	19315	158	742	L	L	L	L	3286	L	L	L	L	292	L	18	55	240
PK303	L	L	877	54	72832	763	L	L	83	55988	L	L	L	L	7741	L	58	999	L
PK304	L	L	5035	51	L	L	L	L	L	2	L	L	L	L	9	L	8	30	68
PK305	L	L	12460	190	9251	152	L	L	L	49503	L	L	L	L	58	L	L	111	132
PK306	L	12869	19706	79	43	L	L	L	L	22	L	L	L	L	849	L	L	41	201
PK307	L	L	6166	65	L	L	L	L	14	L	L	L	L	L	19	L	L	82	86
PK308	L	L	19511	191	28026	313	L	L	71	96716	L	L	L	L	1649	45	L	552	188
PK309	L	L	2785	63	9469	348	L	L	26	20023	L	L	L	L	37	L	24	117	20
PK310	L	L	7127	1680	L	L	L	L	7	L	L	L	L	L	288	L	10	102	80
PK311	L	L	24444	14256	57844	510	L	L	83	88707	L	L	L	L	108	L	68	179	151
PK312	L	206	4151	48	63	L	L	L	9	L	L	L	L	L	205	L	L	28	58
PK313	L	L	3382	1142	6461	97	L	L	36	9597	L	L	L	L	113	12	18	630	39
PK314	L	L	508	80	35235	355	L	L	122	64711	L	L	L	L	24932	L	L	358	L
PK315	42	897	12260	146	61	L	L	L	15	L	L	L	L	L	58	15	78	2510	150
PK316	L	L	8566	75	L	L	L	L	8	L	L	L	L	L	28	L	L	1142	104
PK317	23	L	18642	227	44851	392	L	L	91	105903	L	L	L	L	620	L	65	438	127
PK318	L	L	14708	815	24770	412	L	L	57	105565	L	L	L	L	85	L	42	264	112
PK319	L	L	10679	128	37887	501	L	L	89	109466	L	L	L	28	98	L	L	164	52
PK320	L	4362	6172	149	29462	475	L	L	41	26317	L	515	L	L	174	L	41	1073	49
PK321	L	L	55	112	L	L	L	L	55	L	L	L	L	L	178	83	11	1086	5
PK322	L	L	33286	381	35480	330	L	L	76	91146	L	L	L	L	652	L	L	494	288
PK323	L	L	4813	42	58	L	L	L	6	3	L	L	L	L	19	L	9	66	62

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK324	L	L	5338	102	L	L	L	L	65	L	L	L	L	L	19	8	L	53	72
PK325	L	L	6797	295	L	L	L	L	36	L	L	L	L	L	139	31	L	506	90
PK326	L	L	23815	658	25290	220	L	L	211	90465	L	L	L	L	803	58	44	2438	216
PK327	L	L	7128	71	12018	173	L	L	25	14950	L	10	L	L	39	L	30	330	64
PK328	L	L	1890	40	L	L	L	L	30	3	L	L	L	L	214	L	11	86	26
PK329	L	L	11841	138	31090	388	L	L	60	33236	L	L	L	L	807	L	52	964	95
PK330	L	L	19614	290	24917	423	L	L	101	103515	L	L	L	L	89	L	52	472	175
PK331	L	L	L	34	L	L	L	L	L	L	L	L	L	L	210	L	12	39	2
PK332	L	256	1144	142	213	L	L	L	95	530	L	L	L	L	498	12	11	562	14
PK333	22	L	883	353	36723	431	L	L	70	42148	L	L	L	L	206	L	63	995	L
PK334	L	L	1933	2037	8013	151	L	L	63	17681	L	34	L	L	321	L	17	246	17
PK335	L	L	1213	142	72626	680	L	L	80	52050	L	L	L	L	137	L	70	725	L
PK336	L	L	2253	170	15950	239	L	L	31	20990	L	42	L	L	29	L	L	69	15
PK337	L	L	987	87	2563	55	L	L	11	6206	L	L	L	L	201	L	10	186	11
PK338	19	L	562	209	35326	293	L	L	99	107587	L	L	L	L	157	L	L	640	L
PK339	L	L	1210	L	98263	988	L	L	71	64267	L	L	L	L	112	L	L	481	L
PK340	95	467	6957	285	1034	41	2547	L	257	932	L	L	L	L	210	9	11	1227	86
PK341	L	L	23	295	L	L	L	L	27	L	L	L	L	L	122	L	11	417	L
PK342	L	L	1645	11977	45014	1680	L	L	111	95167	L	L	L	L	659	L	L	703	L
PK343	L	L	4049	47	L	L	L	L	22	L	L	L	L	L	15	L	L	234	58
PK344	L	L	10	89	L	L	L	L	22	2	L	L	L	L	53	12	10	180	L
PK345	L	211	1398	60	L	L	L	L	6	2	L	L	L	L	203	L	10	207	19
PK346	L	6459	737	L	32089	306	L	L	57	50663	L	L	L	L	468	L	L	562	L
PK347	L	L	2497	638	2642	77	L	L	L	6272	L	5	L	L	74	L	12	62	34
PK348	L	L	7	58	L	L	L	L	L	L	L	L	L	L	17	L	L	56	2
PK349	L	L	1260	222	64	L	L	L	6	153	L	L	L	L	74	13	11	158	19
PK350	L	L	1078	889	4417	192	L	L	57	7103	L	L	L	L	311	19	22	352	12
PK351	181	L	4069	138	1045	L	L	L	6	L	L	L	L	L	46	L	L	129	53

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK352	L	L	801	823	4484	131	L	L	56	7885	L	L	L	L	167	L	11	157	9
PK353	L	688	933	422	1502	60	L	L	39	3162	L	L	L	L	91	19	10	296	18
PK354	L	L	207	47	12309	158	L	L	42	59470	L	12	L	L	755	L	27	55	L
PK355	L	L	2475	8328	23788	653	L	L	99	71026	L	702	L	L	731	L	L	166	L
PK356	L	L	545	183	42048	380	L	L	106	121522	L	L	L	L	799	L	L	390	L
PK357	L	589	662	1310	1004	75	L	L	68	1763	L	L	L	L	205	19	13	317	13
PK358	21	L	1631	239	109952	899	L	233	86	70344	L	L	L	L	349	L	139	1085	L
PK359	L	L	485	353	1549	69	L	L	21	2412	L	3	L	L	52	22	8	99	6
PK360	L	L	14	53	L	L	L	L	4	53	L	L	L	L	10	L	7	38	L
PK361	L	1260	2265	323	400	45	L	L	17	970	L	13	L	L	78	63	20	137	29
PK362	L	L	8	44	L	L	L	L	19	L	L	L	L	L	94	L	11	194	6
PK363	L	L	550	7677	34222	642	L	L	93	92951	L	L	L	L	63	L	L	81	L
PK364	L	L	81	73	L	L	L	L	6	L	L	L	L	L	127	L	10	47	L
PK365	L	L	509	338	42639	380	L	L	119	128740	L	L	L	L	775	35	L	728	L
PK366	L	L	504	13989	30242	1092	L	L	65	70862	L	L	L	L	57	L	L	76	L
PK367	L	1056	461	74	L	L	L	41	13	L	L	L	L	L	47	L	22	3900	13
PK368	41	L	2096	138	38551	370	L	L	67	97113	L	L	L	L	65	L	L	139	L
PK369	L	L	627	275	43740	326	L	L	132	116469	L	26	L	L	1014	L	63	631	L
PK370	L	L	4445	21062	24068	1470	L	L	113	67765	L	20	L	L	259	L	37	501	L
PK371	L	L	965	233	32941	386	L	L	74	24193	L	L	L	L	194	L	42	1333	L
PK372	L	L	9	6270	L	L	L	L	42	L	L	L	L	L	555	10	9	162	L
PK373	L	L	L	31	L	L	L	L	L	L	L	L	L	L	10	L	L	47	4
PK374	L	L	221	216	12020	125	L	L	85	59279	L	14	L	L	697	L	L	154	L
PK375	L	L	318	114	L	56	L	L	75	136793	L	L	L	L	10171	L	L	437	20
PK376	L	L	785	44	31157	332	L	L	38	51861	L	L	L	L	4318	L	35	434	L
PK377	L	L	555	L	35769	459	L	L	57	52769	L	L	L	L	59	L	L	355	L
PK378	L	L	58	21	L	L	L	L	27	3	L	L	L	L	54	L	8	135	5
PK379	L	L	131	87	L	L	L	L	8	19	L	L	L	L	15	L	16	65	4

SAMPLE	Cr	Ba	Ti	Cl	Sb	Sn	Cd	Bi	Pb	Br	Se	As	Hg	Au	Zn	Cu	Ni	Fe	V
PK380	L	L	95	453	77	L	L	L	55	L	L	L	L	L	139	59	L	691	L
PK381	35	L	226	110	77	L	L	L	6	L	L	L	L	L	343	L	L	89	10
PK382	L	21808	673	304	21168	188	L	L	84	119167	L	L	L	L	75	L	L	L	L
PK383	L	219	7	75	L	L	L	L	23	L	L	L	L	L	130	L	7	250	L
PK384	L	L	564	13302	48198	2400	L	L	57	94293	L	L	L	L	77	33	L	236	L
PK385	L	L	585	L	60290	572	L	L	72	58226	L	L	L	L	98	L	62	823	L
PK386	L	249	4	124	L	L	L	L	15	L	L	L	L	L	29	L	9	73	L
PK387	L	L	1304	274	10403	215	L	L	55	28254	L	L	L	L	186	33	22	707	9
PK388	L	L	606	L	L	L	L	L	6	L	L	L	L	L	41	L	L	167	9
PK389	L	L	110	151	L	L	L	L	29	10	L	L	L	L	43	8	16	70	3
PK390	L	727	253	58	L	L	L	L	18	L	L	L	L	L	9	L	L	98	7
PK391	L	L	1357	59	L	L	L	L	L	L	L	L	L	L	55	L	11	68	18
PK392	L	1024	L	88	L	L	L	L	9	L	L	L	L	L	42	L	12	46	L
PK393	L	L	916	200	48239	556	L	L	67	56654	L	70	L	L	188	L	L	710	L
PK394	L	L	3559	114	L	L	L	L	8	87	L	L	L	L	332	L	12	94	47
PK395	L	L	12	68	L	L	L	L	L	L	L	4	L	L	3139	15	8	144	L
PK396	L	L	612	355	432	L	L	L	7	691	L	L	L	L	19	L	13	52	11
PK397	19	L	2179	8968	37965	1022	L	L	90	93669	L	L	L	L	307	44	62	1167	L
PK398	L	L	85	51	57	L	L	L	6	L	L	L	L	L	16	L	L	70	2
PK399	L	L	5	229	L	L	L	L	32	L	L	L	L	L	66	10	7	183	L
PK400	L	220	521	181	181	L	L	L	17	3439	L	1635	L	L	50	L	8	60	6

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Finnish Environment Institute

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