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Extremely high levels of PBDEs in children's toys from European markets: causes and implications for the circular economy

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Abstract

Background With the high influx of low-cost plastic toys on the market, there is growing concern about the safety of such toys. Some of these plastic toys contains hazardous chemicals like polybrominated diphenyl ethers (PBDEs) due to the use of recycled plastics in new toy manufacturing. Here, we investigated if toys marketed in Europe are compliant with EU directives to assess the safety of currently used children's toys and identify implications of PBDE content in toys.

Results Eighty-four toys purchased from international toy retailers were screened for bromine using X-ray fluorescence (XRF), and 11 of those with bromine content higher than 500 µg/g were analyzed for ten PBDEs using GC–HRMS. PBDEs were detected in all 11 toys. Σ_{10}PBDE concentrations ranged up to 23.5 mg/g (with a median concentration of 8.61 mg/g), with BDE-209 being the most abundant compound (4.40 mg/g). Eight samples exceeded the EU's Low POP Content Limit (LPCL) of 500 µg/g for the Σ_{10}PBDEs by 6–47 times and the Unintentional Trace Contaminant (UTC) limits of 10 µg/g for Deca-BDE by 12–800 times.

Conclusions PBDEs were up to percent levels, suggesting direct recycling of flame retarded plastic, e.g., e-waste plastics, into toy components. This is a call for concern and requires intervention from all stakeholders involved in the toy market. Overall, the occurrence of non-compliant toys in the EU market, as indicated in this study is primarily attributed to gaps in regulations, inadequate legislation for recycled plastics, the rise of online sales, complexities in global and national supply chains, and economic challenges. Failure to address these issues will hinder the efforts of the plastics industry to transition into a circular economy. This suggests that more actions are needed to address gaps in cross-border enforcement, and stricter sanctions are required for toy manufacturers who fail to adhere to regulations and safety standards.

Keywords Flame retardants, Consumer products, Plastic recycling, E-waste, Enforcement, Compliance

Introduction

The growing availability of low-cost plastic toys in the market has raised concerns about their safety. Plastic toys are widely available from mass market vendors who sell them online or through their physical stores. According to the European Toy Industries Association, one in every four toys in Europe is sold online and this number is expected to rise to one in three by 2027 [1]. The Safety Gate rapid alert system, developed by the European Union (EU) to track dangerous non-food products, reported toys to be the most notified product category entering the EU in 2022, and 23% of all notifications were for toys containing levels of harmful chemicals exceeding what is allowed by EU regulations [2]. Given that 90% of toys on the market contain plastics [3], there are

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concerns about the presence of hazardous chemicals, e.g., PBDEs, due to the use of recycled plastics in new toy manufacturing [4, 5].

Polybrominated diphenyl ethers are used as flame retardants in products like electronics, furniture, textiles, and building material. Due to their persistence in the environment and potential health risks, these chemicals are banned in many regions and listed as persistent organic pollutants under the Stockholm Convention. Although the use of Penta- and Octa-BDEs has been discontinued, Deca-BDEs are restricted in the EU to a concentration equal to or greater than of 0.1% by weight in any article. In addition, their use is limited to specific applications in the EU, China, and the US [6–8], generally in the transportation sector [9]. PBDEs have continued to re-enter circulation through the recycling of older products that contain these chemicals, leading to their presence in new product [10, 11]. The United Nations Environment Programme (UNEP) has estimated that 5 kt of PBDEs could end up in the recycling process and reappear in plastic articles [12]. There are also concerns about the unintentional formation and release of brominated dioxins and furans from these brominated flame retardant-containing (BFRs) plastics [13, 14]. The frequent hand-to-mouth activities of young children create a pathway for ingesting such chemicals from toys. Due to their faster metabolic rates, immature organ systems, rapid growth rates of organs and tissues, and high surface area-to-weight ratios, children are more vulnerable to these contaminants than adults [15, 16]. Lower IQ, hyperactivity, and behavioural and learning disorders have been linked to PBDE exposure in children [17–19]. These health problems resulting from general endocrine disrupting chemical exposures are estimated to cost the EU about €157 billion annually, which is equivalent to 1.23% of the EU's GDP [20].

The EU has established the Toy Safety Directive (TSD) (2009/48/EC), which prohibits or restricts the use of certain hazardous substances and mixtures in toys, to reduce risks to children. Although PBDEs are not specified under the TSD, the EU has adopted certain regulations to reduce their contamination in new plastic products. One regulation specifies that waste articles like electrical plastic casings containing PBDEs above the Low Persistent Organic Pollutant Content Limit (LPCL) of 500 μg/g can only be recycled into new products if its POP contents have been destroyed or irreversibly transformed [21]. In addition, an Unintentional Trace Contaminant (UTC) limit of 10 μg/g each for tetra-, penta-, hexa-, hepta-, and deca-BDE formulation has been set for new plastic articles [22, 23].

There are insufficient data to determine whether plastic toys sold in the EU market comply with these regulations. Of 3548 records in the Safety Gate database flagging chemical hazards in non-food products since 2005, only seven products were flagged for PBDEs (Table S1). The low levels of alerts for PBDE content in children's products and toys can give the impression that this is of limited concern. However, several studies that have investigated BFR content in children's toys contradict this. One of these investigations reported the BFR levels in two toys in the United Kingdom to be above the proposed limits of 500 μg/g [24], while another reported PBDEs in five toys on the European market to be above the previous LPCL of 1000 μg/g [25]. In this study, we investigated if toys marketed in Europe contain PBDEs that comply with EU directives. Our aim was to assess the safety of currently used children's toys in relation to PBDEs and understand the implications of these chemical in the products. We also discussed the challenges that may be responsible for the sale of non-compliant children's toys in the EU market from the viewpoint of the circular economy concept. Our analysis, linking measured contamination in toys with the factors driving this contamination, can provide insight into what actions can be taken to ensure the safety of consumer products and protect public health within the framework of the circular economy.

Materials and methods

Sampling and screening for Br by XRF

Eighty-four children's toys were obtained in France between November and December 2022. Fourteen toys were purchased from online retailers, 67 from large international retailers at outlets in France, and three toys were purchased second hand. These toys were randomly selected, with considerations of price and accessibility. All samples analysed were purchased new except a phone, scout mask, and children's chair. To prioritize the PBDE analysis, toys were initially screened for Br mass fractions with a SCiAps X-200 X-ray fluorescence (XRF) analyzer. Before analysis, each toy was disassembled into parts, and the Br content was measured by placing the instrument sensor as flat as possible on the toy's surface for 5 s. The screening threshold for Br content was set at 500 μg/g and only samples ($n = 11$) above this limit were selected for further destructive chemical analysis (Table S2).

Analysis of PBDEs

The 11 toys with Br content >500 μg/g were further analysed to quantify PBDE concentrations. PBDE standards were purchased from Wellington Laboratories (CA). Only the plastic components of the toys were analysed, with exception of the chair, where the synthetic fabric was analysed. Toy samples were homogenized by cutting

Table 1 Results for PBDEs in toys from the French market

	BDE-28	BDE-47	BDE-66	BDE-99	BDE-85	BDE-100	BDE-153	BDE-154	BDE-183	BDE-209	Σ_{10}PBDE
Rifle	0.012	0.085	<LOD	0.0457	<LOD	0.004	4.04	0.384	6530	8400	14,935
Pistol 1	0.021	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	6800	6840	13,640
Pistol 2	0.003	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	2290	9220	11,510
Phone	<LOD	0.001	<LOD	0.001	<LOD	<LOD	0.02	0.002	0.122	123	123
Combat mask	0.003	0.011	0.003	0.009	<LOD	0.001	0.202	0.022	1.12	3030	3031
Purse handle	0.011	0.125	0.019	0.17	0.012	0.019	<LOD	<LOD	14,100	9380	23,480
Radar	0.003	0.009	0.004	0.01	0.002	0.001	0.188	0.019	1820	6880	8700
Car fenders	0.027	0.081	0.014	0.059	0.005	0.007	0.925	<LOD	4210	4400	8611
Car bumper	0.023	0.071	0.011	0.053	0.003	0.006	0.952	0.098	3030	3160	6191
Scout mask	<LOD	0.0001	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	NA	0.0002
Chair fabric	<LOD	0.0001	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.0006	NA	0.0007
DF	**73**	**82**	**45**	**64**	**45**	**55**	**55**	**45**	**91**	**81**	**100**
Median	**0.003**	**0.009**	**<LOD**	**0.009**	**<LOD**	**0.001**	**0.02**	**<LOD**	**2290**	**4400**	**8611**
Range	**<LOD to 0.027**	**<LOD to 0.125**	**<LOD to 0.019**	**<LOD to 0.170**	**<LOD to 0.012**	**<LOD to 0.019**	**<LOD to 4.040**	**<LOD to 0.384**	**<LOD to 14,100**	**<LOD to 9380**	**0.0002–23,480**

Concentration in µg/g and detection frequency (DF) in %. <LOD indicates below limit of detection

into small chips (<3 mm), frozen using liquid N_2, and homogenized in a ball mill at 30 Hz for 2 min (Retsch, DE). 200 mg of homogenized sample was spiked with ^{13}C-labelled internal standards (1 ng of ^{13}C-BDE-28 to -183 and 5 ng ^{13}C-BDE-209), placed in 20 mL EPA vials and sonicated three times for 20 min in 5 mL *n*-hexane. The extract was evaporated under a gentle nitrogen stream and cleaned using H_2SO_4 modified silica (44%, 8 g) and 1 g Na_2SO_4 in an open tubular column; compounds were eluted with 40 mL *n*-hexane: dichloromethane (1:1 v/v). The eluate was reduced in volume by a nitrogen stream in a SuperVap apparatus (FMS, USA), transferred into a GC vial, and spiked with recovery standards (1 ng BDEs-77 and -138). Instrumental analyses were performed by gas chromatography–mass spectrometry (GC–MS) on a 7890A GC (Agilent, USA) equipped with a Rtx-1614 column (15 m × 0.25 mm × 0.10 μm) (Restek, USA) coupled to an AutoSpec Premier MS (Waters, Micromass, UK). The high-resolution mass spectrometer (HRMS) were operated in EI + mode in a resolution of >10,000 [26, 27].

Quantification validation

The RECETOX Trace Analytical Laboratories are accredited for standard sampling and analysis methods CSN EN ISO/IEC 17025 by the Czech Institute for accreditation, and PBDE methods have been previously applied to plastic polymer samples [26, 27]. Method recoveries were tracked with spike-recovery tests, and recoveries ranged from 81% to 113% (Table S3). All laboratory equipment was washed in an alkali solution, rinsed and baked at 450 °C for 5 h. Three laboratory blanks were analysed alongside the samples, and their average concentration was subtracted from the final concentration of individual PBDEs in each sample. Blanks and detection limits are listed in Table S4. Data for BDE 209 are affected by substantial uncertainty, as most of the samples contained very high amounts of BDE-209, in a few cases saturating the detector, therefore preventing quantification. As a result, the accredited isotope dilution method could not be used for quantification for BDE-209. Concentrations of BDE-209 in the high-concentration samples were calculated using external calibration (Samples numbers 1–9, Table 1). Samples were therefore diluted by a factor 500–1000 and 50 μL of ^{13}C extraction standard (^{13}C BDE 209) was added, followed by nonane up to a final volume of 100 μL. Diluted samples were re-analyzed, and results were recalculated based on the respective dilution factor. Results of quantifications for BDE-209 were not recovery corrected, and the results are likely to be underestimated. BDEs-28 to -183 were quantified by isotope dilution and are therefore adjusted for recoveries.

Results and discussion

Compositional profile of PBDEs

The concentrations and profile of PBDEs measured in the different toys are presented in Fig. 1 and Table 1. All samples had some detected PBDE content, and BDE-183 was detected in all samples except the scout mask. Σ_{10}PBDEs concentration ranged from 2×10^{-4} to 23.5 mg/g (median: 8.61 mg/g). The most abundant PBDE was BDE-209, with a median concentration of 4.40 mg/g (< LOD to 9.38 mg/g), accounting for an average of 66% of PBDEs in all samples (Fig. 1). BDE-183 was the second most abundant, with a median concentration of 2.29 mg/g (<LOD to 14.1 mg/g), accounting for 34%. Eight of 11 toys had very high concentrations of BDE-209; up to 1% BDE-209 in the purse handle. The maximum concentration of BDE-209 in our samples was more than 200,000 times higher than those reported in previous studies for polymeric children's play mats in China [28], 60 times higher than those in hard plastic children toys in Belgium [29], two to four times higher than those found in children's plastic toys in UK [24], and China [30], and comparable to BDE-209 in food contact articles from EU markets [25] and a selection of black and painted plastic products obtained internationally [5] (Fig. 2). The maximum concentration of BDE-183 found in the purse handle (14,100 μg/g) was 2 million times higher than the levels found in play mats in China [28] and 30 to 50 times higher than those found in toys in the UK [24], Belgium [29], and China [30].

The Σ_{10}PBDEs concentrations reported in this study are among the highest reported for children's plastic toys around the world, and this is a call for concern. An association has been made between playing with plastic toys and PBDE levels in hand wipes of children [31] and given the extremely high levels of PBDEs in a subset of toys, young children are at risk of exposure via ingestion and skin contact. There is no functional reason for the presence of Deca-BDE in children's toys. Four samples: pistol 1, pistol 2, rifle, and purse handle, had Σ_{10}PBDEs concentrations over 1% by mass. The highest was the beaded handle of a toy purse which contained a concentration of 2% BDE-209. The remaining products contained PBDEs, but at levels below 2%. PBDE levels below 2% do not impart substantial flame retardancy and suggest that PBDEs were not intentionally added [32, 33]. Rather, the presence of high levels of BDE-209 suggests the direct use of recycled e-waste plastic materials in producing children's toy parts. Some electronics casing uses very high concentrations of FRs, in particular TV casing, with Deca-BDE reported at levels from 40 mg/g up to 20% [34–37]. The use of recycled e-waste plastic in new items has previously been noted [24, 29, 30], including in a recent study by the Health and Environment Alliance (HEAL) [38]. However, the on-going

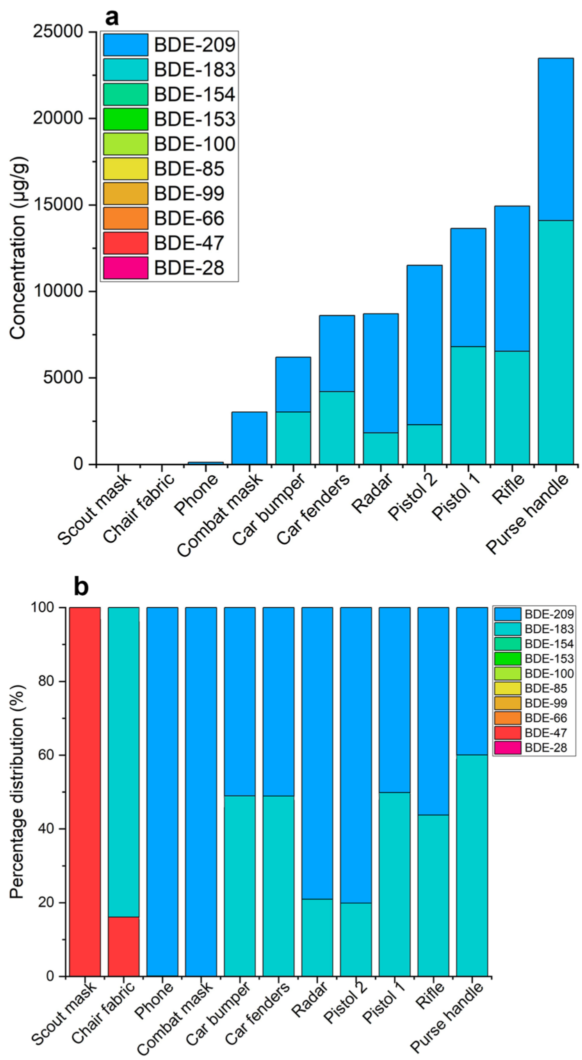

Fig. 1 **a** Concentration in µg/g and **b** percentage distribution of PBDEs in children's toys purchased from France

presence of extremely high levels detected in a subset of toys emphasize that greater attention is needed. The second highest concentrations were found for BDE-183, which is a component in the BDE-209 technical mix, as well as a possible degradation product, so its origin may be closely linked with Deca-BDE. Commercial Deca-BDE mixtures typically contain ≥97% BDE-209, with the remaining 2–3% consisting of minor amounts of nona- and octa-BDEs (≤1% BDE-183), while commercial Octa-BDE mixtures contain between 13% and 42% BDE-183 and 11–22% BDE-197 [39]. The exact composition of the minor BDEs depends on the specific manufacturing process and the purity achieved [40]. It has been reported that about 90% of commercial Deca-BDEs and 70% of commercial Octa-BDEs are found in electronic plastic casings [41, 42]. The presence of high levels of BDE-183 in our samples—sometimes comparable to or exceeding those of Deca-BDE (as seen in the purse handle and pistol 1) suggests two possibilities: (1) the use of Octa-BDE-containing waste plastics in toy manufacturing or the possible debromination of BDE-209 to BDE-183 during plastic extrusion or (2) regranulation at high temperatures during the recycling process [43–45]. Although not specifically quantified, we also noted the presence of other octa- and nona-BDE congeners in the samples (examples in Figures S1–S3), attributed to their presence either as minor components of the technical mixtures and debromination during recycling.

All samples analysed except the phone, scout mask and the chair fabric exceeded the EU's LPCL of 500 µg/g for the concentration of Σ_{10}PBDEs by 6–47 times. In addition, nine of the 11 samples exceeded the UTC limits of 10 µg/g for Deca-BDE by 12–800 times, while seven of the 11 samples exceeded the same limit for Hepta-BDE by 180–1400 times. According to Regulation (EC) No 850/2004, if a plastic fraction contains POPs at a level above the stipulated regulatory limits, then such plastic should either be destroyed, the substance of interest transformed, or the plastic subjected to authorised treatment that includes (1) physicochemical treatment, (2) incineration by land, and (3) used as a fuel to generate energy [46]. According to this directive, eight of the children's plastic toys analysed in this study should be subjected to the aforementioned procedure and not used or sold to the public.

Moreover, a comparison with values from this, and other recent studies suggests that awareness of the potential contamination due to recycling of PBDE-containing plastics has not led to changes in practices or reduced levels; rather the highest levels reported are from this study and other recent studies (Fig. 2).

The Br mass fractions obtained by XRF analysis ranged from 0.655 mg/g in combat mask to 213 mg/g in scout mask (Table S2). Two samples (scout mask and chair fabric) had the highest levels of Br but lowest levels of PBDEs—this suggests that these items contain other brominated compounds that were not target analytes in this study (e.g., alternative BFRs or other organobromine compounds). Because PBDEs may only make up a small portion by mass of the total Br, it is expected that the total Br content in all samples from this study will be higher than the PBDEs. However, no significant correlation was observed between Br and Σ_{10}PBDEs. Moreover, the mass fraction of Br was substantially lower than the concentration of BDE-209 in eight of the analysed toys, which could be an artifact of measurement calibration or inhomogeneity in the toy parts; a study on BFRs in toys

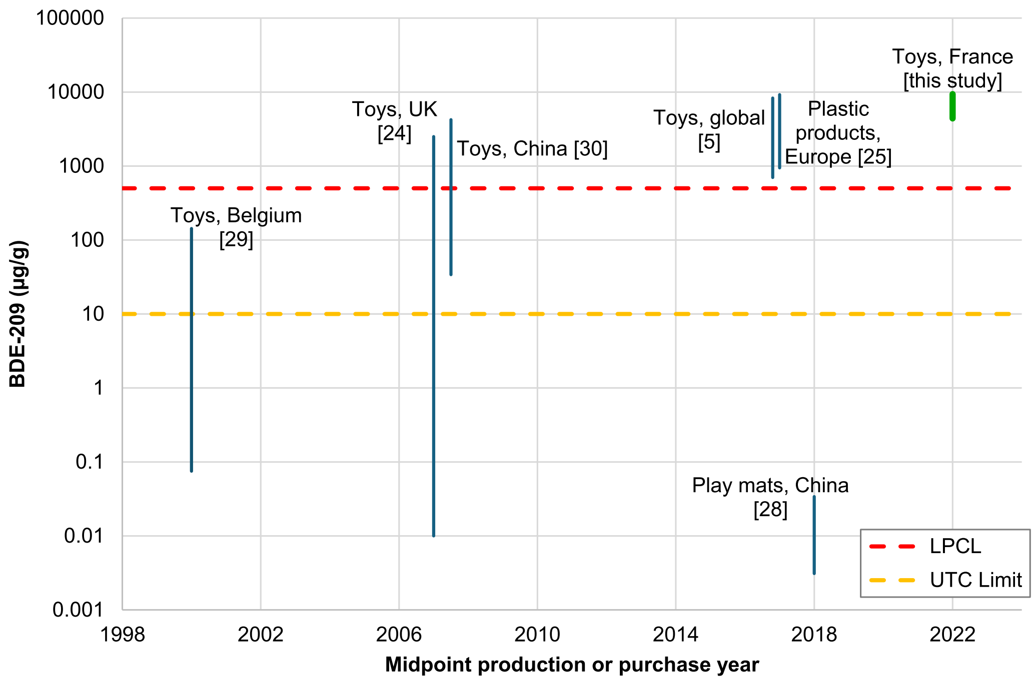

Fig. 2 Levels of unintentionally added BDE-209 in consumer products. Data are from Ionas et al. [29], Fatusin et al. [24], Chen et al. [30], Kajiwara et al. [5], Guzzonato et al. [25], Peng et al. [28], and this study (in *green*). The *blue bars* span from the study median to maximum values, and dates correspond to the midpoint of the sample production or purchase dates, according to the information given in the publication. Minima are not displayed as in most studies minima were below detection limits

from the UK notes that XRF measurements returned substantially different values from different locations in the same toy item [24].

Challenges in enforcement and a way forward

This study has shown that children's toys in the French market contain PBDE at concentrations that far exceed regulatory limits. This suggests that the toys were made directly or indirectly from flame-retarded plastics, such as waste plastics from vehicles, building materials, or end-of-life electronic materials. There are several factors that may have led to the sale of non-compliant toys in EU markets, which poses challenges to market surveillance and custom authorities. Here, we discuss four main challenges and potential solutions.

Regulatory gaps

There are three potential reasons for the presence of toxic compounds in toys: either a lack of regulation, existing regulations are being violated, or loopholes in current regulations are being exploited [15]. In this case, we suspect the latter two reasons are more likely. In the EU, consumers can purchase toys from non-EU websites that were not originally intended by the manufacturer to be sold in the EU. Instead, these toys find their way into the EU market through various global distribution channels without a clear responsible stakeholder to ensure compliance with EU directives [47]. Non-EU economic operators may lack awareness of EU requirements or choose to disregard them. They often rely solely on manufacturer-provided information claiming compliance with EU standards. This loophole allows rogue traders to exploit these channels, selling non-compliant products at reduced prices to avoid the costs of meeting regulatory standards [47].

Several studies have indicated that recycling e-waste plastic is a significant source of hazardous chemicals, not just in toys but also in other plastic products [48–50]. Unfortunately, the fate and behaviour of these chemicals during recycling is still unknown [51, 52]. As a result, it is necessary for recyclers to segregate e-waste materials according to the Waste Framework Directive (WFD) (2008/98/EC), POP (2019/1021), and CENELEC requirements in order to avoid recirculation of hazardous substances [53–55]. The EU eco-design requirements are expected to enhance the reuse, dismantling, and recycling of e-waste. This will also help control the levels of hazardous chemicals in new plastic products [56]. Through the Circular Plastics Alliance, most EU countries have introduced recycling schemes for plastic materials. The EU requires member states to recycle 50% of their plastic material into new products by 2025, but this number still stands at 41% [57]. The relatively low amount of secondary raw materials (SRMs) generated slows the process to attain such a target and this emphasizes the need to boost the rate of recycling to reach the 2025 goal. However, the growing number of directives on products and waste recycling, as detailed in Barouta et al. [55] creates an unstable situation for investment in the circularity of e-plastics. Having numerous regulations for similar substances creates confusion that, in turn, hinders the rate of recycling [58]. The EU has established the 'One substance and one assessment' approach to address these challenges by creating a uniform hazard assessment. This approach ensures that recycled materials and virgin plastics are held to the same standards regarding the level of hazardous substances. This aims to improve the safety of SRMs and make it easier for them to be integrated into the market. However, most plastics will be excluded from the circular economy due to the high cost of removing legacy substances from e-waste plastics [59, 60]. Harmonizing regulations while adhering to previous directives is necessary to support investment in the circularity of e-plastics. Furthermore, the samples analyzed in this study are likely to contain polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs), as products with PBDEs often contain these compounds as byproducts [13, 61]. PBDD/Fs are expected to be added to Annex C of the Stockholm Convention [62], which will establish a legal and regulatory framework for countries to manage and eliminate these substances.

Rise of online marketplace

The rise of online marketplaces and e-commerce platforms have created new problems in product safety. A substantial fraction of non-compliant toys in the EU originate outside the European Economic Area (EEA) via online marketplaces, with only 4% of dangerous toys reported in Safety Gate originating from EU countries [47, 63]. Many toys deemed unsafe and recalled from EU markets can still be found online, often through multiple sellers. A study by the Toy Industries of Europe (TIE) found that 97% of the 200 toys purchased from third-party online sellers did not comply with the EU toy safety regulations, and 76% of those had defects that made them harmful to children [64]. Members of the European Parliament have also expressed concerns about the non-compliance of toys sold online (E-000856/2019; E-003979-18). At a global scale, online sales were estimated to have increased by 21% in 2021 to 2022. In 2020, approximately 44% of large companies engaged in online sales, accounting for approximately 27% of their total sales revenue [65]. This indicates that a significant portion of these companies utilized the internet as a platform to sell their products, contributing substantially to their overall revenue. This process has led online traders to introduce toys into the EU market that meet the legal requirements of other manufacturing countries but do not comply with those of the EU. The disparity in regulatory standards may significantly affect the safety of toys sold in the EU [66]. A significant majority of respondents to public consultation—70% of consumers/environmental groups, 80% of public authorities, and 67% of industry representatives—highlighted the absence of specific regulations governing online sales as a barrier to the effectiveness of the TSD [47]. The TIE has called for more EU regulations to hold online vendors accountable for selling unsafe products [64]. Since the TSD gives manufacturers the sole responsibility of performing a complete conformity assessment on toys, enforcement agencies must then ensure that manufacturers correctly disclose composition of all toy products before they are imported into the member states. Additional policies are needed to cover up gaps in cross-border enforcement, and stricter sanctions are required for toy manufacturers who fail to adhere to regulations and safety standards.

Technical and economic challenges in plastic recycling

One of the likely reasons for the high level of PBDEs in our study is the direct recycling of heavily flame retarded plastics (e.g., e-plastics) into toy components. Before plastic material can be recycled back into new products, the plastic material needs to be treated with appropriate technologies to reduce the levels of toxic chemicals to standard limits. Removing such chemicals before recycling requires a sophisticated and expensive purification process [67]. The cost associated with this purification process from collection to actual processing is very high, even higher than the cost of producing virgin plastics. As of 2024, recycled polyethylene terephthalate costs around 1000 USD per tonne while a virgin plastic around 800 to 900 USD per tonne [68]. Meanwhile, screening waste stream plastics for hazardous substances is highly challenging. The most common analytical techniques for separating plastics containing BFRs from waste streams are XRF, near-infrared spectroscopy, and density separation [10, 69]. However, achieving the POPs threshold of 10 ppm for SRMs is unrealistic because industrial XRF cannot provide validated measurements for concentrations below 1000 ppm [55, 58]. Accurate quantification at ppm levels requires expensive analytical instruments like GC–MS; small-scale recyclers may not find selling SRMs to be a profitable business. Moreover, implementing analytical methods for PBDEs and other toxic chemicals in plastics is another challenge due to the complex matrices and diverse polymer compositions of plastics. The intricate extraction and clean-up processes required to remove interfering substances, along with the potential degradation products from various plastic types, further complicate the analysis. Non-target screening approaches are costly, require specialized instrumentation and data analysis, and are not routinely implemented in product screening [70, 71]. Robust analytical methods are needed to effectively monitor PBDEs and other hazardous chemicals in toys, particularly those from non-EU countries, to ensure proper enforcement and safety.

Supply chain complexities

The complexity of global toy production systems, which characterised by large and complex supply chains with downward pressure on prices creates further challenges in ensuring safe toys. Most children's toys sold in the EU are manufactured in China, where prices are as low as one-fifth of toys made in Europe [72]. The increasing demand for low-cost toys creates pressure on toy manufacturers, which may compromise toy quality through the use of cheap and potentially hazardous materials for production [15]. As a result, manufacturers may struggle to ensure compliance with EU regulations and global standards. Meanwhile, a physical assessment of a toy is insufficient to show if a toy complies with EU regulations; a major determinant is the chemical composition of the products. Unfortunately, most composition data are unavailable and can only be provided by the product manufacturers, Moreover, the content of the recycled plastic may not be known to toy manufacturers beyond the base polymer. Ensuring the traceability of a toy throughout the entire supply chain simplifies and enhances market surveillance. An effective traceability system helps market surveillance authorities identify and track down economic operators who have placed non-compliant toys on the market [47]. The proposed EU digital product passport (DPP) will help enhance traceability and transparency in the toy supply chain [47], by facilitating the sharing of essential product information related to sustainability and circularity (including those specified in Annex III of the Ecodesign for Sustainable Products Regulation proposal), across all the relevant economic actors.

Implications for the circular economy

In an ideal circular economy, plastics are made, used, reused, and recycled back into the system. This ensures that no materials are lost, no toxic chemicals are present, and every part is used as efficiently as possible. However, this system faces challenges due to potential presence of toxic chemicals in plastics like BFR, as highlighted in this study. Recycling toxic materials like e-waste without appropriate treatment hinders the circular economy. Plastic recycling should not be done when the original product contains high levels of hazardous chemicals. The EU has set ambitious targets for collecting and recycling e-waste through the WFD and the Waste from Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU. In addition, the European Commission has adopted a new Circular Economy Plan as part of the European Green Deal. This provides strategies for better product design, promotes circular economy processes, encourages sustainable consumption, and aims to prevent waste while keeping resources in the EU economy for as long as possible. It is imperative that this plan together with regulations and other EU initiatives, be followed and enforced by stakeholders in the plastic industries. Failure to do so not only puts children's health at risk but also jeopardizes investments in the circular economy.

Conclusion

The findings of this study show that some children's toys on the market in France contain extremely high PBDE concentrations. The PBDE levels were far above the regulatory limits, suggesting that the toys were directly or indirectly produced from flame retarded plastics, such as waste plastics from vehicles, building materials, or end-of-life electronic materials. The presence of such levels of PBDEs may pose significant risks to children upon exposure. Given the common European market and global nature of plastic toy manufacturing, we expect this level of contamination mirrors across EU markets, and likely, most international markets. The occurrence of non-compliant toys in the EU market are primarily attributed to gaps in regulations, inadequate legislation for recycled plastics, the rise of online sales, complexities in global and national supply chains, and economic challenges. Failure to address these issues will hinder the efforts of the plastics industry to transition into a circular economy. To this end, more actions are needed to cover gaps in cross-border enforcement, and stricter sanctions are required for toy manufacturers who fail to adhere to regulations and safety standards.

Abbreviations

BFR	Brominated Flame Retardant
DPP	Digital Product Passport
EEA	European Economic Area
EU	European Union
FR	Flame Retardant
HEAL	Health and Environment Alliance
HRMS	High-Resolution Mass Spectrometer
LPCL	Low POP Content Limit
PBDEs	Polybrominated Diphenyl Ethers
POP	Persistent Organic Pollutants
SRMs	Secondary Raw Materials
TIE	Toy Industries of Europe
TSD	Toy Safety Directive
UNEP	United Nations Environment Programme
UTC	Unintentional Trace Contaminant
WEEE	Waste from Electrical and Electronic Equipment
WFD	Waste Framework Directive
XRF	X-Ray Fluorescence

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-024-00999-2.

Additional file 1.

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Author contributions

CO: data curation, writing, reviewing and editing. LM: conceptualization, supervision, data curation, writing, reviewing and editing. OA: methodology, data curation, and writing, reviewing and editing. PK: methodology, data curation, and writing, reviewing and editing. PP: methodology, data curation, and writing, reviewing and editing. MB: conceptualization and sampling. All authors read and approved the final manuscript.

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Availability of data and materials

Data are provided within the manuscript or supplementary information files.

Declarations

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