Abstract

Polybrominated diphenyl ethers (PBDEs) and ‘novel’ brominated flame retardants (NBFRs) are synthetic chemicals widely used in consumer products to enhance their ignition resistance. Since in most applications, these chemicals are used additively, they can transfer from such products into the environment. PBDEs have been classified as significant pollutants in the environment. Knowledge of PBDE and NBFR physicochemical properties provides information about their potential environmental fate and behaviour. This chapter highlights the most important physiochemical properties such as molecular weight, vapour pressure, octanol/air partitioning coefficient, octanol/water partition coefficient, water solubility and organic carbon/water partitioning coefficient that influence the distribution pattern of these contaminants in the environment. In addition, this chapter provides an evaluation of the concentrations of these chemicals in various environmental media such as indoor and outdoor air, indoor dust, soil and sediment, sewage sludge, biota and food, and human tissues.

Keywords: PBDEs, NBFRs, physiochemical properties, environmental levels, fate and behaviour

1. Introduction

Brominated flame retardants (BFRs) are a group of synthetic chemicals added to a wide range of polymers, foam, plastic, textile, and building materials to meet flame retardancy standards set by various jurisdictions worldwide, containing 50–85% bromine by weight [1]. Depending on their mode of incorporation into the polymers to which they are added, they are referred to as either reactive or additive BFRs. Reactive flame retardants, such as tetrabromobisphenol-A
(TBBPA), are chemically bonded to the polymer. Conversely, additive BFRs, such as PBDEs and hexabromocyclododecane (HBCD) are simply blended with the polymers and do not become a part of the base polymer. Additive BFRs are the most common because their application in consumer goods is less complicated than for reactive BFRs [2]. An extensive body of research has reported the presence of BFRs in air, dust, soil, sediment and biota samples. Evidence of their persistence and capacity for bioaccumulation, coupled with concerns about their adverse health effects has led to widespread bans and restrictions on the manufacture and use of PBDEs and their listing under the Stockholm Convention on Persistent Organic Pollutants (POPs) [3]. Such bans and restrictions on the use of BFRs without the relaxation of flammability standards has likely resulted in increased production and use of alternatives referred to collectively as ‘novel’ brominated flame retardants [4]. According to the empirical data, studies suggest that some NBFRs have the same hazard profiles as ‘legacy’ BFRs [5].

2. PBDEs and NBFRs

PBDEs are a family of chemicals with a common structure of a brominated diphenyl ether and have the chemical formula \( \text{C}_{12} \text{H}_{(0-9)} \text{Br}_{(1-10)} \text{O} \). Any of the 10 hydrogen atoms of the diphenyl ether moiety can be exchanged with bromine, resulting in 209 possible congeners. Each individual PBDE is distinguished from others by both the number of bromine atoms and the placement of those atoms (Figure 1). These congeners are numbered using the International Union of Pure and Applied Chemistry (IUPAC) system [6].

Commercial products of PBDEs have been marketed in three main formulations, namely: pentabromodiphenyl ether (Penta-BDE), octabromodiphenyl ether (Octa-BDE) and deca-bromodiphenyl ether (Deca-BDE). The leading commercial Penta-BDE mixture is primarily comprised 28% BDE-47 and 43% BDE-99. A commercial Octa-BDE mixture is comprised of 13–42% BDE-183 and 11–22% BDE-197, while Deca-BDE mixture contains primarily >97% BDE-209 [7].

Bans and restrictions on the use of established BFRs have resulted in the production of alternatives to comply with flammability standards. The term NBFRs refer to brominated flame retardants, which ‘are new to the market or recently observed in the environment due to the restrictions and bans on the use of some “legacy” BFRs’. Other terms such as ‘alternate’, ‘emerging’ or ‘non-PBDEs’ have also been used to refer to these BFRs [4]. It has been indicated that the NBFRs are urgently required because any non-halogenated substituting chemicals can involve significant costs, as industries must adapt their products for all required

![Figure 1. General structure of PBDEs (n + m = 1–10).](image-url)
performances and product standards [1]. The most common NBFRs replacing PBDEs are: a mixture of 2-ethylhexyl-2,3,4,5-tetrabromobenzoate (EH-TBB) and bis (2-ethylhexyl)3,4,5,6-tetrabromophthalate (BEH-TEBP) under the trade name Firemaster 550 as a replacement for Penta-BDEs; 1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE) as a replacement for Octa-BDE; and decabromodiphenyl ethane (DBDPE) as a replacement for Deca-BDE [8]. Figure 2 illustrates the chemical structure of selected NBFRs replacing PBDEs.

2.1. Physicochemical properties of PBDEs and NBFRs

PBDE commercial products are solids at room temperature, not flammable, and do not present a physiochemical hazard [7]. They are hydrophobic contaminants (highly water insoluble) and typically have high log octanol-water partition coefficients.

Similar to PBDEs, NBFRs are highly hydrophobic compounds and displaying low volatility. However, differences in molecular structure between PBDEs and their NBFR replacements result in specific differences in physicochemical properties. For example, the ethane bridge between the aromatic rings in the DBDPE molecule makes it more flexible and hydrophobic than BDE-209, with consequences for its environmental fate and behaviour [4]. In general, BTBPE, BEH-TEBP and DBDPE possess lower vapour pressures and higher log octanol-water partition coefficients compared with Octa-, Penta- and Deca-BDE, respectively. Tables 1 and 2 and Figure 3 illustrate the most important physiochemical properties: molecular weight (MW), vapour pressure ($V_p$), octanol/air partitioning coefficient ($K_{OA}$), octanol/water partition coefficient ($K_{OW}$), water solubility and organic carbon/water partitioning ($K_{OC}$) that influences the environmental fate and behaviour of PBDEs and NBFRs.

![Chemical structure of selected NBFRs replacing PBDEs](http://dx.doi.org/10.5772/intechopen.79823)

Figure 2. Chemical structure of selected NBFRs replacing PBDEs.
2.1.1. Impact of physicochemical properties on the environmental behaviour of BFRs

Knowledge of the physicochemical properties of substances provides information about their potential environmental fate and behaviour.

2.1.1.1. Molecular weight (MW)

Depending on their molecular weight, chemicals show diverse behaviour in environmental and biological systems. With specific regard to PBDEs, variations in the degree of bromination drive variations in physicochemical properties such as vapour pressure, hydrophobicity and lipophilicity, which in turn lead to congener-specific variations in environmental fate and behaviour. For example, while those less brominated congeners prevalent in the commercial Penta- and Octa-BDE formulations are more bioaccumulative in aquatic biota; higher brominated congeners, such as BDE-209, predominated in sediments. However, potential degradation of higher brominated compounds could yield lower brominated PBDEs that display stronger bioaccumulation characteristics than BDE-209 itself [12].

2.1.1.2. Vapour pressure ($V_p$)

$V_p$ is a useful indicator to determine the potential of chemicals to volatilise from surfaces to the atmosphere. Inhalation is less likely to be a substantial pathway of exposure to chemicals.
with a $V_P < 10^{-6}$ mm Hg (10$^{-4}$ Pa). Conversely, inhalation is likely significant for chemicals with a $V_P > 1 \times 10^{-4}$ mm Hg (10$^{-2}$ Pa) [5]. Chemicals including many BFRs possess a $V_P$ between $1 \times 10^{-8}$ and $1 \times 10^{-4}$ mm Hg partition between the gas and particulate phases and are thereby considered semi-volatile. The equilibrium between the two phases is controlled by the $V_P$, the surrounding air temperature, and the concentration and chemical composition of airborne particulate matter. $V_P$ of PBDEs and NBFRs decrease with increasing molecular weight and degree of bromination [5, 7].

### 2.1.1.3. Octanol-air partition coefficient ($K_{OA}$)

$K_{OA}$ is a parameter that describes the partition of semi-volatile organic compounds (SVOCs) between the gas phase and organic matter such as that found in airborne particles. Commonly expressed as log $K_{OA}$, it is the ratio between the concentration of the chemical in air and its concentration in octanol at the equilibrium state. As with $V_P$, log $K_{OA}$ depends on the temperature. Higher log $K_{OA}$ values imply stronger binding to the organic content of particles [13, 14]. As shown in Tables 1 and 2, log $K_{OA}$ values fall between 9.5 and 13.2 for PBDEs and between 12.3 and 19.2 for NBFRs. This indicates that BFRs will deposit readily from the gas phase into indoor dust, soil and vegetative biomass. In addition, the wide range of log $K_{OA}$ values implies a varying abundance of these pollutants in particulate phases [7].

### 2.1.1.4. Water solubility and octanol/water partition coefficient ($K_{OW}$)

As shown in Tables 1 and 2 and Figure 3, in general, PBDE water solubility values are higher than those of NBFRs. Water solubility is strongly inversely related to the $K_{OW}$. Commonly expressed as log $K_{OW}$, this is an important property for assessing the environmental fate and
behaviour of chemicals. Generally, organic chemicals with a log $K_{ow}$ value ≥ 5.0 are very hydrophobic, thereby displaying a high tendency to sorb organic carbon in sediments, soils, and indoor dust and—when combined with a resistance to metabolism—possess a marked capacity for bioaccumulation [7].

### 2.1.1.5. Organic carbon water partitioning coefficient ($K_{OC}$)

Another important physiochemical property is $K_{OC}$, which provides an indication of a chemical to leach from soil to groundwater and to partition from the aqueous phase of water bodies to suspended solids and sediments. Chemicals with high $K_{OC}$ values are strongly sorb to soil [5, 7]. In general, as shown in Tables 1 and 2, $K_{OC}$ values for PBDEs (3.9–6.3) are slightly lower than by those of their replacements (log $K_{OC}$ of NBFRs 5.8–7).

### 2.2. Environmental levels of PBDEs and NBFRs

PBDEs and NBFRs as additive flame retardants can be released from treated products and enter the environment via several ways. These include volatilisation and leaching from treated products, partitioning to indoor dust, leaching from landfills and recycling of waste products [15]. As a consequence of their persistence and potential for long-range atmospheric transport, PBDEs and NBFRs have been detected in Arctic media, transported on airborne particulates rather than the gas phase. The first detection of PBDEs was in 1979 in soil, and slug samples from the USA, with the first detection in vertebrates (fish and marine mammals collected from the Baltic Sea) were in the 1980s. By comparison with legacy BFRs, the occurrence of NBFRs in the environment is at lower levels; however, the last few years has seen a rise in contamination with NBFRs [16].

#### 2.2.1. Levels of PBDEs and NBFRs in indoor and outdoor air

Depending on their $V_p$ and $K_{OA}$, SVOC BFRs can volatilise from treated products and be abundant in both gaseous and particulate phases. The partitioning between the two phases is mainly driven by atmospheric temperature. It is expected that at a given temperature, lower brominated compounds are more abundant in the gas phase, while higher brominated congeners are more prevalent in the particle phase [14].

It is difficult to compare PBDEs levels in air samples between countries, due to the different number of individual congeners, sampling method (passive or active) and the atmospheric phase sampled (vapour, particle or both). PBDEs were detected in indoor air samples from the UK [17], Germany [18], Denmark [19], Sweden [20], USA [21], Canada [22], China [23], Japan [24], and Australia [25]. Concentrations were variable between countries. For the above-mentioned countries, PBDE concentrations were between 17 and 55 pg/m³ in Japan and 210 and 3980 pg/m³ in the USA. In Norway, the maximum concentration of BDE-209 in indoor air samples was 4150 pg/m³ with a median concentration of 3.8 pg/m³ (n = 47) [26].

In outdoor air samples, BFRs were detected at low levels compared with those in indoors. For each of BDE-47, BDE-99 and BDE-100, concentrations in indoor air were 100 times higher than
the outdoor in the UK [17]. In the USA, ΣPBDE concentrations ranged between 10 and 85 pg/m³, with BDE-47 predominant [27]. In China, concentrations of Σtri-hepta-PBDEs ranged between 87.6 and 1941 pg/m³, with BDE-47 and BDE-99 predominant [28].

Recently, in addition to PBDEs, more attention has been paid to NBFRs. Low concentrations of NBFRs were detected in air samples. In Sweden, BEH-TEBP and DBDPE in indoor air ranged <35–150 pg/m³ and <90–250 pg/m³ with detection frequencies of 15 and 8% for BEH-TEBP and DBDPE respectively [29]. In China, only EH-TBB and DBDPE were detected, at very low concentrations [30].

2.2.2. Levels of PBDEs and NBFRs in surface water

As a source of fresh water, lakes are important. In the UK, an average concentrations of tri-hexa-BDEs in nine English lakes was 61.9 pg/L. Spatial variation was found between lakes, however, no correlation was detected between PBDE concentrations and population density. In addition, no evidence a decline in concentrations during the sampling period [31]. Another study [32] in the USA, from 18 stations on the five Great Lakes’ water, reported that the average concentrations of Σtri-deca-BDEs (112 pg/L) were dominated by BDE-47 and BDE-99 with average concentrations of 26.8 and 26.4 pg/L respectively followed by BDE-209 (9.5 pg/L). Average concentrations of BEH-TEBP, EH-TBB and other NBFRs were 10.4, 5.6 and <1.1 pg/L, respectively [32]. In sea water from the European Arctic, concentration of Σ_{10}PBDEs (tri-deca) in dissolved water and suspended phases of seawater ranged from 0.03 to 0.64 pg/L, with BDE-47 and BDE-99 predominant [33].

2.2.3. Levels of PBDEs and NBFRs in sediment and soil

PBDE congener profiles in sediments are dominated by higher brominated congeners such as BDE-209 and DBDPE. This is different from profiles in biota samples, which are dominated by lower brominated congeners, such as BDE-47 and BDE-99 [34]. In marine sediments, BFRs were detected in Canada [35], San Francisco Bay, USA [36], Gulf of Lion, France [37], Northern Arabian Gulf [38], East Java Province, Indonesia [39], Goseong Bay, Korea [40], South China [41], and the Scheldt estuary, the Netherlands [42]. With the exception of the Scheldt estuary, the Netherlands (where sediment concentrations ranged 14–22 ng/g dw for tri-hepta-BDEs and 240–1650 ng/g dw for BDE-209) and south China (for which sediment concentrations fell between 30 and 5700 ng/g dw for BDE-209); concentrations of PBDEs in other countries were very low. In surficial sediments sampled along cruise transects from the Bering Sea to the central Arctic Ocean, Σ_{24}PBDEs (without BDE-209) in the marine sediments ranged from <MDL to 67.8 pg/g dw, with an average concentration of 9.8 ± 11.9 pg/g dw [43]. The study pointed that the Σ_{24}PBDE concentrations show a reduction from 2008 to 2012. In river sediment cores from China, PBDE concentrations ranged between 1.3 and 1800 ng/g dw with the highest levels found at 4–6 cm depth [44].

Soil represents a major sink for many volatile organic pollutants operating during atmospheric transport. In Birmingham, UK, average concentrations of BDE-209 and Σtri-hepta-BDEs in soil samples were 11 and 3.6 ng/g, respectively [45]. These concentrations were higher in sites
closest to Birmingham city centre [45]. In an e-waste recycling area in South China, PBDE and NBFR concentrations in rhizosphere soils and non-rhizosphere soils were 13.9–351 ng/g for PBDEs and 11.6–70.8 ng/g for NBFRs. BDE-209 and DBDPE were predominant compounds [46]. Another study in China emphasised that DBDPE and BDE-209 were the predominant compounds in the forest soil samples. The concentrations of DBDPE and BDE-209 ranged between 25-18,000 pg/g and <dl -5900 pg/g respectively. In the same study, the distribution of BEH-TEBP and most PBDEs were significantly correlated with population density. In addition, the correlation between PBDEs and their replacement products indicates similar environmental behaviour [47]. Possible debromination of BDE-209 to lower brominated congeners in soils and sediments is a major concern [48].

2.2.4. Levels of PBDEs and NBFRs in sewage sludge

Wastewater treatment plants may not be effective in removing PBDEs. About 52–80% and 21–45% PBDEs remained in effluent and dewatered sludge, respectively, post-sewage treatment [49]. On the other hand, both lower brominated PBDEs and BDE-209 could be successfully removed from contaminated sludge under aerobic conditions [50]. In Korea, concentrations of ΣPBDE in sludge ranged from 298 to 48,000 ng/g dry weight, and among 10 NBFRs, DBDPE and BTBPE were only detected in sludge samples. DBDPE and BTBPE concentrations ranged from <dl-3100 to <dl-21.0, with average concentrations of 237 and 1.57 ng/g dwt for DBDPE and BTBPE, respectively [40]. In Spain, the occurrence of eight PBDEs and NBFRs (EH-TBB, BTBPE, BEH-TEBP and DBDPE) was evaluated in wastewater from wastewater treatment plants. With the exception of BEH-TEBP, no PBDEs or NBFRs were detected in unfiltered influent samples. However, 279–2299 ng/g dwt of flame retardants were detected in primary sludge [51].

From 12 countries around the world, the highest levels of DBDPE in slug samples from wastewater treatment plants were found in Germany (216 ng/g dwt) compared with Europe (81 ng/g dwt) and North America (31 ng/g dwt). The highest concentrations of Deca-BDE were found in the UK and the USA with values of 12,000 ng/g dwt and 19,000 ng/g dwt, respectively [52]. In waste biological sludge and treated bio solids from wastewater treatment plants in Canada, BDE-209, BDE-99 and BDE-47 were the predominant compounds with concentrations of 230–82,000, 530–8800 and 420–6000 ng/g, for BDE-209, -99 and -47 respectively [53].

2.2.5. Levels of PBDEs and NBFRs in biota and food

During the last decade, in addition to PBDEs, their replacement of NBFRs has been shown to accumulate in biota. NBFR levels in seven animal species from the Arctic, specifically one fish species, three seabirds, and three mammalian species were investigated. BTBPE and DBDPE were not detected in any of these species, while EH-TBB was found in all species and BEH-TEBP in only five. Concentrations of EH-TBB ranged between 378 and 3460 pg/g wet wt, while those of BEH-TEBP ranged from 573 to 1799 in whole fish, liver, egg and plasma [54]. For PBDEs, Eulaers et al. [55] reported that PBDE concentrations in muscle, liver, adipose, preen gland and feathers in Barn Owls were 7.46–903 ng/g lw in 2008–2009, which were lower
than in those collected in 2003–2004 (46–11,000 ng/g lw). The authors tentatively ascribed the decline to the 2004 European ban of Penta- and Octa-BDE mixtures. By comparison, NBFRs were found to be poorly bioaccumulated (2.3%) [55].

PBDEs and NBFRs have been detected in human food, animal feed and baby food. In the UK, concentrations of Σ17 PBDEs in food samples ranged between 0.02 and 8.91 ng/g whole weight, and, in animal feed, samples ranged between 0.11 and 9.63 ng/g whole weight. The highest PBDE concentrations were detected in fish, processed foods and fish feeds [56]. In home produced eggs from e-waste sites in China, EH-TBB and BEH-TEBP were found in low concentrations in 50% of chicken egg samples, ranged between <dl-1.82 and 1.17–2.6 ng/g for EH-TBB and BEH-TEBP, respectively [57]. In the three categories of baby food (formula, cereal, and puree) from USA and Chinese stores, median concentrations of ΣPBDEs (sum of BDE-17, -28, -47, -49, -99, -100, -153, -183, and -209) were 21 and 36 pg/g for American and Chinese baby foods, respectively [58].

2.2.6. Levels of PBDE and NBFR in human tissues

As discussed above, numerous studies have shown the presence of PBDEs and NBFRs in many media pertinent for human exposure via inhalation, ingestion and dermal routes. Due to their persistent and bioaccumulative properties, PBDEs and NBFRs have been found in human milk, serum, hair and nail samples. EH-TBB, BEH-TEBP, BTBPE, DBDPE, BDE-209 and BDE-153 in paired human serum (n = 102) and breast milk (n = 105) samples from Canada were investigated. Only EH-TBB and BDE-153 (lower brominated degree and more bioaccumulative) had detection frequencies higher than 55% in both serum and human milk samples, while detection frequencies for other BFRs were lower than 30%. Concentrations in serum and human milk were 1.6 and 0.41 ng/g lw for EH-TBB, and 1.5 and 4.4 ng/g lw for BDE-153, respectively [59]. In the UK, the average concentrations of Σtri-hexa-BDE and BDE-209 in human milk were 5.95 and 0.31 ng/g lw respectively. Concentrations of BDE congeners were BDE-47 > BDE-153 > BDE-99 [60]. BDE-47, −99, −100, and −183 were detected in most human hair samples from Hong Kong [61]. Concentrations of PBDEs in human hair samples in females were higher than males [62]. For NBFRs, EH-TBB and BEH-TEBP were detected in hair and nail samples at concentrations between 20 and 240 and 11 and 350 ng/g in hair samples and <17–80 ng/g and <9–71 ng/g in nail samples for EH-TBB and BEH-TEBP respectively [63].

2.2.7. Levels of PBDE and NBFR in indoor dust

As semi-volatile organic compounds (SVOCs) and additive flame retardants, PBDEs and NBFRs can be released from the products via volatilisation into surrounding air, depending on their V_p. Such volatilised pollutants may then undergo deposition to both suspended and settled indoor dust, with the relative partitioning between these two phases governed by the K_{OA} of the BFRs [13].

A large number of investigations around the world have reported high concentrations of BFRs in indoor dust. The highest levels of PBDEs were reported in US dust samples with
### Flame Retardants

| Country (media) [reference] | Median/range — indoor air (pg/m³) |
|---------------------------|----------------------------------|
|                           | BDEs    | EH-TBB | BEH-TEBP | BTBPE  | DBDPE  |
| USA [21]                  | 760     |        |          |        |        |
| Germany [18]              | 37.8    |        |          |        |        |
| Sweden [20]               | 330     |        |          |        |        |
| Australia [25]            | 19      |        |          |        |        |
| China [23]                | 628     |        |          |        |        |
| UK [17]                   | 128     |        |          |        |        |
| Sweden [29]               | <35     | <90    |          |        |        |
| China [30]                | 7.2     |        |          |        | 40     |

### Indoor dust (ng/g)

| Country (media) [reference] | Indoor dust (ng/g) |
|---------------------------|--------------------|
| Germany [78]              | 979.1              |
| USA [79]                  | 133                |
| Canada [80]               | 120                |
| Pakistan [70]             | 143.8              |
| UK [64]                   | 2862               |
| Kuwait [70]               | 339.4              |
| Iraq [72]                 | 631.5              |
| Egypt [71]                | 53.07              |
| Pakistan [81]             | 0.03               |

### Surface water (pg/L)

| Country (media) [reference] | Surface water (pg/L) |
|---------------------------|----------------------|
| European Arctic [33]      | 0.03–0.64            |
| USA, Great Lakes [32]     | 117–623              |
| UK, lakes [31]            | 9.2–171.5            |

### Sediment and soil (pg/g dw)

| Country (media) [reference] | Sediment and soil (pg/g dw) |
|---------------------------|----------------------------|
| Arabian Gulf [38]         | 0.06–0.44                 |
| Netherlands [42]          | 14,000–22,000             |
| China Marin sediment [41] | 30,000–5,700,000          |
| China (river sediment) [44]| 1300–1800                |
| South China (soil) [46]   | 13,900–351,000            |
| China (forest soils) [47] | <dl-5900 (BDE-209)       |
|                        | <dl-1400                |
|                        | 4–643                   |
|                        | 25–1800                 |

### Sewage sludge (ng/g dw)

| Country (media) [reference] | Sewage sludge (ng/g dw) |
|---------------------------|-------------------------|
| Korea [40]                 | 298–48,000              |
| Spain [51]                 | 279–2299 (BFRs)         |
| Canada (biological slug) [53]| 230–82,000 (BDE-209)    |
median concentrations of ΣPBDEs ranging between 1910 and 21,000 ng/g [21, 63]. The UK displayed the second highest PBDE indoor levels with concentrations ranging between 2900 and 10,000 ng/g [64]. For other parts of the world, ΣPBDE median concentrations were: 950 ng/g in Canada [65], 386 ng/g in Germany [18], 510 ng/g in Sweden [20], 1941 ng/g in China [61] and 1200 ng/g in Australia [66]. In the Middle East, the first study in Kuwait in 2006 reported a median concentration of ΣPBDEs of 90.6 ng/g [67], these levels increased in 2011 to a median concentration of 356 ng/g [68]. In Egypt, Iraq and Pakistan, ΣPBDE median concentrations were 46 [69], 635 [70] and 143 ng/g [68], respectively. Similar to the distribution of PBDE congeners in indoor dust from UK and China, BDE-209 was the major BFR detected in indoor dust from the Middle East. The PBDE congener profiles have changed, and Penta-BDE levels were about one-third those measured in previous studies in 2006 [71, 72].

Recently, studies have increasingly measured NBFRs in indoor dust. EH-TBB, BEH-TEBP, BTBPE and DBDPE represented the highest NBFR concentrations in house dust in the USA [73], with a distribution profile of EH-TBB > BEH-TEBP > DBDPE > BTBPE. The median concentrations were 337, 186, 22.3 and 82.8 for EH-TBB, BEH-TEBP, BTBPE and DBDPE respectively [74]. In Europe, NBFR concentrations and profiles differ from those in the USA. The major compounds in European indoor dust are DBDPE and BEH-TEBP, with EH-TBB and BTBPE present at lower levels. In the UK (classroom dust), median concentrations were 25, 96, 9 and 98 for EH-TBB, BEH-TEBP, BTBPE and DBDPE, respectively [75]. Meanwhile, in Sweden, median concentrations of EH-TBB, BEH-TEBP, BTBPE and DBDPE were 51, 47, 320, 2.6, 61, 6.3, and 150 ng/g, respectively [76].

In China, in addition to the elevated concentrations of PBDEs, high concentrations of NBFRs were detected in floor house dust as well. ΣPBDEs ranged between 685 and 67,500 ng/g, and ΣNBFRs ranged between 1460 and 50,010 ng/g in indoor dust from e-waste sites, with BDE-209 and DBDPE the major BFRs. DBDPE was predominant (nd—16,000 ng/g) followed by
BEH-TEBP (nd—1600), BTBPE (0.2–220 ng/g) and EH-TBB (nd—6300 ng/g) [77]. In addition to the mentioned studies, Table 3 summarises concentrations of PBDEs and NBFRs in air, water, sediment, soil, indoor dust and human tissues from different countries around the world.

3. Conclusion

Depending on their physiochemical properties, PBDEs and NBFRs show diverse behaviour in various environmental media and the possibility of human exposure. Low molecular weight compounds (less brominated degree) possess lower vapour pressures and higher log K_{OA}. This implies a high tendency of such chemicals to the gas phase of indoor air and consequently the exposure will occur via inhalation pathway. On the other hand, water solubility and octanol/water partition coefficient (K_{OW}) are important properties to assess the tendency of higher brominated compounds to organic carbon in sediment, soils, and indoor dust, in which the main exposure will occur via ingestion. This is different from profiles in biota samples which are dominated by lower brominated compounds such as BDE-47 and EH-TBB. The highest levels of PBDEs and NBFRs were reported in US, China and UK indoor dust samples, which were dominated by BDE-209, DBDPE and BEH-TEBP with a decline in PBDE levels and rise in NBFRs.

Author details

Layla Salih Al-Omran

Address all correspondence to: laylaalomran@yahoo.com

Department of Chemistry, College of Science, University of Basrah, Basrah, Iraq

References

[1] Danish EPA. Danish Ministry of Environment, Environmental Protection Agency. Fire Safety Requirements and Alternatives to Brominated Flame-Retardants. 2016. No. 1822. Available from: http://www2.mst.dk/Udgiv/publications/[Accessed: January 20, 2018]

[2] Alaee M. An overview of commercially used brominated flame retardants, their applications, their use patterns in different countries/regions and possible modes of release. Environment International. 2003;29(6):683-689. DOI: 10.1016/S0160-4120(03)00121-1

[3] UNEP. Stockholm Convention on POPs. Risk Management Evaluation for Commercial Octabromodiphenyl ether. 2008. Available from: http://chm.pops.int/portals/0/repository/popc4/unep-pops-poprc.4-6.english.pdf [Accessed: December 15, 2017]
[4] Covaci A, Harrad S, Abdallah MA, Ali N, Law RJ, Herzke D, de Wit CA. Novel brominated flame retardants: A review of their analysis, environmental fate and behaviour. Environment International. 2011;37(2):532-556. DOI: 10.1016/j.envint.2010.11.007

[5] USEPA. US Environmental Protection Agency. An Alternatives Assessment for the Flame Retardant Decabromodiphenyl Ether (deca BDE). 2014. Available from: https://www.epa.gov/sites/production/files/2014-05/documents/decabde_final [Accessed: February 16, 2018]

[6] Birnbaum LS, Staskal DF. Brominated flame retardants: Cause for concern? Environmental Health Perspectives. 2004;112(1):9-17. DOI: 10.1289/ehp.6559

[7] USEPA. US Environmental Protection Agency. 2010. An Exposure Assessment of Polybrominated Diphenyl Ethers. Available from: http://www.epa.gov/ncea [Accessed: August 22, 2017]

[8] de Wit CA, Kierkegaard A, Ricklund N, Sellström U. Emerging Brominated Flame Retardants in the Environment. In: Eljarrat E, Barceló D, editors. Brominated Flame Retardants. The Handbook of Environmental Chemistry. Vol. 16. Berlin, Heidelberg: Springer; 2010. DOI: doi.org/10.1007/698_2010_73

[9] Tittlemier SA, Halldorson T, Stern GA, Tomy GT. Vapor pressures, aqueous solubilities, and Henry’s law constants of some brominated flame retardants. Environmental Toxicology and Chemistry. 2002;21(9):1804-1810

[10] ATSDR. Agency for Toxic Substances and Disease Registry. Toxicological Profile for Polybrominated Biphenyls and Polybrominated Diphenyl Ethers. 2004. Available from: http://www.atsdr.cdc.gov/toxprofiles/tp68 [Accessed: March 19, 2018]

[11] EFSA, European Food Safety Authority. Scientific opinion on emerging and novel brominated flame retardants (BFRs) in food. European Food Safety Authority Journal. 2012;10(10):2908. DOI: 10.2903/j.efsa.2012.2908

[12] Domínguez AA, Law RJ, Herzke D, de Boer J. Bioaccumulation of Brominated Flame Retardants. In: Eljarrat E, Barceló D, editors. Brominated Flame Retardants. The Handbook of Environmental Chemistry. Vol. 16. Berlin, Heidelberg: Springer; 2010. DOI: doi.org/10.1007/698_2010_95

[13] Li X, Chen J, Zhang L, Qiao X, Huang L. The fragment constant method for predicting octanol–air partition coefficients of persistent organic pollutants at different temperatures. Journal of Physical and Chemical Reference Data. 2006;35(3):1365-1384. DOI: 10.1063/1.2203356

[14] Weschler CJ, Nazaroff WW. SVOC partitioning between the gas phase and settled dust indoors. Atmospheric Environment. 2010;44(30):3609-3620. DOI: 10.1016/j.atmosenv.2010.06.029

[15] Segev O, Kushmaro A, Brenner A. Environmental impact of flame retardants (persistence and biodegradability). International Journal of Environmental Research and Public Health. 2009;6(2):478-491. DOI: 10.3390/ijerph6020478
[16] Law RJ, Herzke D. Current Levels and Trends of Brominated Flame Retardants in the Environment: Brominated Flame Retardants in the Environment. In: Eljarrat E, Barceló D, editors. The Handbook of Environmental Chemistry. Vol. 16. Berlin, Heidelberg: Springer; 2010. DOI: 10.1016/j.chemosphere.2005.12.007

[17] Harrad S, Wijesekera R, Hunter S, Halliwell C, Baker R. Preliminary assessment of UK human dietary and inhalation exposure to polybrominated diphenyl ethers. Environmental Science and Technology. 2004;38(8):2345-2350. DOI: 10.1021/es0301121

[18] Fromme H, Körner W, Shahin N, Wanner A, Albrecht M, Boehmer S, Parlar H, Mayer R, Liebl B, Bolte G. Human exposure to polybrominated diphenyl ethers (PBDE), as evidenced by data from a duplicate diet study, indoor air, house dust, and biomonitoring in Germany. Environment International. 2009;35(8):1125-1135. DOI: 10.1016/j.envint.2009.07.003

[19] Vorkamp K, Thomsen M, Frederiksen M, Pedersen M, Knudsen LE. Polybrominated diphenyl ethers (PBDEs) in the indoor environment and associations with prenatal exposure. Environment International. 2011;37(1):1-10. DOI: 10.1016/j.envint.2010.06.001

[20] Thuresson K, Björklund JA, de Wit CA. Tri-decabrominated diphenyl ethers and hexabromocyclododecane in indoor air and dust from Stockholm microenvironments 1: Levels and profiles. Science of the Total Environment. 2012;414:713-721. DOI: 10.1016/j.scitotenv.2011.11.016

[21] Johnson-Restrepo B, Kannan K. An assessment of sources and pathways of human exposure to polybrominated diphenyl ethers in the United States. Chemosphere. 2009;76(4):542-548. DOI: 10.1016/j.chemosphere.2009.02.068

[22] Wilford BH, Shoeib M, Harner T, Zhu J, Jones KC. Polybrominated diphenyl ethers in indoor dust in Ottawa, Canada: Implications for sources and exposure. Environmental Science and Technology. 2005;39(18):7027-7035. DOI: 10.1021/es050759g

[23] Chen L, Mai B, Xu Z, Peng X, Han J, Ran Y, Sheng G, Fu J. In-and outdoor sources of polybrominated diphenyl ethers and their human inhalation exposure in Guangzhou, China. Atmospheric Environment. 2008;42(1):78-86. DOI: 10.1016/j.atmosenv.2007.09.010

[24] Takigami H, Suzuki G, Hirai Y, Sakai SI. Brominated flame retardants and other polyhalogenated compounds in indoor air and dust from two houses in Japan. Chemosphere. 2009;76(2):270-277. DOI: 10.1016/j.chemosphere.2009.03.006

[25] Toms LML, Hearn L, Kennedy K, Harden F, Bartkow M, Temme C, Mueller JF. Concentrations of polybrominated diphenyl ethers (PBDEs) in matched samples of human milk, dust and indoor air. Environment International. 2009;35(6):864-869. DOI: 10.1016/j.envint.2009.03.001

[26] Cequier E, Ionas AC, Covaci A, Marcé RM, Becher G, Thomsen C. Occurrence of a broad range of legacy and emerging flame retardants in indoor environments in Norway. Environmental Science and Technology. 2014;48(12):6827-6835. DOI: 10.1021/es500516u
[27] Hoh E, Zhu L, Hites RA. Novel flame retardants, 1,2-bis(2,4,6-tribromophenoxy)ethane and 2,3,4,5,6-pentabromoethylbenzene, in United States’ environmental samples. Environmental Science and Technology. 2005;39(8):2472-2477. DOI: 10.1021/es048508f

[28] Chen LG, Mai BX, Bi XH, Chen SJ, Wang XM, Ran Y, Luo XJ, Sheng GY, Fu JM, Zeng EY. Concentration levels, compositional profiles, and gas-particle partitioning of polybrominated diphenyl ethers in the atmosphere of an urban city in South China. Environmental Science and Technology. 2006;40(4):1190-1196. DOI: 10.1021/es052123v

[29] Newton S, Sellström U, de Wit CA. Emerging flame retardants, PBDEs, and HBCDDs in indoor and outdoor media in Stockholm, Sweden. Environmental Science and Technology. 2015;49(5):2912-2920. DOI: 10.1021/es505946e

[30] Newton S, Sellström U, Harrad S, Yu G, de Wit CA. Comparisons of indoor active and passive air sampling methods for emerging and legacy halogenated flame retardants in Beijing, China offices. Emerging Contaminants. 2016;2(2):80-88. DOI: 10.1016/j.emcon.2016.02.001

[31] Yang C, Harrad S, Abdallah MAE, Desborough J, Rose NL, Turner SD, Davidson TA, Goldsmith B. Polybrominated diphenyl ethers (PBDEs) in English freshwater lakes, 2008-2012. Chemosphere. 2014;110:41-47. DOI: 10.1016/j.chemosphere.2014.03.028

[32] Venier M, Dove A, Romanak K, Backus S, Hites R. Flame retardants and legacy chemicals in Great Lakes’ water. Environmental Science and Technology. 2014;48(16):9563-9572. DOI: 10.1021/es501509r

[33] Möller A, Xie Z, Sturm R, Ebinghaus R. Polybrominated diphenyl ethers (PBDEs) and alternative brominated flame retardants in air and seawater of the European Arctic. Environmental Pollution. 2011;159(6):1577-1583. DOI: 10.1016/j.envpol.2011.02.054

[34] Lee HJ, Kim GB. An overview of polybrominated diphenyl ethers (PBDEs) in the marine environment. Ocean Science Journal. 2015;50(2):119-142. DOI: 10.1007/s12601-015-0010-8

[35] Grant PBC, Johannessen SC, Macdonald RW, Yunker MB, Sanborn M, Dangerfield N, Wright C, Ross PS. Environmental fractionation of PCBs and PBDEs during particle transport as recorded by sediments in coastal waters. Environmental Toxicology and Chemistry. 2011;30(7):1522-1532. DOI: 10.1002/etc.542

[36] Klosterhaus SL, Stapleton HM, La Guardia MJ, Greig DJ. Brominated and chlorinated flame retardants in San Francisco Bay sediments and wildlife. Environment International. 2012;47:56-65. DOI: 10.1016/j.envint.2012.06.005

[37] Salvadó JA, Grimalt JO, López JF, de Madron XD, Heussner S, Canals M. Transformation of PBDE mixtures during sediment transport and resuspension in marine environments (Gulf of Lion, NW Mediterranean Sea). Environmental Pollution. 2012;168:87-95. DOI: 10.1016/j.envpol.2012.04.019

[38] Gevao B, Boyle EA, Aba AA, Carrasco GG, Ghadban AN, Al-Shamroukh D, Alshemmari H, Bahloul M. Polybrominated diphenyl ether concentrations in sediments from the
Northern Arabian Gulf: Spatial and temporal trends. Science of the Total Environment. 2014;491:148-153. DOI: 10.1016/j.scitotenv.2013.12.122

Ilyas M, Sudaryanto A, Setiawan IE, Riyadi AS, Isobe T, Takahashi S, Tanabe S. Characterization of polychlorinated biphenyls and brominated flame retardants in sediments from riverine and coastal waters of Surabaya, Indonesia. Marine Pollution Bulletin. 2011;62(1):89-98. DOI: 10.1016/j.marpolbul.2010.09.006

Lee S, Song GJ, Kannan K, Moon HB. Occurrence of PBDEs and other alternative brominated flame retardants in sludge from wastewater treatment plants in Korea. Science of the Total Environment. 2014;470-471:1422-1429. DOI: 10.1016/j.scitotenv.2013.07.118

Zhang XL, Luo XJ, Chen SJ, Wu JP, Mai BX. Spatial distribution and vertical profile of polybrominated diphenyl ethers, tetrabromobisphenol A, and decabromodiphenylethane in river sediment from an industrialized region of South China. Environmental Pollution. 2009;157(6):1917-1923. DOI: 10.1016/j.envpol.2009.01.016

Verslycke TA, Vethaak AD, Arijs K, Janssen CR. Flame retardants, surfactants and organotins in sediment and mysid shrimp of the Scheldt estuary (The Netherlands). Environmental Pollution. 2005;136(1):19-31. DOI: 10.1016/j.envpol.2004.12.008

Ma Y, Halsall CJ, Crosse JD, Graf C, Cai M, He J, Gao G, Jones K. Persistent organic pollutants in ocean sediments from the North Pacific to the Arctic Ocean. Journal of Geophysical Research: Oceans. 2015;120(4):2723-2735. DOI: 10.1002/2014JC010651

Jin J, Liu W, Wang Y, Tang XY. Levels and distribution of polybrominated diphenyl ethers in plant, shellfish and sediment samples from Laizhou Bay in China. Chemosphere. 2008;71(6):1043-1050. DOI: 10.1016/j.chemosphere.2007.11.041

Drage DS, Newton S, de Wit CA, Harrad S. Concentrations of legacy and emerging flame retardants in air and soil on a transect in the UK West Midlands. Chemosphere. 2016;148:195-203. DOI: 10.1016/j.chemosphere.2016.01.034

Wang S, Wang Y, Song M, Luo C, Li J, Zhang G. Distributions and compositions of old and emerging flame retardants in the rhizosphere and non-rhizosphere soil in an e-waste contaminated area of South China. Environmental Pollution. 2016;208(Pt B):619-625. DOI: 10.1016/j.envpol.2015.10.038

Zheng Q, Nizzetto L, Li J, Mulder MD, Sáňka O, Lammel G, Bing H, Liu X, Jiang Y, Luo C, Zhang G. Spatial distribution of old and emerging flame retardants in Chinese forest soils: Sources, trends and processes. Environmental Science and Technology. 2015;49(5):2904-2911. DOI: 10.1021/es505876k

Law RJ, Covaci A, Harrad S, Herzke D, Abdallah MAE, Fernie K, Toms L-ML, Takigami H. Levels and trends of PBDEs and HBCDs in the global environment: Status at the end of 2012. Environment International. 2014;65:147-158. DOI: 10.1016/j.envint.2014.01.006

Deng D, Chen H, Tam NFY. Temporal and spatial contamination of polybrominated diphenyl ethers (PBDEs) in wastewater treatment plants in Hong Kong. Science of the Total Environment. 2015;502:133-142. DOI: 10.1016/j.scitotenv.2014.08.090
[50] Stiborova H, Vrkoslavova J, Lovecka P, Pulkrabova J, Hradkova P, Hajslova J, Demnerova K. Aerobic biodegradation of selected polybrominated diphenyl ethers (PBDEs) in wastewater sewage sludge. Chemosphere. 2015;118:315-321. DOI: 10.1016/j.chemosphere.2014.09.048

[51] Cristale J, Lacorte S. PBDEs versus NBFR in wastewater treatment plants: Occurrence and partitioning in water and sludge. AIMS Environmental Science. 2015;2(3):533-546. DOI: 10.3934/environsci.2015.3.533

[52] Ricklund N, Kierkegaard A, McLachlan MS. An international survey of decabromodiphenyl ethane (deBDethane) and decabromodiphenyl ether (decaBDE) in sewage sludge samples. Chemosphere. 2008;73(11):1799-1804. DOI: 10.1016/j.chemosphere.2008.08.047

[53] Kim M, Guerra P, Theocharides M, Barclay K, Smyth SA, Alaee M. Polybrominated diphenyl ethers in sewage sludge and treated biosolids: Effect factors and mass balance. Water Research. 2013;47(17):6496-6505. DOI: 10.1016/j.watres.2013.08.022

[54] Sagerup K, Herzte D, Harju M, Evenset A, Christensen GN, Routti H, Fuglei E, Aars J, Strom H, Gabrielsen GW. New brominated flame retardants in Arctic biota. Statlig Program for forurensningsovervåking. 2010. Available from: http://www.miljodirektoratet.no/old/kliif/publikasjoner/2630/ta2630 [Accessed: February 29, 2018]

[55] Eulaers I, Jaspers VLB, Pinxten R, Covaci A, Eens M. Legacy and current-use brominated flame retardants in the Barn Owl. Science of the Total Environment. 2014;472:454-462. DOI: 10.1016/j.scitotenv.2013.11.054

[56] Fernandes AR, Mortimer D, Rose M, Smith F, Panton S, Garcia-Lopez M. Bromine content and brominated flame retardants in food and animal feed from the UK. Chemosphere. 2016;150:472-478. DOI: 10.1016/j.chemosphere.2015.12.042

[57] Zheng X, Xu F, Luo X, Mai B, Covaci A. Phosphate flame retardants and novel brominated flame retardants in home-produced eggs from an e-waste recycling region in China. Chemosphere. 2016;150:545-550. DOI: 10.1016/j.chemosphere.2015.09.098

[58] Liu LY, Salamova A, Hites RA. Halogenated flame retardants in baby food from the United States and from China and the estimated dietary intakes by infants. Environmental Science and Technology. 2014;48(16):9812-9818. DOI: 10.1021/es502743q

[59] Zhou SN, Buchar A, Siddique S, Takser L, Abdelouahab N, Zhu J. Measurements of selected brominated flame retardants in nursing women: Implications for human exposure. Environmental Science and Technology. 2014;48(15):8873-8880. DOI: 10.1021/es5016839

[60] Abdallah MAE, Harrad S. Polybrominated diphenyl ethers in UK human milk: Implications for infant exposure and relationship to external exposure. Environment International. 2014;63:130-136. DOI: 10.1016/j.envint.2013.11.009

[61] Kang Y, Wang HS, Cheung KC, Wong MH. Polybrominated diphenyl ethers (PBDEs) in indoor dust and human hair. Atmospheric Environment. 2011;45(14):2386-2393. DOI: 10.1016/j.atmosenv.2011.02.019
[62] Tang L, Lei B, Xu G, Ma J, Lei JQ, Jin SQ, Hu GY, Wu MH. Polybrominated diphenyl ethers in human hair from the college environment: Comparison with indoor dust. Bulletin of Environmental Contamination and Toxicology. 2013;91(4):377-381. DOI: 10.1007/s00128-013-1056-x

[63] Liu LY, Salamova A, He K, Hites RA. Analysis of polybrominated diphenyl ethers and emerging halogenated and organophosphate flame retardants in human hair and nails. Journal of Chromatography A. 2015;1406:251-257. DOI: 10.1016/j.chroma.2015.06.003

[64] Harrad S, Ibarra C, Abdallah MAE, Boon R, Neels H, Covaci A. Concentrations of brominated flame retardants in dust from United Kingdom cars, homes, and offices: Causes of variability and implications for human exposure. Environment International. 2008;34(8):1170-1175. DOI: 10.1016/j.envint.2008.05.001

[65] Harrad S, Abdallah MAE, Covaci A. Causes of variability in concentrations and diastereomer patterns of hexabromocyclododecanes in indoor dust. Environment International. 2009;35(3):573-579. DOI: 10.1016/j.envint.2008.10.005

[66] Sjödin A, Päpke O, McGahee E, Focant JF, Jones RS, Pless-Mulloli T, Toms LML, Herrmann T, Müller J, Needham LL. Concentration of polybrominated diphenyl ethers (PBDEs) in household dust from various countries. Chemosphere. 2008;73(1):S131-S136. DOI: 10.1016/j.chemosphere.2007.08.075

[67] Gevao B, Al-Bahloul M, Al-Ghadban AN, Al-Omair A, Ali L, Zafar J, Helaleh M. House dust as a source of human exposure to polybrominated diphenyl ethers in Kuwait. Chemosphere. 2006;64(4):603-608. DOI: 10.1016/j.chemosphere.2005.11.055

[68] Ali N, Ali L, Mehdi T, Dirtu AC, Al-Shammari F, Neels H, Covaci A. Levels and profiles of organochlorines and flame retardants in car and house dust from Kuwait and Pakistan: Implication for human exposure via dust ingestion. Environment International. 2013;55:62-70. DOI: 10.1016/j.envint.2013.02.001

[69] Hassan Y, Shoeib T. Levels of polybrominated diphenyl ethers and novel flame retardants in microenvironment dust from Egypt: An assessment of human exposure. Science of the Total Environment. 2015;505:47-55. DOI: 10.1016/j.scitotenv.2014.09.080

[70] Al-Omran LS, Harrad S. Polybrominated diphenyl ethers and “novel” brominated flame retardants in floor and elevated surface house dust from Iraq: Implications for human exposure assessment. Emerging Contaminants. 2016;2(1):7e13. DOI: 10.1016/j.emcon.2015.10.001

[71] Schreder ED, La Guardia MJ. Flame retardant transfers from U.S. households (dust and laundry wastewater) to the aquatic environment. Environmental Science and Technology. 2014;48(19):11575-11583. DOI: 10.1021/es502227h

[72] Stapleton HM, Misenheimer J, Hoffman K, Webster TF. Flame retardant associations between children’s handwipes and house dust. Chemosphere. 2014;116:54-60. DOI: 10.1016/j.chemosphere.2013.12.100
[73] Brown FR, Whitehead TP, Park JS, Metayer C, Petreas MX. Levels of non-polybrominated diphenyl ether brominated flame retardants in residential house dust samples and fire station dust samples in California. Environmental Research. 2014;135:9-14. DOI: 10.1016/j.envres.2014.08.022

[74] La Guardia MJ, Hale RC. Halogenated flame-retardant concentrations in settled dust, respirable and inhalable particulates and polyurethane foam at gymnastic training facilities and residences. Environment International. 2015;79:106-114. DOI: 10.1016/j.envint.2015.02.014

[75] Ali N, Harrad S, Goosey E, Neels H, Covaci A. “Novel” brominated flame retardants in Belgian and UK indoor dust: Implications for human exposure. Chemosphere. 2011;83(10):1360-1365. DOI: 10.1016/j.chemosphere.2011.02.078

[76] Sahlström LMO, Sellström U, de Wit CA, Lignell S, Darnerud PO. Estimated intakes of brominated flame retardants via diet and dust compared to internal concentrations in a Swedish mother–toddler cohort. International Journal of Hygiene and Environmental Health. 2015;218(4):422-432. DOI: 10.1016/j.ijheh.2015.03.011

[77] Zheng X, Xu F, Chen K, Zeng Y, Luo X, Chen S, Mai B, Covaci A. Flame retardants and organochlorines in indoor dust from several e-waste recycling sites in South China: Composition variations and implications for human exposure. Environment International. 2015;78:1-7. DOI: 10.1016/j.envint.2015.02.006

[78] Fromme H, Hilger B, Kopp E, Miserok M, Volkel W. Polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCD) and “novel” brominated flame retardants in house dust in Germany. Environment International. 2014;64:61-68. DOI: 10.1016/j.envint.2013.11.017

[79] Stapleton HM, Allen JG, Kelly SM, Konstantinov A, Klosterhaus S, Watkins D, McClean MD, Webster TF. Alternate and new brominated flame retardants detected in U.S. house dust. Environmental Science and Technology. 2008;42(18):6910-6916. DOI: 10.1021/es801070p

[80] Shoeib M, Harner T, Webster GM, Sverko E, Cheng Y. Legacy and current-use flame retardants in house dust from Vancouver, Canada. Environmental Pollution. 2012;169:175-182. DOI: 10.1016/j.envpol.2012.01.043

[81] Ali N, Harrad S, Muenhor D, Neels H, Covaci A. Analytical characteristics and determination of major novel brominated flame retardants (NBFRs) in indoor dust. Analytical and Bioanalytical Chemistry. 2011;400(9):3073-3083. DOI: 10.1007/s00216-011-4966-7
