

AIRBORNE POLYBROMINATED DIPHENYL ETHERS IN A COMPUTER CLASSROOM OF COLLEGE IN TAIWAN

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ABSTRACT

This study characterized the airborne exposure of students to thirty polybrominated diphenyl ether congeners inside and outside a computer classroom in a southern Taiwan college. Arithmetic mean values of total indoor and outdoor polybrominated diphenyl ether concentrations were 125.0 pg/m³ (89.8 to 203.9 pg/m³) and 110.3 pg/m³ (83.5 to 157.0 pg/m³), respectively. Total indoor polybrominated diphenyl ether concentrations were one order of magnitude lower than those detected in homes in Birmingham, United Kingdom and in Ottawa, Canada but were several times higher than those measured in the ambient air in Ottawa, Canada and from the Bohai Sea to the Arctic. The five highest indoor concentrations of polybrominated diphenyl ether congeners were decabromodiphenyl ether (23.0 pg/m³), 4,4'-dibromodiphenyl ether (15.9 pg/m³), 2,2',3,4,4',5,5',6-octabromodiphenyl ether (10.6 pg/m³), 2,4-dibromodiphenyl ether (10.3 pg/m³) and 2,2',3,4,4',5',6-heptabromodiphenyl ether (10.0 pg/m³). Although indoor and outdoor total polybrominated diphenyl ether concentrations did not significantly differ, the indoor concentrations of 2,4-dibromodiphenyl ether, 2,2',4-tribromodiphenyl ether, 2,4,4'-tribromodiphenyl ether, 2,2',4,5'-tetrabromodiphenyl ether and 2,3',4',6-tetrabromodiphenyl ether were significantly higher than their outdoor concentrations. This study suggests the following measures: 1) to increase the air exchange rate and open classroom doors and windows for several minutes before classes to reduce indoor PBDE concentrations; 2) to reduce polybrominated diphenyl ether emissions from new devices, it's better to use computer-related products that meet the Restriction of Hazardous Substances Directive adopted by the European Union.

Keywords: Polybrominated diphenyl ethers, Exposure, Indoor, Computer classroom

INTRODUCTION

In recent years, the issue of indoor air quality (IAQ) and indoor environmental quality (IEQ) in schools and educational institutions has been widely discussed (Chiang *et al.*, 2001; Shendell *et al.*, 2004; Van Dijken *et al.*, 2006; Zhang *et al.*, 2006; Corgnati *et al.*, 2007). However, IAQ or IEQ in school computer classrooms has not been elucidated. The current information technology era requires the use of computers for many classes and courses, and the time spent in computer classrooms is significantly longer than in the past. Computer classrooms are highly confined indoor spaces subject to multiple air pollutants such as polybrominated diphenyl ethers (PBDEs). Research indicates that PBDEs may

have harmful effects on the thyroid gland as well as the endocrine, reproductive, liver and nervous systems (Darnerud *et al.*, 2001; Birnbaum and Staskal, 2004). A study by Guvenius *et al.*, (2003) also stated that PBDE exposure may impair infant brain development. Therefore, the hazards of PBDE exposure in a computer classroom are worthy of attention and investigation.

The PBDEs were identified in the atmospheres of Hoburgen (1 pg/m³) and Ammarnas (8 pg/m³), in Sweden according to a report by De Wit (2002). That study also showed that the highest 2,2',4,4'-tetrabromodiphenyl ether (BDE47) levels were found on polyurethane foam plugs (gas phase) while higher levels of 2,2',4,4',5-pentabromodiphenyl ether (BDE99) and 2,2',4,4',6-pentabromodiphenyl ether (BDE100)

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were found on filters (particulate phase), which suggests that PBDEs can spread over long distances. In 2004, indoor airborne PBDE concentrations in England and Canada were measured approximately 40 times higher than those of outdoors (Harrad *et al.*, 2004; Wilford *et al.*, 2004). Median indoor and outdoor PBDE concentrations are reported as 762 pg/m³ and 18 pg/m³, respectively, in England and 100 pg/m³ and <0.1–4.4 pg/m³, respectively, in Canada.

PBDEs are typically used as brominated flame retardants in electronic and electrical products and architectural materials. Extensive use of flame retardant in electronic equipment can increase PBDE concentrations in air, and this phenomenon is particularly common in the electronics recycling industry (Sjödin *et al.*, 2001; Pettersson-Julander *et al.*, 2004). BDE47 and BDE99 are also found in the air in computer and electronic product assembly plants, which suggest that such substances can spread as air particles through electronic products and result in further human exposure (Bergman *et al.*, 1999).

Julander *et al.*, (2005) investigated the effects of PBDE concentrations on thyroid hormone levels of workers in electronic dismantling factories and reported that BDE28 showed significant increases over working times. Jakobsson *et al.*, (2002) compared serum PBDE concentrations between computer technicians with heavy workloads, clerks working full-time at computer screens and hospital cleaners with no computer experience. They quantified median lipid weights of 2,2',4,4',5,5'-hexabromodiphenyl ether (BDE153) (4.1 pmol/g), 2,2',3,4,4',5',6-

heptabromodiphenyl ether (BDE183) (1.3 pmol/g) and BDE209 (1.6 pmol/g) in computer technicians. These median concentrations were significantly higher than those in clerks and hospital cleaners. These results indicate that PBDEs used in computer and electronic products may pollute working environments and accumulate in human tissues.

This study measured PBDE concentrations in and near a computer classroom in a southern Taiwan college. The PBDE concentrations were measured in students using the computer classroom, and PBDE characteristics were analyzed in the air. Further, PBDE levels were compared between indoor and outdoor air. The study results may serve as a reference for government regulation and inspection of indoor environments and also encourage further studies of air quality in indoor learning environments.

MATERIALS AND METHODS

Sampling protocol

The sampled areas were a computer classroom and an open space in front of a teaching building in a southern Taiwan college campus. Table 1 shows the classroom characteristics, including room volume, air conditioner type, number of computers and monitor type. The sampling program in this study was divided into two phases. In the first phase conducted between September 4 and September 9, 2007 (n=2), one indoor air sample and one outdoor air sample were collected. The second phase conducted between November 22 and November 26, 2007 (n=5) included three indoor and two outdoor samples.

Table 1: Classroom information including room volume (m³), air conditioner type, number of computers (no.) and monitor type

Room volume	Air conditioner type	Number of computers	Monitor type
384	water-cooled package / stand-alone (cycling system)	61	liquid crystal display (LCD)

Air samples were collected using a PS-1 high-volume air sampler (General Metal Works, USA) fitted with a total suspended particulate inlet modified to hold a glass fiber filter and a precleaned polyurethane foam (PUF) as described previously (Harrad *et al.*, 2004). The typical sampling flow rate was 0.25 m³/min. To

minimize underestimation of concentrations, the total volume of air drawn from the computer classroom could not exceed its indoor volume and allowed to re-equilibrate for an identical period (Harrad *et al.*, 2004). The indoor air sampling was conducted over a period of approximately 24 hours for each sample and in the absence of

the classroom occupants, all electrical appliances including computers and monitors were switched on during sampling. The outdoor air sampling was conducted using the same equipment used for the indoor air sampling, but in view of the anticipated lower concentration likely to be present in the outdoor air, the total volume of outdoor air drawn was continuously for approximately 120 hours per sample.

Chemical analyses

The NIEA M802.00B method, referred to as USEPA Method 1614 and implemented by the Environmental Protection Administration, Executive Yuan, R.O.C. (Environmental Protection Administration issued an Order No. 0960034749 dated May 8, 2007) was used to determine the PBDE content in the air samples. In this study, filter and PUF were analyzed as a unit to avoid the confounding effects of low analyte quantities in the samples. The analytical methods are described in detail below.

All reagents were residue grade and included the following compounds: hexane, toluene, dichloromethane, methanol, nonane, acetone, sulphuric acid and sodium sulfate anhydrous granules (Tedia, USA). Silica (100–200 mesh, Fisher Scientific, USA) was activated by heating at 180 °C for 1 hour before use. The silica was then cooled to room temperature and stored in a glass bottle with a screw cap and Teflon pad. Alumina (50–200 mesh, Brockmann grade I, Lancaster Synthesis, USA) was activated at 170 °C to 180°C before use. Isotope-labeled PBDE standard solutions included BDE-CVS-E, MBDE-MXE, BDE-CVS-EISS, BDE-MXE (Wellington Laboratories, Canada), BDE-139S, BDE-140S, BDE-203S and BDE-208S (AccuStandard, USA).

A suitable Soxhlet extraction apparatus was selected according to the sample volume. A clean flask containing Teflon boiling stone was connected to the Soxhlet extraction tube, and toluene was used for reflux after adding 20- μ L surrogate standards. Heat was adjusted to produce reflux at least 4 times per hour. After 22 \pm 2 hours of extraction, samples were cooled to room temperature, and the toluene extraction solvents were condensed to nearly dry conditions

using a rotary evaporator.

Dichloromethane (< 200 μ L) was added into the sample tubes containing extract to dissolve inner material followed by addition of 7-mL hexane and 4-mL sulphuric acid with 20 seconds of vigorous agitation. Samples were allowed to stand until stratified. The upper layer organic solvent was then moved transferred to a clean tube, and the acid solvent in the lower layer was mixed with 7-mL hexane and washed again. The clean-up procedure for the lower layer acid solvent was performed twice as described previously. All organic solvents collected in the three clean-up procedures were concentrated using nitrogen blowdown to a final volume of ca. 7-mL hexane. The concentrated sample extracts were subjected to acidic silica column chromatography to remove interference. The acidic silica columns were pre-cleaned with 10-mL hexane, and sample extracts were loaded. The columns were then eluted with 5-mL hexane three times.

The eluted solvents were collected using the same Turbo tube and concentrated using nitrogen blowdown to ca. 1 mL of hexane. The concentrated sample extracts were then subjected to acidic alumina column chromatography. The acidic alumina columns were pre-cleaned with 10-mL hexane, and sample extracts were loaded. The columns were then eluted with 5-mL hexane three times. The eluted solvents were collected by test tube and stored. Dichloromethane/hexane (50/50, v/v) mixture (5 mL) was used to elute the acidic alumina column eight times.

The eluted solvents were collected in a Turbo tube then concentrated using nitrogen blowdown to near dryness. Dichloromethane was used to wash the upper inner tube wall, and the tube was then concentrated to near dryness by nitrogen evaporation. Ten μ L of internal standards were added to the sample tubes before instrumental analyses.

The instrumental determination was performed using an HP6890 high-resolution gas chromatograph (HRGC) (Agilent, USA) and a high-resolution mass spectrometer (HRMS) (Micro-mass Autospec Ultima, UK). For the pretreated samples, the qualitative and quantitative analyses of thirty PBDE congeners were performed: using the ¹³C isotope dilution method and HRGC/

HRMS 2,4-dibromodiphenyl ether (BDE7), 4,4'-dibromodiphenyl ether (BDE15), 2,2',4-tribromodiphenyl ether (BDE17), 2,4,4'-tribromodiphenyl ether (BDE28), BDE47, 2,2',4,5'-tetrabromodiphenyl ether (BDE49), 2,3',4,4'-tetrabromodiphenyl ether (BDE66), 2,3',4',6-tetrabromodiphenyl ether (BDE71), 3,3',4,4'-tetrabromodiphenyl ether (BDE77), 2,2',3,4,4'-pentabromodiphenyl ether (BDE85), BDE99, BDE100, 2,3',4,4',6-pentabromodiphenyl ether (BDE119), 3,3',4,4',5-pentabromodiphenyl ether (BDE126), 2,2',3,4,4',5'-hexabromodiphenyl ether (BDE138), 2,2',3,4,4',6-hexabromodiphenyl ether (BDE139), 2,2',3,4,4',6'-hexabromodiphenyl ether (BDE140), BDE153, 2,2',4,4',5,6'-hexabromodiphenyl ether (BDE154), 2,3,3',4,4',5-hexabromodiphenyl ether (BDE156), BDE183, 2,2',3,4,4',6,6'-heptabromodiphenyl ether (BDE184), 2,3,3',4,4',5',6-heptabromodiphenyl ether (BDE191), 2,2',3,3',4,4',5,6'-octabromodiphenyl ether (BDE196), 2,2',3,3',4,4',6,6'-octabromodiphenyl ether (BDE197), 2,2',3,4,4',5,5',6-octabromodiphenyl ether (BDE203), 2,2',3,3',4,4',5,5',6-nonabromodiphenyl ether (BDE206), 2,2',3,3',4,4',5,6,6'-nonabromodiphenyl ether (BDE207), 2,2',3,3',4,5,5',6,6'-nonabromodiphenyl ether (BDE208) and BDE209, were performed. The instrumental analysis conditions included a chromatography column (DB-5HT, 15 m × 0.25 mm × 0.1 μm, Agilent, USA), injection port connected to a capillary column (splitless, 250°C) and carrier gas (helium, 1.0 mL/min). Injection volume was 1 μL. Column temperatures of 100°C were held for 4 minutes then increased at 40°C/min to 200°C and held for 3.5 minutes and finally increased at 10°C/min to 325°C and held for 2.5 minutes.

Quality assurance and quality control

At the beginning of developing the PBDE analytical method, solutions of native analytes and relevant isotope-labeled standards were added to the sampling glass cartridges. After the above extraction and clean-up procedures, the sample analysis results were used to calculate the initial precision and recovery (IPR) of the PBDE analytical method. The IPR test data met the quality control criteria of the NIEA M802.00B

method used in this study (data not shown).

Before practical sample extraction and clean-up, isotope-labeled PBDE standards (surrogate standards) were added to each sample to quantify PBDE levels in samples and to evaluate the method performance. In this study, recoveries of the isotope-labeled standards of TrBDE, TeBDE, PeBDE, HxBDE, HpBDE and DeBDE were between 34.0% (¹³C-BDE209, 10Br) and 148.5% (¹³C-BDE209, 10Br). These met the quality control criteria of the NIEA M802.00B method (data not shown).

After each batch analysis or after every ten practical samples, blank matrix analyses were performed using the same procedures as those for the practical sample analyses. The recovery results of native analytes and surrogate standards added to the blank matrices met the quality control criteria of NIEA M802.00B method (data not shown).

Data treatment and analysis

Data were filed and calculated by EXCEL 2003 (Microsoft, U.S.A.). SPSS v12.0 (SPSS, U.S.A.) was used for statistical analysis. Sample values lower than detection limits (DL) were set to DL/2 to construct the concentration distribution profiles of PBDE congeners and for further data treatment. The student *t*-test was used to assess whether PBDE concentrations significantly differed between indoor and outdoor air. A *p* value < 0.05 (two-tailed) was considered statistically significant when testing the hypotheses.

RESULTS

Concentrations of total PBDEs in indoor and outdoor air

Table 2 presents the concentrations of total PBDEs in the indoor and outdoor air of the computer classroom sampled in two phases. The total PBDE concentration in indoor air collected in the first phase was 89.8 pg/m³. The second phase yielded mean (136.7 pg/m³), standard deviation (58.4 pg/m³) and range (99.2–203.9 pg/m³) of PBDE concentration levels. The total PBDE concentration for outdoor air collected in the first phase was 83.5 pg/m³, and the mean PBDE concentration, standard deviation and range were 123.8, 47.0 and 90.5–157.0 pg/m³,

respectively, in the second phase. Combined data from phases I and II showed that the mean PBDE concentration, standard deviation and range in indoor air were 125.0, 53.1 and 89.8–203.9 pg/m^3 , respectively, and corresponding values in outdoor air were 110.3, 40.6 and 83.5–157.0 pg/m^3 , respectively. However, the mean concentrations of total PBDEs in indoor and outdoor air did not significantly differ ($p = 0.813$).

Table 2: Concentrations (pg/m^3) of total PBDEs in indoor and outdoor air of the computer classroom sampled in two phases

Sample	Mean	Standard Deviation	Range
Phase I			
Indoor (n=1)	89.8	–	–
Outdoor (n=1)	83.5	–	–
Phase II			
Indoor (n=3)	136.7	58.4	99.2–203.9
Outdoor (n=2)	123.8	47.0	90.5–157.0
Phases I and II ^a			
Indoor (n=4)	125.0	53.1	89.8–203.9
Outdoor (n=3)	110.3	40.6	83.5–157.0

^a Mean total PBDE concentration in indoor and outdoor air did not significantly differ ($p=0.813$).

Congener and homolog profiles

Fig. 1 shows the concentration distribution profile of PBDE congeners in the indoor and outdoor air of the sampled computer classroom. The top five concentrations of PBDE congeners in indoor air and corresponding percentages were BDE209 (23.0 pg/m^3 , 18.4%), BDE15 (15.9 pg/m^3 , 12.7%), BDE203 (10.6 pg/m^3 , 8.5%), BDE7 (10.3 pg/m^3 , 8.3%) and BDE183 (10.0 pg/m^3 , 8.0%). These five congeners comprised 55.9% of the total PBDE concentration. Comparatively, the top five concentrations of PBDE congeners, which comprised 76.9% of the total PBDE concentration in outdoor air, were BDE209 (53.3 pg/m^3 , 48.3%), BDE207 (9.1 pg/m^3 , 8.2%), BDE206 (8.6 pg/m^3 , 7.8%), BDE203 (8.2 pg/m^3 , 7.5%) and BDE208 (5.7 pg/m^3 , 5.1%). The mean BDE209 concentration in outdoor air (53.3 pg/m^3) was significantly higher than that in indoor air (23.0 pg/m^3) ($p < 0.05$). However, the mean BDE7, BDE17, BDE28, BDE49 and BDE71 concentrations in indoor air were significantly higher than those of outdoor air ($p < 0.05$).

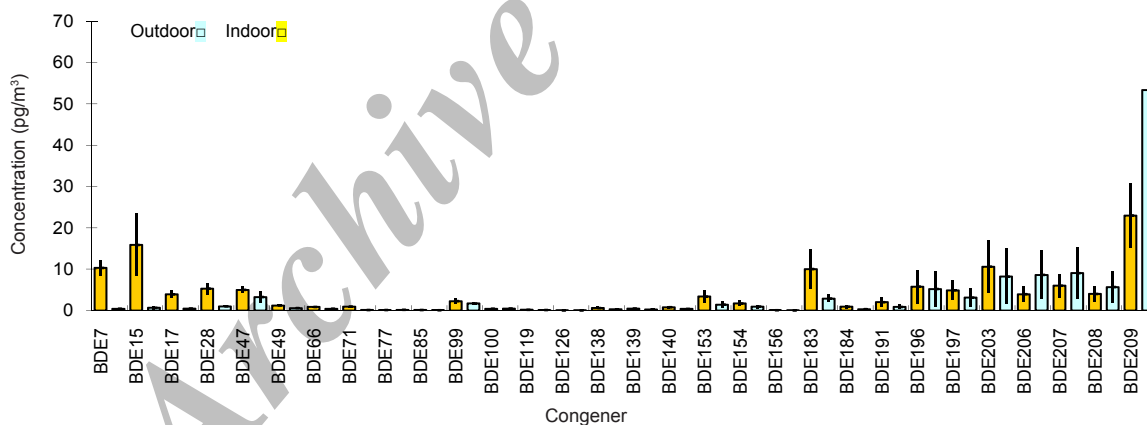


Fig. 1: PBDE congener profile found in indoor and outdoor air of the computer classroom sampled. Mean values \pm standard error of the mean ($p < 0.05$)

Fig. 2 shows the concentration distribution profile of PBDE homologs in the indoor and outdoor air sampled from the computer classroom. The di-BDEs (13.1 pg/m^3), tri-BDEs (4.6 pg/m^3), hepta-BDEs (4.3 pg/m^3), octa-BDEs (7.1 pg/m^3), nona-BDEs (4.7 pg/m^3) and deca-BDEs (23.0 pg/m^3) were the predominant homologs in the indoor air samples while octa-BDEs (5.5 pg/m^3), nona-BDEs (7.8 pg/m^3) and deca-BDEs (53.3 pg/m^3) were predominant in the outdoor air samples.

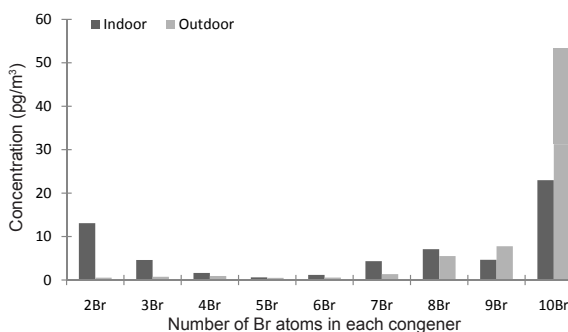


Fig. 2: PBDE homolog profile found in indoor and outdoor air of the computer classroom sampled

DISCUSSION

Table 3 compares airborne PBDE concentrations in the computer classroom analyzed in this study with reported PBDE concentrations in various working environments in countries elsewhere. The PBDE congener concentrations in the dismantling hall at a Swedish electronics recycling plant were 240 (BDE47) to 1900 times (BDE183) higher than those measured inside the computer classroom in this study (Sjödin *et al.*, 2001).

The total PBDE concentration (eight congeners) in the indoor air of the dismantling facility in a Swedish electronics recycling plant was approximately 1385 times higher than that revealed in this study. Harrad *et al.*, (2004) tested PBDE concentrations in indoor air in ten different workplaces in Birmingham, England.

Harrad reported that test concentrations of PBDE congeners in the ten surveyed facilities were 7 (BDE153) to 543 times (BDE100) higher than those observed here. The total PBDE concentration (five congeners) in ten places was about 218 times higher than that observed in this study. Test concentrations of PBDEs congeners in outdoor air from the electronics recycling plant were 3 (BDE17) to 500 times (BDE100) higher than those tested here (Pettersson-Julander *et al.*, 2004). The total PBDE concentration (twenty-two congeners) in the air outside a dismantling facility was about 56 times higher. However, the PBDE concentration in the indoor air in office with computers at a Swedish electronics recycling plant (Sjödin *et al.*, 2001) was comparable to that observed in this study.

Table 3: Reference values for airborne PBDE concentrations in the computer classroom in this study and those for workplaces reported in the literature

Exposure Category	Site	Congener	Mean Concentration ($\mu\text{g} / \text{m}^3$)	Ratio	Literature
Dismantling hall at an electronics recycling plant (n=12) ^{c,d}	Sweden	BDE47	1200 / 5.0	240.0	Sjödin <i>et al.</i> (2001)
		BDE85	170 / 0.2	850.0	
		BDE99	2600 / 2.3	1130.4	
		BDE100	250 / 0.4	625.0	
		BDE163	3900 / 3.4	1147.1	
		BDE174	570 / 1.7	335.3	
		BDE183	19000 / 10.0	1900.0	
		BDE209	36000 / 23.0	1565.2	
		sumBDE	63690 / 46.0	1384.6	
Unspecified workplace (n=10) ^e	Birmingham, U.K.	BDE47	1669 / 5.0	333.8	Harrad <i>et al.</i> (2004)
		BDE99	852 / 2.3	370.4	
		BDE100	217 / 0.4	542.5	
		BDE153	22 / 3.4	6.5	
		BDE154	28 / 1.7	16.5	
		sumBDE	2788 / 12.8	217.8	
Outside a dismantling facility working with installing and removing white goods (n=3) ^e	Sweden	BDE17	10 / 3.9	2.6	Pettersson-Julander <i>et al.</i> (2004)
		BDE28	30 / 5.3	5.7	
		BDE47	500 / 5.0	100.0	
		BDE49	200 / 1.2	166.7	
		BDE66	70 / 0.9	77.8	
		BDE71	20 / 1.0	20.0	
		BDE85	20 / 0.2	100.0	
		BDE99	900 / 2.3	391.3	
		BDE100	200 / 0.4	500.0	
		BDE119	30 / 0.2	150.0	
		BDE138	20 / 0.6	33.3	
		BDE153	70 / 3.4	20.6	
		BDE154	30 / 1.7	17.6	
		BDE156	10 / 0.1	100.0	
		BDE183	200 / 10.0	20.0	
		BDE184	40 / 0.9	44.4	
		BDE191	10 / 2.0	5.0	
		BDE196	70 / 5.8	12.1	
		BDE197	200 / 4.9	40.8	
		BDE206	100 / 3.9	25.6	
		BDE207	100 / 6.0	16.7	
		BDE209	1700 / 23.0	73.9	
sumBDE	4600 / 82.7	55.6			
Office with computers at an electronics recycling plant (n=4) ^{c,d}	Sweden	BDE183	8.2 / 10.0	0.8	Sjödin <i>et al.</i> (2001)
		BDE209	83.0 / 23.0	3.6	

^a Data from literature. ^b Indoor PBDE concentrations observed in this study. ^c Samples collected using personal sampler. ^d Concentration of particle-associated brominated flame retardants. ^e Samples collected using high-volume sampler.

Table 4 compares the airborne PBDE concentrations measured in this study with those reported for non-working environments in other countries. The concentrations of each PBDE congener measured in the indoor air of houses in Birmingham, England (Harrad *et al.*, 2004) and in Ottawa, Canada (Wilford *et al.*, 2004) exceeded those observed in this study: 0.6 (BDE153) to 85 times (BDE47) and 0.5 (BDE153) to 32 times (BDE47), respectively. The total PBDE concentrations in the Birmingham and Ottawa studies were about 41 times (five congeners) and 11 times (ten congeners) higher, respectively, than those observed here. The concentrations

of each PBDE congener and the total PBDE concentration (five congeners) in the indoor air in the computer classroom in this study were about 2 (BDE99) to 250 times (BDE17) higher and about 8 times higher than those in outdoor air in Ottawa, Canada, respectively (Wilford *et al.*, 2004). The PBDE concentration in indoor air in this study was slightly lower than that in outdoor air in Birmingham, England (Harrad *et al.*, 2004). However, concentrations of several PBDE congeners were substantially higher than those in the ambient air from the Bohai Sea to the Arctic with the exception of BDE47, BDE66, BDE85, BDE99 and BDE100 (Wang *et al.*, 2005).

Table 4: Reference values for airborne PBDE concentrations in the computer classroom in this study and those for non-workplaces reported in the literature

Exposure Category	Site	Congener	Mean Concentration (L ^g / T ^h) (pg/m ³)	Ratio	Literature
Domestic microenvironments (n=7) ^c	Birmingham, U.K.	BDE47	424 / 5.0	84.8	Harrad <i>et al.</i> (2004)
		BDE99	70 / 2.3	30.4	
		BDE100	27 / 0.4	67.5	
		BDE153	1.9 / 3.4	0.6	
		BDE154	1.9 / 1.7	1.1	
		sumBDE	5.5 / 12.8	41.0	
Homes (n=6-73) ^d	Ottawa, Canada	BDE17	12 / 3.9	3.1	Wilford <i>et al.</i> (2004)
		BDE28	24 / 5.3	4.5	
		BDE47	160 / 5.0	32.0	
		BDE66	2.9 / 0.9	3.2	
		BDE71	11 / 1.0	11.0	
		BDE85	0.72 / 0.2	3.6	
		BDE99	42 / 2.3	18.3	
		BDE100	10 / 0.4	25.0	
		BDE153	1.6 / 3.4	0.5	
		BDE154	1.9 / 1.7	1.1	
sumBDE	260 / 24.1	10.8			
Outdoor air (n=2-5) ^d	Ottawa, Canada	BDE17	0.017 / 3.9	0.004	Wilford <i>et al.</i> (2004)
		BDE28	0.095 / 5.3	0.018	
		BDE47	0.870 / 5.0	0.174	
		BDE99	1.100 / 2.3	0.478	
		BDE100	0.110 / 0.4	0.275	
		sumBDE	2.200 / 16.9	0.130	
Outdoor air (n=7) ^c	Birmingham, U.K.	BDE47	9.4 / 5.0	1.9	Harrad <i>et al.</i> (2004)
		BDE99	5.0 / 2.3	2.2	
		BDE100	1.4 / 0.4	3.5	
		BDE153	2.9 / 3.4	0.9	
		BDE154	1.8 / 1.7	1.1	
		sumBDE	21 / 12.8	1.6	
Ambient air (n=3-46) ^{c,e}	from the Bohai Sea to the Arctic	BDE28	0.20 / 5.3	0.038	Wang <i>et al.</i> (2005)
		BDE47	10.8 / 5.0	2.160	
		BDE66	0.23 / 0.9	0.383	
		BDE85	0.25 / 0.2	1.250	
		BDE99	6.14 / 2.3	2.670	
		BDE100	1.38 / 0.4	3.450	
		BDE138	0.06 / 0.6	0.100	
		BDE153	0.28 / 3.4	0.082	
		BDE154	0.22 / 1.7	0.129	
		BDE183	0.03 / 10.0	0.003	
		BDE209	4.35 / 23.0	0.189	
		sumBDE	23.9 / 52.8	0.453	

^a Data from literature. ^b Indoor PBDE concentrations observed in this study. ^c Samples collected using high-volume sampler. ^d Samples collected using passive air sampler. ^e Particulate samples.

The analytical results of this study show that the total PBDE concentration in indoor air in the computer classroom was three times lower than that in the dismantling hall at an electronics recycling plant (Table 3), two times lower than that in other indoor working environments (Table 3) and one order lower than that in indoor home air (Table 4). However, total PBDE concentrations in indoor air in the computer classroom were similar to levels in an office with computers (Table 3).

Two explanations for the above results are proposed. Firstly, the computer-related equipment used in the computer classroom had been used for several years and consequently had lower rate of PBDE emissions than newly installed equipment. Secondly, some studies did not reveal concentrations of certain PBDE congeners such as BDE183 and BDE209, which are the predominant congeners in the computer classroom analyzed here. Therefore, these congeners may have been underestimated when comparing the total PBDE concentrations determined in the computer classroom with those reported in previous studies. Nevertheless, total indoor PBDE concentrations in the examined computer classroom was still about 8 times higher than total outdoor PBDE concentrations in Ottawa, Canada (Table 4).

Congener concentrations of BDE28, BDE138, BDE153 and BDE183 were also higher in the computer classroom in this study than those in the ambient air sampled from the Bohai Sea to the Arctic; the concentrations in the classroom were several dozen to several hundred times higher in magnitude (Table 4).

The result of this study revealed that mean total PBDE concentrations did not significantly differ between indoor and outdoor air of the computer classroom (Table 2). These findings differ from the results of Harrad *et al.*, (2004) in a Birmingham study and Wilford *et al.*, (2004) in an Ottawa study, respectively, which reported total indoor PBDE concentrations 25 and 118 times higher, respectively, than outdoor concentrations (Table 4). Outdoor PBDE concentrations in this study were higher than those reported in Japan (Watanabe *et al.*, 1992), Sweden (de Wit, 2002), Canada (Wilford *et al.*, 2004) and the Bohai Sea to the Arctic (Wang *et al.*, 2005). Whether this was due to gas emissions from the nearby

recycling plant is unclear. Further, although total PBDE concentrations did not significantly differ between indoor and outdoor air of the studied computer classroom, the viewpoint of home ventilation likely to be a source to the outdoors in urban areas (Strandberg *et al.*, 2001; Butt *et al.*, 2004) is still not applicable to this study due to the concentration distribution profiles of PBDE congeners and homologs differing from one another (Figs. 1 and 2). The mean indoor concentrations of low PBDE congeners such as BDE7, BDE17, BDE28, BDE49 and BDE71 significantly exceeded the outdoor concentrations. This suggests that these compounds were primarily derived from the computer-related equipments in the computer classroom, which is consistent with the results reported by Julander *et al.*, (2005) and by Wilford *et al.*, (2004).

Previous studies of electronics recycling plants and other indoor environments have focused on quantifying BDE47, BDE99, BDE100, BDE153, BDE154, BDE183 and BDE209 (Sjödin *et al.*, 1999; Sjödin *et al.*, 2001; Harrad *et al.*, 2004; Pettersson-Julander *et al.*, 2004), indicated that the concentration levels of BDE47, BDE99, BDE183 and BDE209 in indoor air were higher among all PBDE congeners detected (Sjödin *et al.*, 2001; Pettersson-Julander *et al.*, 2004). Additionally, the BDE47, BDE99, BDE100, BDE183 and BDE209 concentrations detected in the serum of workers exposed to these compounds were higher than those in workers who were not exposed (Pettersson-Julander *et al.*, 2004; Sjödin *et al.*, 1999). Therefore, some researchers suggest that these compounds are likely the main source of exposure to PBDE components. Our study identified BDE99, BDE153, BDE183 and BDE209 (PBDE congeners) with higher concentrations in indoor air in the computer classroom (Fig. 1), particularly BDE153, which revealed higher levels in indoor and outdoor air than in other studies (Table 4).

Indoor concentrations of di-BDE and tri-BDE congeners such as BDE7, BDE17, BDE28, BDE49 and BDE71 were also significantly higher than outdoor concentrations. Further, indoor concentrations of hepta-BDE, octa-BDE and nona-BDE congeners such as BDE196, BDE197, BDE203, BDE206, BDE207 and BDE208 were

higher than outdoor concentrations (Figs. 1 and 2). This study examined thirty congeners, many of which have not been previously reported.

In summary, although total PBDE concentrations in the indoor air of the computer classroom was clearly lower than those reported elsewhere for various indoor environments, the concentration was still several times higher than that in outdoor environments. Further, Harrad *et al.*, (2004) suggested that using indoor electronic equipment and polyurethane foam chairs can significantly increase indoor PBDE concentrations. Therefore, the issue of PBDE exposure in computer classrooms cannot be ignored.

Whether PBDE concentrations are affected by the number of computers used, computer age and the building construction materials also merits further study. Additionally, PBDE concentrations in outdoor air in this study were high; the main components were hepta-, octa-, nona- and deca-BDEs. These values may have resulted from PBDE emissions from the nearby recycling plant, but further investigation is needed. The analytical results of this study suggest that increasing air exchange rates or opening doors and windows before classes can reduce indoor PBDE concentrations (Chang *et al.*, 2009). In July, 2006, the EU initiated the RoHS, in which the importation of products containing six substances, including PBDEs, was curtailed. Therefore, our results suggest that restricting computer-related products that do not comply with the EU RoHS should have be of priority concern in a program aimed at reducing PBDE emissions from new devices.

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