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Multi-residue method for the determination of brominated and organophosphate flame retardants in indoor dust

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ABSTRACT

A new method was optimized for the simultaneous determination of several flame retardants (FRs) in indoor dust, namely polybrominated diphenyl ethers (PBDEs), hexabromocyclododecanes (HBCDs), novel brominated flame retardants (NBFRs) and organophosphate ester flame retardants (OPFRs). The method was based on two previously validated analytical methods for NBFRs and OPFRs, which were combined in order to include even a large number of FRs. An ultrasonic extraction method and two-stage clean-up by adsorption chromatography was optimized using an indoor dust standard reference material (SRM 2584). The 1st cleanup step was essential for fractionation of analytes in the dust extracts, while the 2nd step was important for the further removal of interferences. Analysis of cleaned dust extracts was performed with gas chromatography electron impact ionization mass spectrometry for OPFRs, gas chromatography electron capture negative ionization mass spectrometry for PBDEs and NBFRs and liquid chromatography electrospray ionization tandem mass spectrometry for HBCDs. Method validation by matrix spiking demonstrated good accuracy ranging from 81 to 130%. Matrix effects were investigated by spiking sodium sulfate and dust with analyte standards. Typical recoveries ranged between 80 and 110% at both spiking levels, though occasional deviations were observed at low spiking concentrations. Precision between different days was generally below 24% relative standard deviation (RSD) at low concentrations and below 11% RSD at high concentrations. Method limits of quantification for BFRs ranged between 0.04 (BDE 28) and 17 ng/g (BDE 209), 6 ng/g for sum HBCDs, and for OPFRs between 10 (triphenyl phosphate) and 370 ng/g (tri-*iso*butyl phosphate). The method was applied to SRM 2585 and to a set of indoor dust samples from various countries. The newly developed method will be employed for the monitoring of human exposure via dust ingestion to phased-out and alternate FRs.

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1. Introduction

Flame retardants (FRs) are additives which are used in consumer products to reduce their flammability. Common applications include building materials, vehicles, textiles, furniture, foams, electrical and electronic goods. Until recently, the most widely used brominated FRs were polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCD), and tetrabromobisphenol A (TBBP-A) [1]. After increasing evidence of their persistence in the environment [2,3], presence in human serum [4], and toxicity [5], the use of Penta- and Octa-BDE mixtures was banned in the European Union [6] and the two mixtures were listed in 2009 under the Stockholm Convention on Persistent Organic Pollutants [7]. In 2008, the European Court of Justice ordered a ban on the use of Deca-BDE in electrical and electronic appliances [8]. The use of HBCD has also been decreased after rising concern of persistence [9], bioaccumulation in the environment [10], presence in human body fluids [11], and toxicity in laboratory animals [12]. HBCD is currently being evaluated as a candidate for the list of Persistent Organic Pollutants [13].

These bans and restrictions in use have led to the increased use of alternate FRs also referred to as novel brominated FRs (NBFRs), and organophosphate esters (OPFRs). Octa-BDE and Deca-BDE were replaced with 1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE) and decabromodiphenyl ethane (DBDPE), respectively, while Penta-BDE was replaced with Firemaster 550, containing 2-ethylhexyl-2,3,4,5-tetrabromobenzoate (TBB) and bis(2-ethylhexyl)-3,4,5,6-tetrabromo-phthalate (TBPH) [14,15]. Next to its substitution for Penta-BDE in flame retarded foams, TBPH is also used as a plasticizer in neoprene and a FR plasticizer in various PVC applications [16]. Currently, BTBPE and DBDPE have been detected in various environmental media, such as air, dust, soil, sediment, and sewage sludge [14–22]. The levels of BTBPE and DBDPE

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remained below those of Penta-BDE and BDE 209 in indoor dust, though in sediment DBDPE reached higher concentrations than Penta-BDE levels, but lower than BDE 209 [19]. Recently, TBPH and TBB have been detected in US home dust at concentrations below those of HBCDs [15] and the sum of 30 PBDE congeners [23]. In Belgian home dust TBB and TBPH concentrations were about 20 times lower compared to BDE 209 [22]. OPFRs, which have flame retardant and plasticizing properties, have been produced and consumed increasingly this decade [24]. As a result, they have been detected in indoor dust, indoor air, and surface water at levels comparable or even higher than BFRs, including BDE 209 [23,25–32], although concentrations of OPFRs in sediment seem lower [33].

Several analytical protocols have been developed for the quantification of FRs in dust. For BFRs, most extraction procedures were based on Soxhlet extraction or pressurized liquid extraction (PLE) [15,17,34], while for OPFRs a wider range of techniques have been applied, including ultrasonication [23,25,26]. Clean-up of dust extracts is mostly done by adding concentrated sulfuric acid to the raw extract [17,34,35]. The major disadvantage of this technique is that it does not allow the analysis of a broad range of compounds since some analytes, such as TBPH and OPFRs, undergo degradation in such conditions. Sometimes, an additional step such as gel permeation chromatography or SPE using Florisil or silica is introduced to remove more interferences, but this increases the sample preparation time [17,18,36].

So far, a sample preparation protocol that combines the extraction and clean-up protocols for four groups of FRs (PBDEs, HBCDs, NBFRs, OPFRs) has not yet been investigated. Moreover, the measurement of each group was done separately, thus requiring a higher sample amount. Other disadvantages of such analysis protocols were: (1) the use of large solvent volumes for Soxhlet extraction and for clean-up by gel permeation chromatography; (2) the consumption of high sample amounts which are not always available; (3) complicated and lengthy clean-up procedures or long extraction times which have low sample throughput; and (4) the use of more expensive techniques such as microwave assisted extraction or pressurized liquid extraction which are not available in all laboratories.

The principal aim of this study was to develop and validate an analysis method for indoor dust which should include several groups of FRs. This procedure addresses each of the above mentioned issues by using smaller solvent volumes, lower sample amount, and shorter extraction time, resulting also in lower costs. The setup of the sample preparation method allows for 24–36 samples to be processed per day, which means a higher sample throughput. The analysis of cleaned extracts was performed according to established separation and detection methods for each group of FRs. The determination of NBFRs and PBDEs was performed by gas chromatography electron capture negative ionization mass spectrometry (GC/ECNI-MS) [21,37]. Individual HBCD isomers were analyzed by liquid chromatography electrospray ionization MS [37]. OPFRs were analyzed by GC coupled with electron impact ionization (EI) MS [29]. The method was applied to indoor dust SRM 2585 which is certified for PBDEs and to a set of dust samples collected from various countries.

2. Experimental

2.1. Materials (chemicals and reagents)

Solvents used during analysis were all of analytical grade. *n*-Hexane (Hex) was purchased from Acros Organics (Geel, Belgium). Acetone (Ac), dichloromethane (DCM), ethyl acetate (EA), isooctane and methanol (MeOH) were purchased from Merck (Darmstadt, Germany).

Standards of BDE 28, 47, 99, 100, 153, 154, 183 and 209, α-HBCD, β-HBCD, γ-HBCD, BTBPE, DBDPE, hexachlorocyclopentadienyldibromocyclooctane (HCDBCO), TBB, TBPH and labeled internal standards (IS) ^{13}C-BDE 209, ^{13}C-α-HBCD, ^{13}C-β-HBCD and ^{13}C-γ-HBCD were purchased from Wellington Laboratories (Guelph, ON, Canada). BDE 77 and 128 (IS) were obtained from AccuStandard Inc. (New Haven, CT, USA). Standards of TEP, tri-*n*-propyl phosphate (T*n*PP), tri-*iso*butyl phosphate (T*i*BP), tri-*n*-butyl phosphate (T*n*BP), triphenyl phosphate (TPP), tris(2-chloroethyl) phosphate (TCEP), triscresyl phosphate (TCP, mixture of 4 isomers), and tris(1,3-dichloropropyl) phosphate (TDCPP, mixture of 2 isomers) were purchased from Chiron AS (Trondheim, Norway). Triamyl phosphate (TAP; IS) was purchased from TCI Europe (Zwijndrecht, Belgium). Labeled TPP-d15 (IS) and tris(2-butoxyethyl) phosphate (TBEP) were purchased from Sigma Aldrich. Tris(1-chloro-2-propyl) phosphate (TCPP, mixture of 3 isomers) was purchased from Pfaltz & Bauer (Waterbury, CT, USA). Purity of analytical standards was >98%, except for TBEP (>94%). Standard stock solutions were prepared in *iso*-octane, except for NBFRs which were prepared in a mixture of *iso*-octane:toluene (8:2, *v/v*).

Indoor dust SRMs (2584 and 2585) were purchased from the US National Institute of Standards and Technology (NIST, Gaithersburg, MD, USA). Empty polypropylene filtration tubes (3 mL) SPE cartridges and 500 mg/3 mL Supelclean™ ENVI™-Florisil® cartridges were purchased from Supelco (Bellefonte, PA, USA). Silica gel, anhydrous sodium sulfate (Na_2SO_4), and concentrated sulfuric acid (H_2SO_4, 98%) were purchased from Merck. The preparation of acid impregnated silica (44%, *w/w*) was carried out as described elsewhere [38]. Glass test tubes were cleaned by soaking for at least 12 h in an alkali solution (diluted RBS 35, pH 11–12). After washing, the tubes were rinsed with water and dried at 100 °C for at least 12 h. The tubes were rinsed with Hex before use.

2.2. Sample collection

Indoor dust samples (n = 12) were collected using vacuum cleaners with similar power (1600 W) using the same sampling protocol; nylon sampling socks inserted in the nozzle of the vacuum cleaner. A detailed procedure of sample collection is described elsewhere [29,37]. Three dust samples were collected from Romania, one was collected from Spain and the remaining eight were of Belgian origin. The room used for sample collection was not always specified. After collection, all dust samples were passed through a pre-cleaned, Hex rinsed 500 μm mesh sieve to remove large debris and particles and to insure a better sample homogeneity before analysis.

2.3. Method description

A sample aliquot (around 75 mg) was accurately weighed and spiked with IS (^{13}C-α-, β-, γ-HBCD, ^{13}C-BDE 209, BDE 77, BDE 128, TAP, and TPP-d15). Samples were extracted using 2 mL Hex–Ac (3:1, *v/v*) by a combination of vortexing and ultrasonic extraction (2 × 1 min vortex and 5 min ultrasonic extraction) which was repeated three times. After each extraction cycle, dust extracts were centrifuged at 3500 rpm for 2 min and supernatants were collected and transferred into clean glass tubes. The pooled supernatants were evaporated until dryness under a gentle nitrogen flow and redissolved in 1 mL Hex. Prior to fractionation, Florisil® cartridges were prewashed with 6 mL of Hex. The extracts were quantitatively transferred and fractionation was achieved by eluting with 8 mL of Hex (Fraction 1 – F1) and 10 mL of EA (Fraction 2 – F2).

The 1st fraction (F1) was evaporated until 1 mL and quantitatively transferred onto acidified silica 44% cartridges (prewashed with 6 mL Hex) for a second clean-up. The extracts were eluted with 10 mL of Hex/DCM (1:1, *v/v*), and afterwards evaporated until dryness under gentle nitrogen flow and reconstituted in 100 μL of

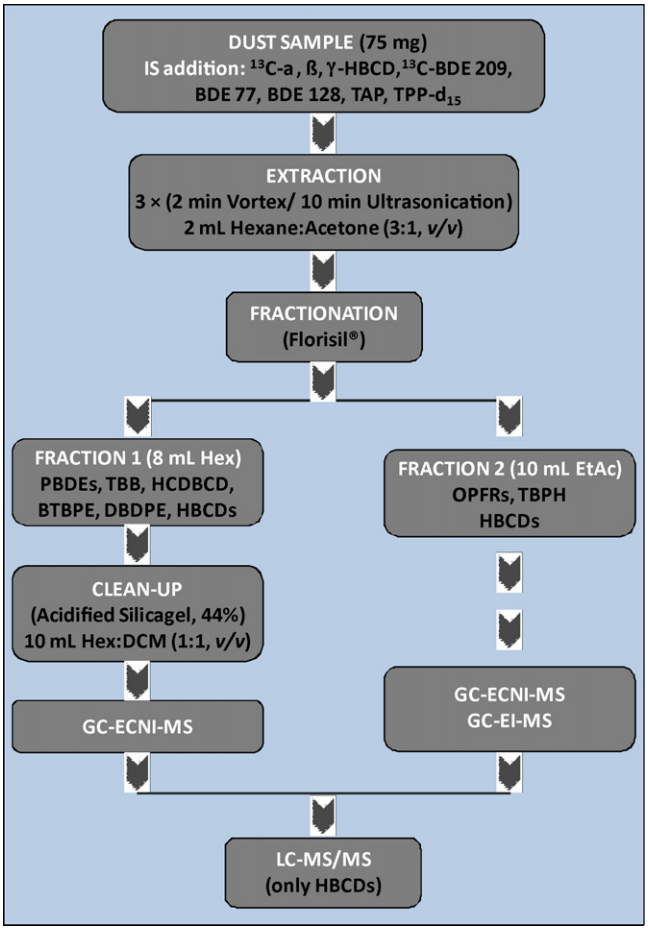

Fig. 1. Schematic representation of the analytical procedure.

iso-octane. In the 2nd fraction (F2), IS BDE 128 was added for the quantification of TBPH, followed by evaporation until dryness and resolubilized in 100 μL of *iso*-octane.

Since HBCD diastereomers were distributed into F1 and F2, for their determination, both fractions were recombined after GC-analysis, evaporated until dryness and resolubilized in 100 μL of methanol. Before injection in the LC, extracts were filtrated using nylon filters (0.45 μm). A schematic representation of the sample preparation procedure is shown in Fig. 1.

2.4. Optimization and validation experiments

The final method was derived from existing methods used for the determination of OPFRs [29] and NBFRs in dust [21]. Firstly, two sorbents were selected for a sequential clean-up, namely Florisil® (500 mg) and acid silica 44% (1 g). Optimization experiments were done by spiking SPE sorbents with standard solutions and testing different elution volumes of Hex, EA and Hex–DCM (1:1, *v/v*). For the choice of the extraction solvent, equal amounts of SRM 2584 dust were extracted with Hex–Ac (3:1, *v/v*) or DCM.

The final method was validated by performing spiking experiments on Na_2SO_4 using two concentration levels, Qlow and Qhigh, and three replicates for each level. Next, recovery, matrix effects and the precision between different days ($RSD_{between}$) were assessed using the same concentration levels spiked on a low contaminated dust sample, using three replicates per level and executed on three different days. The recovery was calculated by subtracting the blank concentrations and divided by the calculated concentration of a mixed solution of standards (having the same concentrations).

In order to test the suitability of the new method, equal amounts of SRM 2585 were analyzed on 6 different days. The calculated concentrations were compared to certified or indicative values for all analyzed compounds.

2.5. GC analysis

GC/ECNI-MS: Analysis of F1 containing PBDEs, DBDPE, BTBPE, HCDBCO and TBB, and analysis of F2 containing TBPH was performed with an Agilent 6890 GC coupled to an Agilent 5973 MS operated in electrochemical negative ionization (ECNI) mode. The GC system was equipped with electronic pressure control and a programmable-temperature vaporizer (PTV). 2 μL of cleaned extract were injected on a DB-5 column (15 m × 0.25 mm × 0.10 μm) using solvent vent injection. The injection temperature was set at 92 °C, hold 0.04 min, ramp 700 °C/min to 295 °C. Injection was performed under a pressure of 0.19 bar until 1.25 min and purge flow to split vent of 50 mL/min after 1.25 min. The GC temperature program was 90 °C, hold 1.50 min, ramp 10 °C/min to 300 °C, hold 3 min, ramp 40 °C/min to 310 °C, hold 5 min. Helium was used as a carrier gas with a flow rate of 1.0 mL/min. The mass spectrometer was employed in selected ion monitoring (SIM) mode. Dwell times were set on 35 ms. The ion source, quadrupole and interface temperatures were set at 250, 150 and 300 °C, respectively and the electron multiplier voltage was at 2200 V. Methane was used as moderating gas. BDE 28 to BDE 154, TBB and HCDBCO were quantified with BDE 77 as IS and BDE 183, BTBPE and TBPH were quantified with BDE 128. BDE 209 and DBDPE were quantified with ^{13}C-BDE 209. An overview of analytes containing detailed nomenclature and applied abbreviation, together with ions acquired for identification and quantification purposes on the GC–EI-MS and GC–ECNI-MS are presented in Table 1.

GC/EI-MS: Analysis of OPFRs in F2 was performed with an Agilent 6890 GC coupled to an Agilent 5973 MS operated in electron impact ionization (EI) mode. The GC system was equipped with electronic pressure control and a programmable-temperature vaporizer (PTV). One microliter of purified extract was injected on a HT-8 column (25 m × 0.22 mm × 0.25 μm) using cold splitless injection. The injection temperature was set at 90 °C, hold 0.03 min, ramp 700 °C/min to 290 °C. Injection was performed using a pressure of 1 bar until 1.25 min and purge flow to split vent of 50 mL/min after 1.25 min. The GC temperature program was 90 °C, hold 1.25 min, ramp 10 °C/min to 240 °C, ramp 20 °C/min to 310 °C, hold 16 min. Helium was used as a carrier gas with a flow rate of 1.0 mL/min. The mass spectrometer was run in selected ion monitoring (SIM) mode. Dwell times ranged between 20 and 30 ms in different acquisition windows. The ion source, quadrupole and interface temperatures were set at 230, 150 and 300 °C, respectively and the electron multiplier voltage was at 2200 V. TAP was used as IS for the quantification of TEP, T*n*PP, T*i*BP, T*n*BP, TCEP, TCPP and TBEP. TPP-d15 was used to quantify TPP, TDCPP and TCP (Table 1).

2.6. LC analysis

The determination of individual HBCD isomers after the combination of the extracts was achieved using a dual pump Agilent 1100 Series liquid chromatograph equipped with autosampler and vacuum degasser. A Kinetex C18 reversed phase (RP) analytical column (100 mm × 2.1 mm i.d., 2.6 μm particle size) was used for the separation of α-, β-, and γ-HBCD. A mobile phase of: (a) ammonium acetate 2 mM in water/methanol (1:1, *v/v*) and (b) methanol at a flow rate of 250 μL/min was applied for elution of HBCD isomers; starting at 70% (b) for 2 min, then increased linearly to 100% (b) over 3 min; held for 4 min followed by a linear decrease to 70%

Table 1
Nomenclature and analytical characteristics of measured flame retardants.

Abbreviation	Full name	Quantifier ion (*m/z*)	Qualifier ion (*m/z*)
BDE 77 (IS)	3,3′,4,4′-Tetrabromodiphenyl ether	79	81
BDE 128 (IS)	2,2′,3,3′,4,4′-Hexabromodiphenyl ether	79	81
^{13}C-BDE 209 (IS)	^{13}C-labeled decabromodiphenyl ether	495	497
TAP (IS)	Triamyl phosphate	239	169
TPP d15 (IS)	Triphenyl phosphate – d15	341	339
^{13}C-HBCDs (IS)	^{13}C-labeled hexabromocyclododecanes	652.6 → 79	652.6 → 81
BDE 28	2,4,4′-Tribromodiphenyl ether	79	81
BDE 47	2,2′,4,4′-Tetrabromodiphenyl ether	79	81
BDE 99	2,2′,4,4′,5-Pentabromodiphenyl	79	81
BDE 100	2,2′,4,4′,6-Pentabromodiphenyl ether	79	81
BDE 153	2,2′,4,4′,5,5′-Hexabromodiphenyl ether	79	81
BDE 154	2,2′,4,4′,5,6′-Hexabromodiphenyl ether	79	81
BDE 183	2,2′,3,4,4′,5′,6-Heptabromodiphenyl ether	79	81
BDE 209	Decabromodiphenyl ether	487	485
TBB	2-ethylhexyl-2,3,4,5-tetrabromobenzoate	357	359
HCDBCO	Hexachlorocyclopentadienyldibromo-cyclooctane	310	79
BTBPE	1,2-bis(2,4,6-tribromophenoxy)ethane	79	81
TBPH	Bis(2-ethylhexyl)-3,4,5,6-tetrabromo-phthalate	384	515
DBDPE	Decabromodiphenyl ethane	79	81
TEP	Triethyl phosphate	155	99
T*n*PP	Tri-*n*-propyl phosphate	183	99
T*i*BP	Tri-isobutyl phosphate	211	155
T*n*BP	Tri-n-butyl phosphate	211	155
TCEP	Tris(2-chloroethyl) phosphate	249	251
TCPP	Tris(1-chloro-2-propyl) phosphate	277	279
TBEP	Tris(2-butoxyethyl) phosphate	299	199
TPP	Triphenyl phosphate	326	325
TDCPP	Tris(1,3-dichloropropyl) phosphate	381	379
TCP	Tricresyl phosphate (mixture of *o*, *m* and *p*)	368	367
HBCDs	hexabromocyclododecanes	640.6 → 79	640.6 → 81

(b) over 0.5 min and held for 11.5 min. The target analytes were baseline separated on the RP column with retention times of 3.9, 4.7 and 5.2 min for α-, β- and γ-HBCD, respectively. MS analysis was performed using an Agilent 6410 triple quadrupole MS system operated in the electrospray negative ionization mode. N_2 was used as drying gas at a flow of 10 L/min and heated to 300 °C. Nebulizer pressure was 35 psi and capillary voltage 4000 V. HBCD isomers were quantified by isotope dilution. MS/MS detection operated in the MRM mode was used for quantitative determination of the HBCD isomers based on *m/z* 640.6–79 and *m/z* 652.6–79 for the native and ^{13}C-labeled diastereomers, respectively. Fragmentor voltage and collision energy were set as 80 and 15 V, respectively.

3. Results and discussion

3.1. Optimization

The choice of elution solvents, namely Hex and EA for Florisil and Hex–DCM for acidified silica 44% was based on previous findings [21,29]. To assess appropriate elution volumes, standard mixtures containing all analytes were spiked directly onto Florisil® cartridges and eluted with 8, 10 or 12 mL of Hex, followed in each case by 10 mL of EA. PBDEs, BTBPE, DBDPE, TBB, HCDBCO eluted completely in the first fraction after 8 mL of Hex. TBPH and OPFRs eluted completely in the second fraction. HBCD was divided between the two fractions, thus for analysis of HBCD isomers using LC, both fractions were recombined before injection on LC. When spiking the standard mixtures on acidified silica 44%, complete elution of PBDEs and NBFRs (TBB, HCDBCO, BTBPE, and DBDPE) was achieved using 10 mL of Hex–DCM. OPFRs and TBPH eluted in the second fraction of Florisil® which was not further purified since they were not stable on acidified silica.

Two extraction solvents were tested on equal amounts of SRM 2584 dust; after spiking with IS, dust was extracted with 2 mL of DCM or Hex–Ac (3:1, *v/v*) in triplicate. Concentrations of various FRs in dust extracts obtained from SRM 2584 were comparable between both extraction solvents for most compounds (BDE 28 to BDE 183, DBDPE, TBPH, TBB, T*n*BP, TBEP, TPP, TDCPP, and TCP). Relative differences, calculated as the extraction yield ratio DCM to Hex–Ac for each compound, ranged between 0.87 (TBB) and 1.12 (TCP), with low variation between replicates (maximum 14% RSD). Obviously, both solvents were suitable to extract all target compounds. Relative differences observed for BTBPE (1.26) was caused by an aberrant value in one of the DCM replicates (27% RSD). When this value was excluded, the relative difference became 1.06 with a RSD of 9%. Extraction of BDE 209 and TCPP appeared to be more efficient with DCM, with relative differences of 1.65 and 1.19, respectively. BDE 209 showed more variation in DCM extracts (33% RSD) but even after exclusion of an aberrant value, concentrations in DCM extracts were higher. Concentrations of TCEP were higher when Hex–Ac was used for extraction (relative difference 0.71), while TCPP reached higher levels in DCM extracts, which was remarkable taking their similar structure into account. Other compounds, such as TEP, T*n*PP, DBDPE and T*i*BP, could not be quantified or compared; the first three were below LOQ and the last one showed irreproducible blanks. Hex–Ac was chosen as final extraction solvent, because of a better separation between dust and supernatant after centrifugation, which allowed easier handling during analysis and therefore lower losses of compounds and variability compared to DCM.

The use of ultrasonication has not yet been reported for the extraction of PBDEs and HBCDs from a dust matrix, although this technique was applied for OPFRs [25–27]. While PBDEs and HBCDs are mostly extracted using Soxhlet extraction [18,28,35,37,40] or PLE [15,17,34,39,41,42], OPFRs have been extracted using cold

Table 2
Spiking experiments on a low contaminated dust sample. Each level consists of three replicate measurements on three different days. LOQ_m is the method limit of quantification. RSD: relative standard deviation within and between different days.

Compound	LOQ_m (ng/g)	Low contaminated dust (ng/g)	Qlow				Qhigh			
			Spiked amount (ng)	Recovery (%)	RSD within (%)	RSD between (%)	Spiked amount (ng)	Recovery (%)	RSD within (%)	RSD between (%)
BDE 28	0.04	<0.04	0.60	98	1	2	4	94	3	4
BDE 47	0.13	0.20	0.60	98	2	2	4	94	2	2
BDE 99	0.18	0.26	0.60	91	9	10	4	93	8	8
BDE 100	0.24	<0.24	0.60	113	1	1	4	97	2	2
BDE 153	0.18	0.24	0.60	104	1	2	4	102	2	2
BDE 154	0.71	<0.71	0.60	102	1	1	4	101	2	2
BDE 183	1.6	1.8	0.60	103	2	5	4	95	2	2
BDE 209	17	64.3	30.6	99	2	2	378	100	6	5
BTBPE	1.1	1.8	5	93	2	2	25	87	2	2
DBDPE	7.1	20.0	6.3	93	17	24	21	102	6	11
HCDBCO	2.8	<2.8	5	100	2	2	25	95	3	4
TBB	9.0	<9.0	5	131	4	4	25	130	4	4
TBPH	0.1	1.49	5	107	3	6	25	111	2	6
TEP	30	<30	20	89	39	52	250	84	39	35
T*n*PP	50	<50	20	109	9	13	250	102	6	5
T*i*BP	370	755	20	81	246	315	250	99	10	20
T*n*BP	10	15	20	93	3	4	250	96	2	2
TCEP	110	<110	20	142	4	6	250	110	2	3
TCPP	10	<10	20	103	2	3	250	99	1	1
TBEP	50	450	20	235	12	13	250	108	1	2
TPP	10	14	20	111	12	10	250	90	6	8
TDCPP	10	<10	20	125	9	8	250	99	6	10
TCP	40	<40	20	124	8	7	250	94	6	8
α-HBCD	3	<3	50	97	5	6	75	102	4	4
γ-HBCD	4	<4	25	98	4	4	37.5	100	3	3
$\sum$HBCDs	10	<10	75	98	4	3	112.5	100	3	3

Table 3
Mean values and standard deviations (ng/g dust) of flame retardants measured in SRM 2585 ($n = 6$).

Compound	LOQ_m	Mean value (SD)	Indicative or certified value (SD)[a]	Percentage of indicative or certified value
BDE 28	0.04	32.8 (1.1)	46.9 (4.4)	69
BDE 47	0.13	409 (11)	497 (46)	81
BDE 99	0.18	742 (23)	892 (53)	79
BDE 100	0.24	116 (3)	145 (11)	81
BDE 153	0.18	97 (2)	119 (1)	91
BDE 154	0.71	77.2 (2.7)	83.5 (2.0)	80
BDE 183	1.6	32.3 (4.8)	43 (3.5)	73
BDE 209	17	2150 (231)	2510 (190)	84
BTBPE	1.1	39 (14)	32[a,b]	122
DBDPE	7.1	<7.1	<20[a]	–
HCDBCO	2.8	<2.8	<2[a]	–
TBB	9.0	26 (2)	40[a,b]	65
TBPH	1.0	574 (49)[c]	652[a,b]	88
TEP	30	<30	<50[a]	–
T*n*PP	50	<20	<20[a]	–
T*i*BP	370	–	–	–
T*n*BP	10	190 (10)	180 (20)[a]	106
TCEP	110	680 (60)	700 (170)[a]	97
TCPP	10	860 (70)	820 (100)[a]	105
TBEP	50	63,000 (2000)	49,000 (9 600)[a,d]	129
TPP	10	1160 (140)	990 (70)[a]	117
TDCPP	10	3180 (70)	2020 (260)[a,d]	157
TCP	40	1140 (30)	1070 (110)[a]	107
α-HBCD	3	19.0 (9)	19.0 (4)	100
β-HBCD	3	4.2 (1.4)	4.3 (1.1)	99
γ-HBCD	4	119 (42)	120 (22)	99
$\sum$HBCDs	10	141 (45)	148 (22)	95

[a] Indicative values of NBFRs were taken from Ali et al. [22], OPFRs from Van den Eede et al. [29]. HBCDs were taken from Abdallah et al. [34].
[b] Based on 2 replicas.
[c] Based on 5 replicas.
[d] No explanation can be given for the differences observed for TDCPP and TBEP.

extraction [25,45], Soxhlet extraction [25,28], microwave assisted extraction [43], PLE [23], or matrix solid phase dispersion [44]. PBDEs, HBCDs or NBFRs are usually extracted with Hex [17,42], mixtures of Hex and DCM (often 1:1, *v/v*) [34,36,41], or DCM [15,35,39]. A few methods were based on Hex–Ac (1:1, *v/v*) [37] or toluene [18]. Extraction of OPFRs was done with Hex–DCM (1:1, *v/v*) [23] and DCM [26,29] although more polar extraction solvents such as acetone [27,43–45] or mixtures containing acetone [25] were also used. Hex–Ac (3:1, *v/v*) was therefore a suitable solvent both for apolar PBDEs, HBCDs and NBFRs and the more polar OPFRs. The treatment of dust extracts with concentrated sulfuric acid or clean up on acidified silica has been a common approach for PBDEs, HBCDs, BTBPE and DBDPE in dust. However, milder techniques, such as clean up on silica, alumina or Florisil, were also applied [15,39,40], making it possible to determine also TBPH in dust [15]. No standard approach exists for OPFRs, extracts were cleaned up by centrifugation or filtration [26,27] by SPE using Oasis HLB sorbent [43], by eluting on an alumina column [23] or by using selective extraction techniques such as matrix solid phase dispersion with alumina and Florisil [44]. Alumina has the possibility to remove more polar interferences, but TPP can adsorb to it [44]. By using Florisil before the acidified silica step, it was still possible to analyze less chemically stable compounds and remove interferences before PBDE analysis on ECNI-MS.

Our eluting conditions were very similar to others who have also used Hex for elution on Florisil [17] and Hex–DCM for elution on acidified silica [18,36]. Stapleton et al. [15] used Hex–DCM (1:1, *v/v*) on Florisil which is necessary to elute also TBPH in that fraction.

3.2. Method validation

Spiking experiments: The results from the spiking experiments on Na_2SO_4 indicated that all PBDEs and NBFRs, except TBPH, were completely eluted in F1. OPFRs and TBPH were eluted in F2, which was beneficial as these compounds were not stable on acidified silica (44%). Relative recoveries were calculated based on the injection of a standard solution with the same concentration compared to the Qlow and Qhigh spiked samples (Table 2). Accuracy was generally acceptable and ranged between 81 and 131%. Losses of TEP and T*n*PP in F2 occurred mostly during evaporation and were due to their high volatility [29]. Accuracy of TBEP and TCEP was less good (>160%) at the Qlow level (20 ng, equivalent to 267 ng/g dust). Interferences might have been eluted from Florisil cartridges, since it was decided to pre-wash the cartridges only with Hex to prevent elution of TBPH in both fractions.

Some matrix effects were observed for TBB with relative recoveries of 131% at Qlow and 130% at Qhigh (Table 2). For TCEP, matrix effects resulted in a Qlow recovery of 142%. Relative recovery of TBEP was 235%, although no matrix interferences for the latter two compounds were seen at Qhigh level (Table 2).

Method precision between days ($RSD_{between}$, Table 2) was acceptable at the Qhigh level for all compounds with maximum RSD of 11% for DBDPE, except for TEP (30%) and T*i*BP (20%), resulting from variable losses during evaporation and variable blanks, respectively. For Qlow, the precision between different days ($RSD_{between}$) was acceptable with values below 24% for all compounds except again for TEP (52%), and T*i*BP (315%). The precision and accuracy for BFRs with this analytical method is similar to other published methods [15,39,40]. Analytical methods for OPFRs often do not include T*i*BP, but when included, they show the same precision and also a similar accuracy at levels similar to the Qhigh level [26,43,44].

Method limits of quantification (LOQ_m) were based on three times the standard deviation of blank values and divided by a typical amount of dust for analysis (75 mg). LOQ_ms ranged between 0.04 ng/g (BDE 28) and 17 ng/g (BDE 209), 10 ng/g for the sum of

Table 4
Concentrations (ng/g dust) of brominated and organophosphate ester flame retardants in indoor dust samples from various countries.

	D-01 Belgium (2010)	D-02 Belgium (2006)	D-03 Belgium (2006)	D-04 Belgium (2010)	D-05 Belgium (2010)	D-06 Romania (2007)	D-07 Spain (2006)	D-08 Romania (2007)	D-09 Romania (2007)	D-10 Belgium (2010)	D-11 Belgium (2010)	D-12 Belgium (2010)
BDE 28	0.09	<0.04	0.21	0.15	0.87	0.11	0.13	0.05	0.10	0.51	0.10	0.17
BDE 47	2.91	6.19	8.84	21.7	135	2.40	2.29	1.07	0.76	3.20	0.78	1.11
BDE 100	0.76	3.01	2.31	3.90	24.9	0.75	1.01	0.23	0.31	0.49	0.25	<0.24
BDE 99	3.50	17.8	12.0	44.3	232	4.60	7.49	0.76	1.17	2.98	0.75	1.26
BDE 154	0.35	2.04	1.06	1.68	10.7	0.54	0.68	0.07	0.17	0.22	0.21	0.26
BDE 153	0.73	3.21	2.47	5.43	23.8	1.11	1.87	0.12	0.34	0.54	1.80	0.80
BDE 183	1.93	3.04	5.80	0.42	1.04	1.30	1.30	0.32	0.32	1.01	15.1	3.07
BDE 209	167	156	176	40.8	263	3920	105	25.9	37.0	11,190	3460	847
TBB	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0
HCDBCO	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8
BTBPE	1.42	2.13	1.78	<1.1	3.41	<1.1	1.51	681	<1.1	2.26	11.4	7.68
DBDPE	6365	31.5	224	7.14	57.0	182	5820	543	684	314	107	67.0
TBPH	8.10	11.0	10.3	2.42	6.02	3.25	3.79	12.7	8.13	4.82	6.19	8.19
TEP	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
T*n*PP	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
T*i*BP	966	957	1100	689	2130	688	750	599	624	2370	745	529
T*n*BP	32	71	1510	52	127	138	27	39	49	258	75	239
TCEP	75	147	81	141	76	40	82	1450	1310	1350	205	285
TCPP	617	186	711	85	486	1020	185	8	629	404	525	533
TBEP	3430	5160	36,400	1670	3180	2720	<50	<50	2350	19,000	3240	<50
TPP	236	237	574	229	315	3750	818	105	263	492	550	2640
TDCPP	95	139	184	239	361	666	124	19	151	544	77	124
TCP	29	138	394	102	129	430	89	2350	86	1110	55	110
α-HBCD	64.6	143	12.2	204	503	89.4	30.9	29.1	93.8	1550	257	125
β-HBCD	<3.0	354	3.8	21.1	71.0	<3.0	<3.0	<3.0	5.0	442	41.4	15.6
γ-HBCD	15.7	583	1101	17.0	22.6	80.5	22.5	9.8	28.5	193	47.1	23.4
$\sum$HBCDs	80.3	1080	1117	242	596	172	55.6	41.5	127	2185	345	164

HBCD diastereomers. These values demonstrate a good sensitivity of the method for BFRs [15,17,34,40]. For OPFRs, LOQ_ms were typically higher and varied between 10 ng/g (TPP) and 370 ng/g (T*i*BP). TCEP and TBEP had calculated LOQ_ms of 110 and 50 ng/g, respectively, although results would be inaccurate at this concentration as recoveries exceeded 140% at 267 ng/g. Nevertheless, the sensitivity for most OPFRs was close to other analytical methods [23,26,27,44].

Analysis of SRM 2585: The comparison of concentrations according to the above described analytical procedure with the certified values and previously reported concentrations showed some divergence (Table 3). OPFR values were similar to those reported by Van den Eede et al. [29], except for slightly different values for TDCPP and TBEP. In neither case, the extraction solvent could not be the cause, as no differences were seen during method optimization. A possible explanation for the higher value of TBEP is the extrapolation of the calibration curve. T*i*BP values are not displayed because of the irreproducible and high blanks (680 ± 245 ng/g). Concentrations measured with the new analytical method range between 69% (BDE 28) and 91% (BDE 154) of the certified values. RSDs were 3% for lower PBDEs (BDE 28–154) and <14% for BDE 183 and BDE 209. HBCD presented higher RSD (up to 30%), most probably due to the need to combine F1 and F2 prior to the LC/MS/MS analysis.

No certified values for NBFRs exist and therefore results were compared to data from previous analyses [22]. HCDBCO and DBDPE were again not detected, and no significant differences were seen for concentrations of TBPH and BTBPE. However, mean value TBB 26 ng/g was different from 40 ng/g reported earlier, although the latter value is based on duplicate measurements only.

3.3. Method applicability

The new analytical method was applied to 12 indoor dust samples, which were collected from Belgian, Spanish and Romanian homes (Table 4). HCDBCO, TEP and T*n*PP were not detected above LOQ in any of the analyzed samples. Concentrations of T*n*BP, TCEP, TPP, TDCPP and TCP, and BFRs in these dust samples were in the range of previously reported values for Belgium [22,29,37]. T*i*BP concentrations were corrupted by a high and variable blank contribution.

Highest concentrations for T*n*BP (1500 ng/g) and TBEP (36,000 ng/g) were observed in D-03 (Belgium). D-08 (Romania) contained highest amounts of BTBPE 681 ng/g, TBPH 12.7 ng/g, TCEP 1450 ng/g and TCP 2350 ng/g. Sample D-05 (Belgium) contained highest concentration of Penta-BDE (sum 47, 99, 100, 153, 154): 427 ng/g. D-11 (Belgium) showed higher levels of BDE 183 (15.1 ng/g). Sample D-10 (Belgium) had the highest concentration of BDE 209 (11,190 ng/g) and HBCD (sum of isomers 2185 ng/g) and contained also high amounts of TBEP: 19,000 ng/g. Sample D-06 was taken from Romania and showed higher levels of TPP (3750 ng/g).

Other BFRs were also detected in these samples, but since the analytical procedure was not validated for these compounds, no concentrations are reported here. Hexabromobenzene (HBB) was detected in 50% of the samples. BDE 196, 197, 203, 206, 207, and 208 were detected in all samples.

4. Concluding remarks

We developed a reliable method for the analysis of phased-out and current-use FRs in small amounts of indoor dust. The analytical procedure is based on ultrasonic extraction and a two stage clean-up by solid phase extraction. OPFRs were quantified on GC/EI-MS, PBDEs and NBFRs on GC/ECNI-MS, and HBCDs on LC/ESI-MS/MS. Method validation proved that accuracy, precision and limits of quantification are satisfying for most compounds. We also applied the method to NIST SRM 2585 and a set of dust samples. The results of the SRM obtained with the current method were in agreement to the previously reported and certified values. The method allows saving time, as 24–36 samples can be processed daily. Although the investigated FRs possess different chemical properties, it would be valuable to develop such combined methods also for other matrices to save samples and increase the gathered amount of data at the same time.

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