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Current background human exposure to polybrominated diphenyl ethers: a review

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Abstract

Introduction. Polybrominated diphenyl ethers (PBDEs) have been used as flame retardants for years, until they were banned following their inclusion in the Stockholm Convention on Persistent Organic Pollutants (2001). The chemical and physical properties of PBDEs determine their ability to spread and accumulate in the environment and bioaccumulate along food chains. More than 90% of total human exposure to PBDEs comes from food. Chronic exposure to PBDEs can cause hepatotoxic, thyrotoxic, neurotoxic, genotoxic, immunotoxic, developmental toxic and potential carcinogenic effects in humans. Although the ban began decades ago, PBDEs are still present in various environmental matrices.

Method. This review aims to assess the current picture of human exposure to PBDEs by collecting and evaluating data from human biomonitoring studies available worldwide over the last 10 years.

Results and conclusions. The analysis of chosen papers suggests that levels of BDE-47, BDE-99, BDE-100 and BDE-153 have a global unclear trend, depending on the geographical area in question in the last ten years.

Key words
- human exposure
- PBDEs
- flame retardants
- general population
- concentration levels in biological fluids

INTRODUCTION

Polybrominated diphenyl ethers (PBDEs) are a family of 209 congeners that differ in the number and position of bromine atoms attached on the two aromatic rings, produced by the bromination reaction of diphenyl oxide. They are stable compounds characterized by boiling temperatures ranging from 310 to 425 °C and low vapour pressures with values ranging from approximately 10^{-1} Pa for mono-brominated to 10^{-13} Pa for decaBDE (BDE-209) at 298.15 K; they are also highly lipophilic substances whose solubility in water is extremely low and decreases with increasing bromination degree. The n-octanol-water partition coefficient, log (K_{OW}), varies between 4.28 and 9.9 [1].

The most important industrial use of PBDEs has been as flame retardants, with the aim of reducing the flammability of various materials used in everyday products. PBDEs have been widely incorporated into items like foam cushioning and fabrics in sofas/chairs and plastics for electrical and electronic equipment such as TV monitors, computers, and printers [2-4].

The most widely used flame retardants for years were mixtures of PBDEs containing mainly tetra-, penta-, octa- and deca-brominated congeners, until they were banned following their inclusion in the Stockholm Convention on Persistent Organic Pollutants [5]. Among the aforesaid congeners, deca-PBDE was the most widely produced one, accounting for approximately 75% of total PBDEs production [6]. Due to their wide use, PBDEs were released into the environment during industrial manufacturing, use of end products, and nowadays, they can be still liberated in the environment during waste management operations [7-9].

With the implementation of Directive 2002/95/EC (known as RoHS – Restriction of Hazardous Substances) [10], PBDEs use in electrical and electronic equipment has been discontinued; various measures have been adopted to regulate or phase out PBDEs in several countries, leading to their ban in the EU in 2004 [11]. The replacement of PBDEs with other flame retardants primarily driven by concerns regarding their persistence, bioaccumulation capacity and toxicity [12].

The chemical and physical properties of PBDEs determine their ability to spread and accumulate in the environment and bioaccumulate along food chains. Bioaccumulation capacity is congener-specific, and

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generally, congeners with a lower degree of bromination can bioaccumulate to a greater extent than those with a higher degree of bromination. Highly brominated congeners, such as deca-BDE, are found mainly in environmental matrices such as sediments and soils, while they are difficult to detect in biota [13]. This indicates that the bioaccumulation of highly brominated PBDEs congeners (particularly deca-BDE) is relatively low. In mammals, including humans, PBDEs accumulate mainly in adipose tissue, the gastrointestinal tract and the liver.

The general population's exposure to PBDEs (*Figure 1*) occurs mainly through the diet, especially from animal sources such as fish, meat, eggs and fats. Specifically, it has been estimated that in the general population, more than 90% of total human exposure to PBDEs comes from food [14, 15]. Also, inhalation of household dust seems to be an important route of exposure to these contaminants [4, 16, 17]. In addition, for newborn and infants, relevant exposure sources are breast milk consumption [18-20], and exposure through the placenta during the prenatal life period [21-23], and household dust [4]. Four congeners (PBDE-47, -99, -153, and -209) were most frequently found in the environment and in human biological media: for them toxicological studies suitable for dose response assessments were available [24]. For the identical reason, the same ones were also taken into consideration by the European Food Safety Authority [25, 26] to develop advice for human consumption. Chronic exposure to PBDEs can cause hepatotoxic, thyrotoxic, neurotoxic, genotoxic, immunotoxic, developmental toxic and potential carcinogenic effects in humans [15, 27]. The International Agency for Research on Cancer (IARC) classified PBDEs as "probably carcinogenic to humans" (Group 2A) based on mechanistic similarities to polychlorinated biphenyls [28].

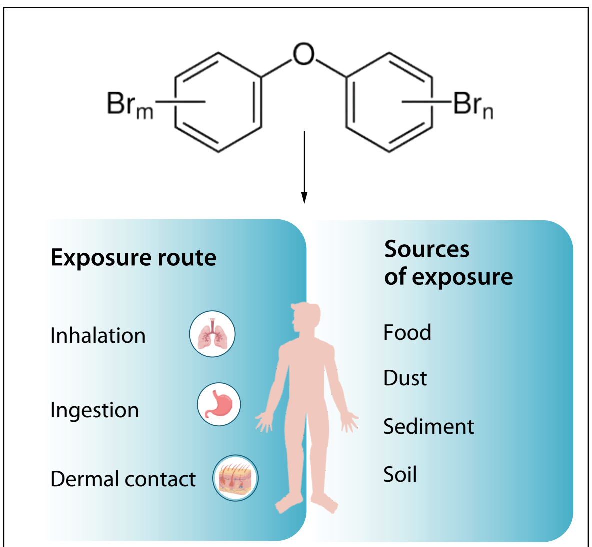

Figure 1
Routes and sources of human exposure to polybrominated diphenyl ethers (PBDEs).

Despite the restrictions, PBDEs are now mainly found in bulky waste and municipal waste consisting of electrical and electronic equipment and plastics, for which recovery and recycling activities can promote their re-release into the environment [4, 7-9]. For this reason, it is extremely important to continue monitoring the presence of PBDEs in the environment and in humans. The best way to assess the extent of human exposure to PBDEs is through human biomonitoring, i.e., by measuring their concentration in tissues or biological fluids. The best matrix for assessing the internal dose of this type of compound is human blood/serum, although they can also be measured in other matrices, including breast milk. Among all matrices, blood is widely used and is considered the ideal matrix for most chemicals due to its contact with the whole organism and its equilibrium with organs and tissues where chemicals are stored. In the human body, PBDEs accumulate mainly in adipose tissue from which they can pass into plasma or serum lipids and from there reach tissues and target organs [29]. PBDEs have been measured in human serum in various countries around the world. This review aims to assess the current picture of human exposure to PBDEs by collecting and evaluating data available worldwide over the last 10 years.

METHOD

Bibliographic research and study selection

In this review, PubMed, Google Scholar, ACS Publications, and Science-Direct databases were consulted. The search results were updated on November 10, 2025. Keywords including "human exposure, PBDEs or polybrominated diphenyl ethers, flame retardants, general population, levels, women, men, breast milk or human milk, blood, serum, pregnant women, PBDE-47, PBDE-99, PBDE-100, PBDE-153, PBDE-209" were considered involving 2-3 keywords for each search.

This review aims to assess the current exposure to PBDEs of the general population worldwide. Due to restrictions on the use of PBDEs, the number of exposure assessment studies is declining. The phase-out, which began with voluntary manufacturer actions in the early 2000s [30] and was later reinforced by regulations (the Stockholm Convention and the EU's POPs Regulation) [5], is expected to have led to a decrease in human exposure to PBDEs in recent years. For this reason, we have considered all geographical areas of the planet, from the USA to China, from India to Europe, from Africa to Oceania. We also included studies that assessed exposure to multiple contaminants (e.g., polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins and -furans (PCDDs/PCDFs), hexabromocyclododecane (HBCDD), per- and polyfluoroalkyl substances (PFASs), etc.). Further inclusion criteria were: (1) papers published from 2020 to 2025 in scientific journals; (2) studies on general population; (3) studies with a sampling year from 2015 onwards; (4) studies reporting results on lipid weight.

Upon initial review, a total of 48 studies were deemed valid for our purposes. After further screening and evaluation, 13 final studies were selected. The workflow was also presented in *Figure 2*. Most of the selected stud-

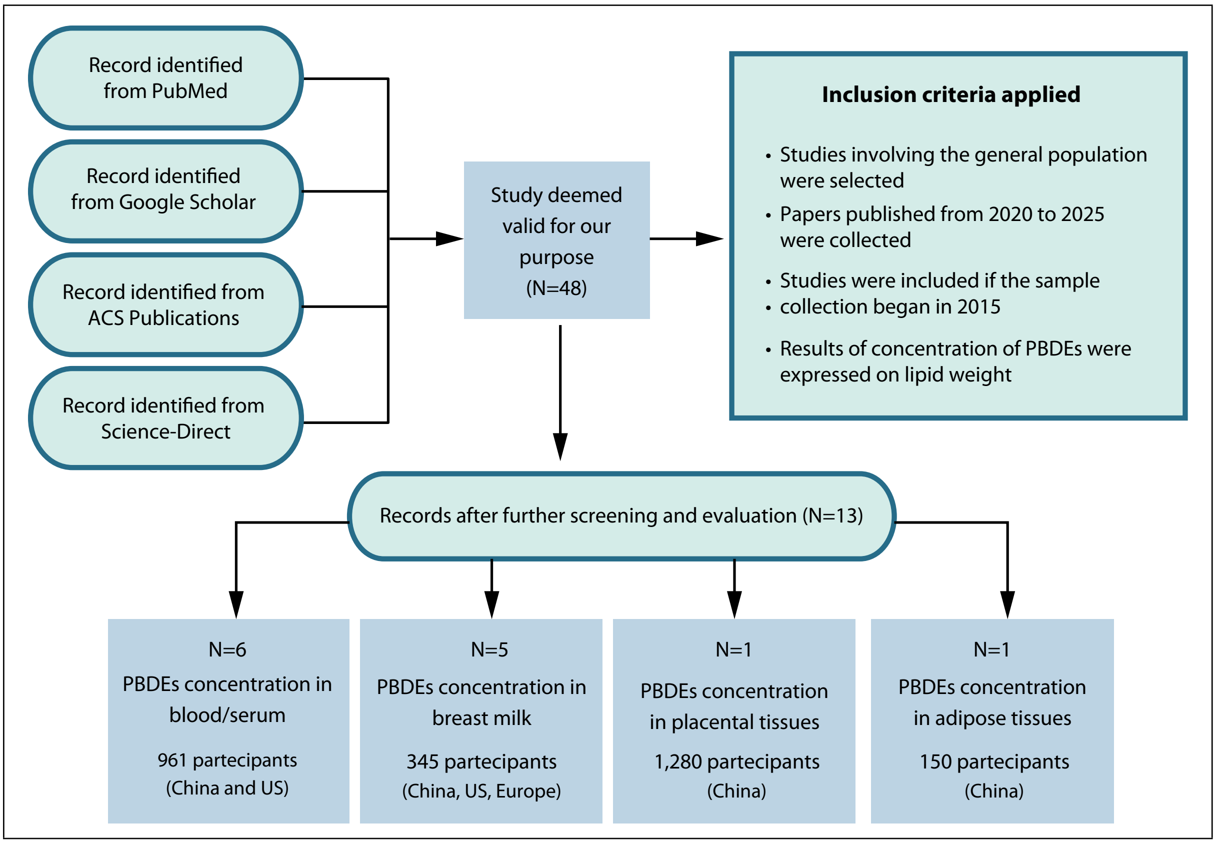

Figure 2
Reference scheme for selecting polybrominated diphenyl ethers (PBDEs) biomonitoring studies.

ies were from China. We found that human serum and breast milk were the most analyzed matrices. PBDEs were also detected in placenta and adipose tissue samples. Unfortunately, no articles relating to exposure of the male population were found that met our selection criteria. Data relating to the male population only were usually included in studies on the general population. However, in this paper we consider the study conducted by [16] on males, despite it was published in 2019, to collect some indicative information about this group of population.

In our study, we selected PBDE-47, -99, -100, and -153 for analysis because they were the most frequently quantified and reported as individual congeners in the available literature. No quantitative meta-analysis was conducted in this review paper.

RESULTS

Due to the heterogeneity of the papers (samples, countries, laboratories, detection method and data processing), we present a summary of the collected data. The PBDEs levels, year and country of sampling, sample size, and sampling period were reported in *Table 1*, where studies are listed in ascending order by sampling date. Only studies carried out by methods based on high sensitivity and specificity techniques, and in which analytical reliability was specifically warranted, were taken into consideration. The arithmetic mean, median, and geometric mean concentrations of PBDEs were summarized and compared to assess the presence of these compounds in human matrices. Minimum and maximum values, along with concentration ranges, were also reported when available. The median concentration was used for comparison to reduce the influence of skewed distributions. When the median value was unavailable, the geometric mean or arithmetic mean was used instead.

All studies were published from 2020 to 2025, except for [16], and samples were collected between 2015-2023. Eight of the studies exclusively sampled women of reproductive age [31-38]. Mixed male and female studies generally had wider age ranges [39-41]. As mentioned above, only one study concerned male exposure [16]. In collected data, PBDEs concentrations in blood/serum were reported in six studies [16, 32, 38-41], which included 961 participants from four countries (three from Asia and one from USA); levels in breast milk were reported in five studies [31, 33-36], which included 345 participants from five countries. In one study [36], PBDEs levels were measured in 1,280 Chinese placental tissues, while in another research [41] 150 adipose tissue samples were analyzed in female patients undergoing plastic surgery from Hospital in China.

Globally, the total concentrations of the four selected PBDEs Σ_4[PBDE-47, -99, -100, -153] ranged from 0.10 to 26.12 ng/g on lipid weight (lw) in blood and from 0.03 to 3.90 ng/g lw in breast milk. Within these totals, PBDE-153 was the highest contributing congener in both blood and breast milk while the lowest contributing congeners were PBDE-99 in blood and PBDE-100

Table 1
Summary of PBDEs biomonitoring data from international studies. The following information is reported: article source, year and country of sampling, matrix and sample size, age of participants and their BMI, and concentration of PBDE-47, -99, -100, and -153

Year of sampling	Country	Matrix and number of samples	Age of participants (years)	BMI	PBDE-47 (ng/g lw)	PBDE-99 (ng/g lw)	PBDE-100 (ng/g lw)	PBDE-153 (ng/g lw)	Ref.
2014-2015	Colombia	Breast milk, 60	26.1±7.0	24.4±4.1	Mean±SD: 0.78±0.91 Range: 0.06-5.5 25th 50th 75th 95th: 0.28 0.50 0.94 2.26	Mean±SD: 0.28±0.47 Range: <LOD-2.28 25th 50th 75th 95th: 0.04 0.13 0.27 1.50	Mean±SD: 0.24±0.44 Range: <LOD-2.23 25th 50th 75th 95th: <LOD 0.09 0.20 1.25	Mean±SD: 0.14±0.2 Range: <LOD-1.12 25th 50th 75th 95th: 0.04 0.06 0.16 0.50	Torres-Moreno *et al.* 2023 [31]
2016	Laizhou Bay, north China	Serum, 172 adults (118 males and 54 females)	21-58 Mean: 36	17.4-34.1 Mean: 24.2	Median: 0.482 Mean: 1.84 GM: 0.607 Range: 5.50×10^{-2}-85.8	Median: 0.434 Mean: 2.53 GM: 0.600 Range: 3.10 $\times10^{-2}$-66.8	Median: 0.251 Mean: 1.69 GM: 0.333 Range: 2.20 $\times10^{-2}$-104	Median: 2.25 Mean: 4.65 GM: 2.62 Range: 0.147-104	Zhao *et al.*, 2021 (a) [39]
2014-2018	USA (California)	Serum, 506 pregnant women	32±5.4	–	Median: 10.9 Max: 364.3	Median: 4.1 Max: 141.3	Median: <LOQ Max: 90.2	Median: 9.59 Max: 232.1	Eick *et al.*, 2020 [32]
2016-2017	Qingyuan People's Hospital, China	Serum,76 adult males living in an e-waste area	37.5±8.6 20-50 years	23.74±2.81	GM: 0.95±2.30	GM: 0.55±1.64	GM: 0.28±0.62	GM: 3.32±4.93	Yu *et al.* 2019 [16]
2016-2018	Germany	Breast milk, 100	20-45 Median: 34	–	Median: 0.204 Mean: 0.314 Max: 0.122	Median: 0.062 Mean: 0.086 Max: 2.42	Median: 0.054 Mean: 0.076 Max: 0.419	Median: 0.378 Mean: 0.464 Max: 0.453	Fromme *et al.*, 2022 [33]
2018	Beijing, China	Breast milk, 105	20-40	–	Median: 0.0759 Mean: 0137 Min.: 0.0336 Max: 1.71	Median: 0.0344 Mean: 0.0468 Min.: 0.0091 Max: 0.296	Median: 0.0336 Mean: 0.0513 Min.: 0.00739 Max: 0.643	Median: 0.389 Mean: 0.527 Min.: 0.114 Max: 5.67	Zhao *et al.*, 2021 (b) [34]
2019	China	Adipose tissue of women, 150	35.91 ± 10.61 (21-84)	–	Median: 2.01 Mean: 2.72	Median: 0.43 Mean: 0.72	Median: 0.69 Mean: 1.03	Median: 26.12 Mean: 30.44	Zhang *et al.*, 2022 [41]
2019	USA	Breast milk, 50	24-42; mean: 35	–	Median:3.17 Mean: 14.1 Range: <0.46-347	Median:1.44 Mean: 7.5 Range: <0.3-207	Median:1.73 Mean: 14.2 Range: <0.3-313	Median:3.90 Mean: 10.8 Range: <0.68-131	Schreder *et al.* 2023 [35]
2019-2022	Zagreb, Croatia	Breast milk, 30	26-42	–	Median: <LOQ Max: 1.5	Median: 0.04 Max: 3.4	Median: <LOQ Max: 0.98	Median: 0.23 Max: 0.83	Jagic *et al.*, 2024 [36]
2020-2021	Zunyi, southwest China	Placental tissue, 1,280	27.3 ± 5.1	22.5±3.5	Median: 0.34 Min.: 0.02 Max: 67.5	Median: 0.53 Min.: 0.06 Max: 86.7	Median: 0.67 Min.: 0.06 Max: 57.6	Median: 1.00 Min.: 0.11 Max: 74.5	Liu *et al.*, 2024 [37]
2020-2022	Jiangsu province, China	Blood, 104 control group of pregnant women	30.1±3.1	22.5±3.7	Median: 4.39 Range: 0.45-153.99	Median: 0.10 Range: 0.06-7.55	Median: 0.11 Range: 0.06-4.27	Median: 0.17 Range: 0.10-7.17	Ma *et al.*, 2023 [38]
2022	Thailand	Blood, 26 control group of adults (7 men and 19 women)	46-68		Median: <LOQ Range: <LOQ-0.83	Median: <LOQ Range: <LOQ-2.33	Median: <LOQ Range: -	Median: <LOQ Range: <LOQ-0.38	Walaska *et al.*, 2024 [40]
2023	Mongolia, China	Serum, 77 agro-pastoralists (37 females and 40 males)	>64 Median: 72	Median: 26.6	Median: 0.38 Mean: 1.24 Range: ND-19.8	Median: 1.88 Mean: 3.44 Range: ND-17.5	Median: 1.87 Mean: 3.04 Range: ND-23.0	Median: 0.66 Mean: 1.25 Range: ND-6.8	Dalutai *et al.*, 2025 [42]

PBDEs: polybrominated diphenyl ethers; BMI: body mass index; SD: standard deviation; LOD: limit of detection; LOQ: limit of quantification; GM: geometric mean; ND: non-detect.

in breast milk, respectively. The selected studies reported data collected from 2,736 biological samples (serum/blood, breast milk, placental tissue, and adipose tissue) from the general population, aged 20 to 50, across various countries. Only in [39] and [40] an older population (46-80 years) was selected.

Figure 3 provides indication of relative differences between matrices and geographical regions: median blood/serum and breast milk PBDEs concentrations were reported in studies carried out in Asia, USA and Europe (Germany and Croatia). The four studies [33-36] analyzing breast milk showed PBDE-47 and -PBDE-153 to be the predominant PBDEs congeners. In milk samples PBDE-153 concentration was the highest value among all four congeners considered except for breast milk samples from Colombian women where PBDE-47 was the main congener [31].

A similar pattern was observed in two studies carried out in blood/serum samples: PBDE-153 was the major congener in early studies in China [16, 39]; subsequently, PBDE-47 was the major congener in other studies carried out in China by [38] and in USA by [32], respectively. Results showed that human exposure in male population seems to be like that of women [16]. In *Figure 3* we showed results in Mongolia [42] and Thailand [40] also. Patterns were different with a predominance of penta-PBDEs (PBDE-99 and -100). Despite the limited number of papers available, some considerations may be made: a decrease in PBDE-153 over time appears to be common to all matrices analyzed, except for adipose tissue in Chinese women where hydrophobic environmental chemicals, as PBDEs, tend to accumulate [43-45].

PBDEs total concentrations and proportions varied between Asia, USA, and EU regions as might be expected based on varied national usage of PBDEs flame retardants. In USA penta-BDE technical mix was more heavily used, whereas in Europe penta- BDE use was lower than that in the USA and penta- and octa-BDE were banned in 2004. These findings indicate that many factors such as regional PBDEs regulations, time of phase out of PBDE use, previous quantity of PBDE used, and half-life of congeners can be key factors in distribution and levels of analytes in human matrices. China implemented some restrictions on penta-BDE and octa-BDE in 2014 (https://www.mee.gov.cn/gkml/hbb/bgg/201404/t2014040 1_270007.htm), but deca-BDE products are not subject to any regulations.

DISCUSSION

This review aimed to assess the current picture of human exposure to PBDEs by collecting and evaluating data available worldwide over the last 10 years. A total of 12 studies met all our criteria; one study published before 2020 [16] was also considered to have information on male population. Despite the limited number of papers available, the number of samples analysed was substantial. Four congeners were selected because they are more frequently reported in the literature. China is the country with the highest number of studies: environmental contamination is a particular concern due to the production and utilization of deca-BDE products and to the concentration of PBDEs in certain areas near electronic waste disposal sites.

Several studies suggest that PBDE-47 and -99 have a decreasing trend in Asia, Europe and Oceania since 2004, except the North American region where a continuous increase was registered [46]. Although the three main commercial mixtures (penta-, octa-, and deca- PBDE) were included in the Stockholm Convention in 2004 [5], human exposure to PBDEs varied depending on congener-specific differences in metabolism and persistence in the body: the half-lives of deca- to

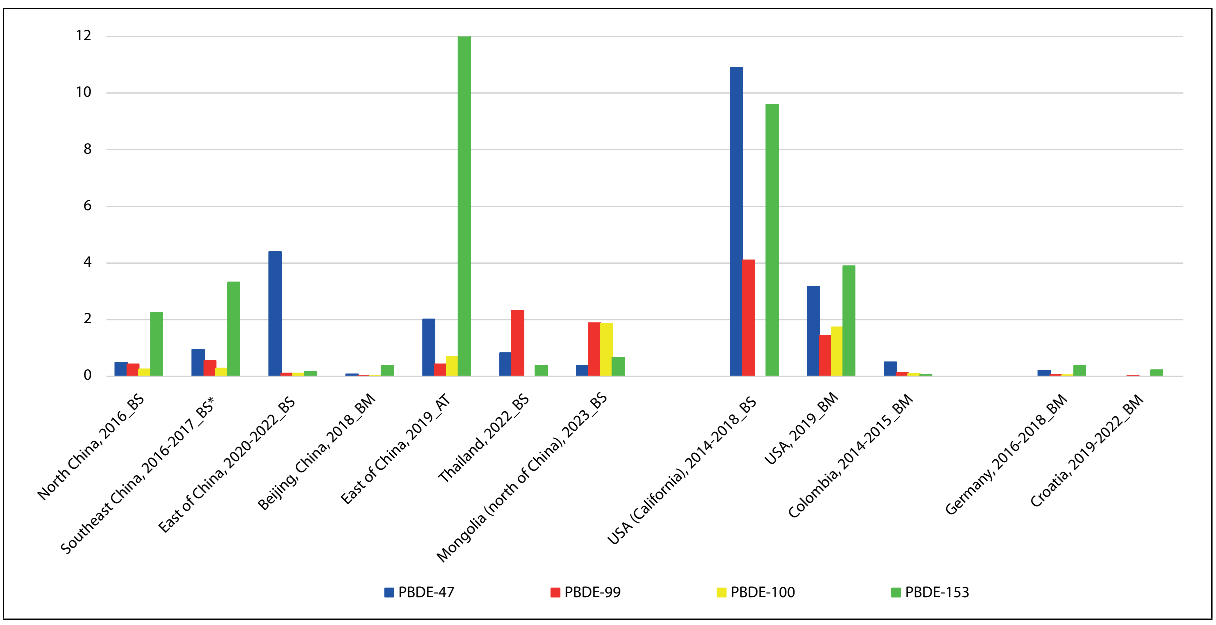

Figure 3
Median polybrominated diphenyl ethers (PBDEs) concentrations (ng/g lw) in blood/serum (BS), breast milk (BM), and adipose tissue (AT) from China, USA, and Europe studies over the period 2015-2022. Values * are geometric means.

hepta-BDEs in serum increased with decreasing number of bromine substituents [47]. In particular, PBDE-47 and -99 have human elimination half-lives of approximately 0.37-3 and 0.77-8 years, respectively [48-50], while the human elimination half-life of PBDE-153 is between 3.5 and 11.7 years [48-50]. The longer persistence suggests why PBDE-153 usually has higher levels than other congeners, especially after 2015. One of the main metabolic pathways is reductive debromination in which higher-brominated congeners are transformed into lower-brominated congeners. For the fully brominated BDE-209, the apparent half-life was as short as 15 days [47]. PBDE-209 undergoes reductive debromination to form lower-brominated congeners, including nona- and octa-BDEs [47]. Mörck *et al.* [51] found that up to 90% of a single oral dose of PBDE-209 is excreted via feces, and a portion is metabolized resulting in hydroxylated metabolites that may be more toxic than the parent compound. It should also be noted that human exposure to PBDEs has continued over time, as many countries have only ratified the Stockholm Convention in recent years. Furthermore, PBDEs are still present in furniture, building materials, e-waste, and waste electrical and electronic equipment. In some regions of the world, such as China and Nigeria, the disposal of electrical waste containing PBDEs represent a major problem [8, 9, 52]: in some Chinese regions in the vicinity of the e-waste recycling area remains elevated [53]. Several studies in China suggest an important human exposure to PBDEs from house dust ingestion, especially in people residing in rural areas, southern regions, or near e-waste-contaminated areas [4, 8, 54, 55].

Although the industrialized nations had gradually implemented restrictive measures, the temporal trend of PBDEs concentrations remained ambiguous. In human biomonitoring studies the rate of decline is often divergent between congeners and age groups of population. In NHANES study [56] it was observed that PBDEs reported in serum samples from the years 2005-06 to 2013-14 decreased in concentration, except PBDE-153, for which concentrations increased by 12.0% and 8.4% for the age groups 40-59 and ≥60 years, respectively

Analysis of selected studies for this paper shows an unclear trend in the last ten years for the four considered congeners of PBDEs. This tendency is also evident in *Figure 4* where our results are shown with that obtained in studies carried out in women sera in the previous decade [57]. The data indicates that it is difficult to accurately determine the trend in exposure. Indeed, due to the different patterns of use and periods of restriction, the available data cannot be considered as a whole, but they must be examined with specific geographical and policy area. In fact, except for European data, which shows a certain downward trend, others do not appear to follow a characteristic pattern. Of the four selected PBDEs, PBDE-47 and PBDE-153 appear to be the predominant congeners, alternating discontinuously in time and space. This is particularly evident in the US and China. Further data are essential in order to accurately assess human exposure to PBDEs, particularly in regions such as the USA and China, where large-scale industrial production, the size and characteristics of the territory and its contamination can significantly influence the results. Conclusions on selected PBDEs are limited because of the lack of papers. This is the main limitation of our review: the lack of recent human biomonitoring studies on PBDEs limits the evaluation of current population exposures. Due to global

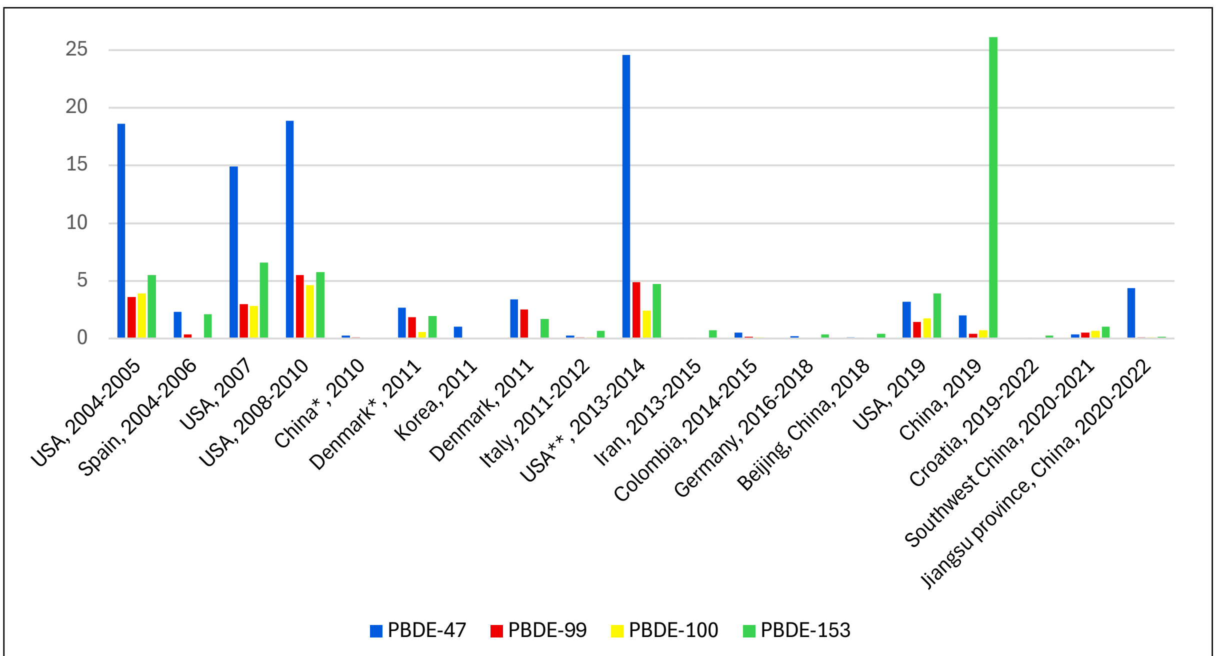

Figure 4
Polybrominated diphenyl ethers (PBDEs) concentrations (ng/g lw) in biological samples from women of various countries over the period 2004-2022. Median, mean *, and geometric mean ** estimates are reported.

restrictions on the production and use of PBDEs, research has shifted to newer or emerging substances. In our opinion, due to the chemical and physical properties of persistence, bioaccumulation, and toxicity of PBDEs, continuous studies are necessary to monitor these substances both in the environment and in humans. It is essential to understand trends in human exposure to PBDEs, especially in regions where the production or improper disposal of products containing these substances is significant in order to understand the mobility, transformation, and impact of PBDEs-containing products still in use (e.g., in old furniture, electronics).

Despite the above commented limitations, the current review represents a comprehensive effort to synthesize the knowledge on human exposure to PBDEs in the last decade.

CONCLUSION

This review aims to assess the current exposure to PBDEs of the general population worldwide. Because of the lack of recent studies, the analysis of chosen papers suggests that levels of PBDE-47, -99, -100 and -153 have a global unclear trend in the last ten years. Due to different patterns of use and banning period, the available data cannot be considered as a whole, but they must be examined with specific geographical and policy area. As PBDEs are still present in furniture, building materials, electronic equipment and e-waste despite recent restrictions, it is essential to continue assessing human exposure to these contaminants through biomonitoring studies.

Authors' contributions

AA was involved in literature search, data collection, data analysis and interpretation, writing; IC contributed to the literature search, data collection and revising the manuscript; VM contributed to the literature search and revising the manuscript; NM was involved in literature search, visualisation of charts and figures and revising the manuscript; RM contributed to data analysis and interpretation, and revising the manuscript; SV contributed to the literature search and revising the manuscript; AMI contributed to writing and revising the manuscript, charts and figures.

All Authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

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Availability of data and materials

This manuscript used data from published studies and public databases; therefore, no original data are available for sharing.

Conflicts of interest statement

All Authors declared that there are no conflicts of interest.

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