Aerosol and Air Quality Research

ORIGINAL RESEARCH
https://doi.org/10.4209/aaqr.220264

Polybrominated Dibenzo-*p*-dioxins/Furans (PBDD/Fs) and Diphenyl Ethers (PBDEs) in the Indoor and Outdoor of Gymnasiums

Ching-Kai Su[1,2], Jian-He Lu[3], How-Ran Chao[1,3,4,5*], Wei-Hsiang Chang[6], Ming-Hsien Tsai[7], Chih-Lung Wang[8,9], I-Cheng Lu[1], Yu-Ting Chang[1], Hsiao-Chi Chuang[10], Wan-Nurdiyana-Wan Mansor[11], Yi-Chyun Hsu[12], Ying-I Tsai[13], Shang-Ming Ma[14]

[1] Department of Environmental Science and Engineering, National Pingtung University of Science and Technology, Pingtung 91201, Taiwan
[2] Department of Internal Medicine, Kaohsiung Veterans General Hospital Pingtung Branch, Pingtung 91245, Taiwan
[3] Emerging Compounds Research Center, General Research Service Center, National Pingtung University of Science and Technology, Pingtung 91201, Taiwan
[4] Institute of Food Safety Management, College of Agriculture, National Pingtung University of Science and Technology, Pingtung 91201, Taiwan
[5] School of Dentistry, College of Dental Medicine, Kaohsiung Medical University, Kaohsiung 807, Taiwan
[6] Department of Food Safety/ Hygiene and Risk Management, College of Medicine, National Cheng Kung University, Tainan 701, Taiwan
[7] Department of Child Care, National Pingtung University of Science and Technology, Pingtung 91201Taiwan
[8] Department of Civil Engineering and Geomatics, Cheng Shiu University, Kaohsiung 833, Taiwan
[9] Center for Environmental Toxin and Emerging-contaminant Research, Cheng Shiu University, Kaohsiung 833, Taiwan
[10] School of Respiratory Therapy, College of Medicine, Taipei Medical University, Taipei 110, Taiwan
[11] Faculty of Ocean Engineering Technology & Informatics, Universiti Malaysia Terengganu, 21300, Malaysia
[12] Department of Environmental Engineering, Kun Shan University, Tainan 710, Taiwan
[13] Department of Environmental Engineering and Science, Chia Nan University of Pharmacy & Science, Tainan 71710, Taiwan
[14] Department of Recreational Sport and Health Promotion, National Pingtung University of Science and Technology, Pingtung 91201Taiwan

OPEN ACCESS

Received: July 2, 2022
Revised: August 21, 2022
Accepted: August 21, 2022

*** Corresponding Author:**
hrchao@mail.npust.edu.tw

Publisher:
Taiwan Association for Aerosol Research
ISSN: 1680-8584 print
ISSN: 2071-1409 online

ABSTRACT

It is still unknown whether the organobromine compounds in the indoor environment of the gyms would affect human health. This study tried to investigate $PM_{2.5}$ and indoor-dust levels of polybrominated dibenzo-*p*-dioxins/furans (PBDD/Fs) and diphenyl ethers (PBDEs) in the gyms and then to further assess the health risks of the gym users and employees who were exposed to these organobromines through inhalation and ingestion. The gyms were to be examined for PBDD/DF/DEs on $PM_{2.5}$ indoors and outdoors and in indoor dust. The results showed that indoor-dust, indoor $PM_{2.5}$, and outdoor $PM_{2.5}$ levels of PBDD/Fs were 37.8 ± 13.7 pg WHO_{2005}-TEQ g^{-1} and 0.00650 ± 0.00340 and 0.00469 ± 0.00101 pg WHO_{2005}-TEQ m^{-3}, respectively, in the gyms, while for PBDEs, they were 2670 ± 2330 ng g^{-1} and 9.54 ± 4.68, and 8.27 ± 3.46 pg m^{-3}. The PBDEs levels observed in this study were relatively lower when compared with the current global data of $PM_{2.5}$ and indoor dust levels of PBDEs. The observed $PM_{2.5}$-bound PBDDFs and PBDEs in the indoor gyms were not related to those in the outdoor gyms, but certain PBDE level was associated with PBDD/Fs in the indoor dust of the gyms. It suggested that the outdoor emission might not be correlated with the indoor emission, whereas indoor-dust PBDD/Fs might be converted from the pyrolysis of indoor-dust PBDEs. To assess the risks, the non-dietary daily intakes of PBDEs and PBDD/Fs were estimated as 1.61–2.11 × 10^{-7} and 4.15–5.42 × 10^{-13} mg kg b.w.$^{-1}$ day^{-1}, respectively, in the employees and 5.04–6.58 × 10^{-8} and 1.29–1.69 × 10^{-13} mg kg b.w.$^{-1}$ day^{-1}, respectively, in the gym users. The values didn't exceed the critical levels when the gym employees and users were assessed by non-cancer and cancer risks of organobromines. In conclusion, although the gym employees and users inhaled more $PM_{2.5}$ during the exercise, the risks of PBDD/DE/DFs were still under the acceptable levels.

Keywords: $PM_{2.5}$, Indoor dust, PBDEs and PBDD/Fs, Gym, Health risks

1 INTRODUCTION

Due to the high prevalence of hypertension, hyperglycemia, and hyperlipidemia in Taiwan (Hsu *et al.*, 2021), these chronic diseases are related to metabolic syndromes and are also associated with people with insufficiently physical exercise (Booth *et al.*, 2012). For the improvement of the health of the Taiwanese citizens, the Health Promotion Administration, and the Ministry of Health and Welfare, Taiwan encourage the citizens for sufficient activities which in turn accelerated the exponentially increased numbers of gymnasiums or gyms in Taiwan (Chou and Huang, 2021). The gyms were provided for sports and physical activity in the indoor environment. The indoor air quality (IAQ) in the microenvironments of the gyms was related to human health, especially for physical activities. The exponentially increased numbers of indoor sports facilities and workers were observed due to the dramatical increase of sports enthusiasts in the last decade in Taiwan (Chou and Huang, 2021). Thus, the concerns of both public and government (Environmental Protection Administration, Taiwan (TEPA)) for IAQ of the gyms have been raised. It was observed that the concentration levels of carbon dioxide (CO_2) and particulate matters (PMs) were significantly affected by the time of elevated human occupation, frequent human activity, and poor ventilation in fitness centres or gyms (Castro *et al.*, 2015; Andrade and Dominski, 2018; Slezakova *et al.*, 2018; Salonen *et al.*, 2020). A gym located in a university was known to contain higher levels of $PM_{2.5}$, PM_{10}, and carbonyl compounds including acrolein and formaldehyde indoors than that outdoors (Alves *et al.*, 2013; Castro *et al.*, 2015). $PM_{2.5}$ levels in gyms or fitness centres were also notably associated with human occupation and frequent activities (Castro *et al.*, 2015). This indicated that the short-term physical activity like cardio activities might have significant effects on the daily inhalation dose and it was also demonstrated that the exercising females possibly inhaled the ultrafine particulate (UFP) 1.2 times higher when compared with the exercising males in the fitness centres (Slezakova *et al.*, 2018).

$PM_{2.5}$ is ubiquitously existed in the indoor and outdoor environment (Bai *et al.*, 2021; Navinya *et al.*, 2020; Yu *et al.*, 2021). Several types of environmental pollutants, including metals, organic compounds, and microbes, are contaminated on $PM_{2.5}$ (Chen *et al.*, 2021; Shen *et al.*, 2020; Siudek and Ruczyńska, 2021; Vega *et al.*, 2021). To raise the public concerns, $PM_{2.5}$ has been demonstrated to cause the adverse effects on animal models and human bodies (Chao *et al.*, 2018; Chung *et al.*, 2020; Zhang *et al.*, 2020). In our previous study (Chao *et al.*, 2016), respirable PBDEs were detectable in the indoor (i.e., library, rail station, and supermarket) and outdoor (i.e., urban, rural, and industrial areas) environments.

Like the other indoor environments in workplaces, a lot of consumer products or electronic equipment are now available in the gyms also. It is still unknown whether the brominated flame retardants (BFRs), such as polybrominated diphenyl ethers (PBDEs) and the dibrominated by-product of BFRs, including polybrominated dibenzo-*p*-dioxins/furans (PBDD/Fs), are widespread in the gym environments. However, it has been demonstrated to have a negative impact on human exposure to PBDEs or PBDD/Fs leading to human health effects such as decreased semen quality, alteration of thyroid and growth hormone homeostasis, delay of neurological behaviour and neurodevelopment, and disruption of menstrual cycles and pregnancy periods (Chao *et al.*, 2014a). Our previous studies indicated that PBDEs or PBDD/Fs were found in several indoor environments including residential houses, classrooms in elementary schools, offices, medical and dental clinics, and workplaces in electronic and vehicle dismantler factories (Chao *et al.*, 2014c; Shy *et al.*, 2015; Chao *et al.*, 2016; Chou *et al.*, 2016; Gou *et al.*, 2016a, 2016b). $PM_{2.5}$-bound PBDEs were also observed in public indoor environments like libraries, rail stations, department stores, offices, hospitals, and supermarkets in Taiwan (Chao *et al.*, 2016). Among PBDEs, BDE-209 was the predominated PBDE congener in the Taiwanese microenvironments (Chao *et al.*, 2014c; Shy *et al.*, 2015; Chao *et al.*, 2016; Chou *et al.*, 2016; Gou *et al.*, 2016a, 2016b). Our previous findings (Shy *et al.*, 2015) showed that for the non-dietary daily intake of PBDEs in the indoor environment of the residential houses, indoor air inhalation intake was 1.88 and 1.29% of the total in male and female adults, respectively, and the house dust was the main exposure pathway of the non-dietary PBDEs intake.

To the best of our knowledge, this was the first study addressed the investigation of the POPs in the indoor environment of the gyms especially for $PM_{2.5}$-bound PBDD/DF/DEs and these organobromines in indoor dust. It was studied that the increment of respiratory ventilation and the inhalation of air through the mouth rather than the nasal, which has particle-filtering apparatus, during the exercise was accelerated in the case of gym users with exposure to the environmental contaminants via inhalation or ingestion. Finally, this study also assessed the health risks of the gym users and employees after they were exposed to PBDD/DF/DEs.

2 METHODS

2.1 Chemicals and Reagents

The native mixtures of standards of twelve congeners of PBDD/Fs (2,3,7,8-TeBDF, 1,2,3,7,8-PeBDF, 2,3,4,7,8-PeBDF, 1,2,3,4,7,8-HxBDF, 1,2,3,4,6,7,8-HpBDF, OctBDF, 2,3,7,8,-TeBDD, 1,2,3,7,8-PeBDD, 1,2,3,7,8,9-HxBDD, 1,2,3,4,6,7,8-HxBDD, 1,2,3,4,6,7,8-HpBDD, and OctBDD) and fourteen congeners of PBDEs (BDE-28, 47, 99, 100, 153, 154, 183, 196, 197, 203, 206, 207, 208, and 209) were purchased from Cambridge Isotope Laboratories (Andover, MA, USA). The $^{13}C_{12}$-labeled internal standards of organobromine compounds, such as nine $^{13}C_{12}$-labeled PBDEs (BDE-28, 47, 99, 153, 154, 183, 197, 207, and 209) and PBDD/Fs (2,3,7,8-TeBDF, 1,2,3,7,8-PeBDF, 2,3,4,7,8-PeBDF, 1,2,3,4,7,8-HxBDF, 1,2,3,4,6,7,8-HpBDF, OctBDF, 2,3,7,8,-TeBDD, 1,2,3,7,8-PeBDD, 1,2,3,7,8,9-HxBDD, 1,2,3,4,6,7,8-HxBDD, 1,2,3,4,6,7,8-HpBDD and OctBDD) were obtained from Wellington Laboratories (Guelph, Canada). The HPLC grade solvents including n-hexane, toluene, were HPLC purchased from Tedia (Fairfield, USA), Sigma-Aldrich (St. Louis, USA), and Merck (Darmstadt, Germany). Sodium sulfate, alumina oxide, potassium oxalate, and silica gel of the highest-grade purity were obtained from Merck.

2.2 Sampling Areas and Sample Collection

The gyms, which were the commercial gyms such as Les Mills or Equinox with various exercise devices (e.g., treadmill, exercise bike, and fitness equipment), including 4 gyms in Kaohsiung and 2 gyms in Pingtung were in southern Taiwan and the indoor dust, indoor $PM_{2.5}$, and outdoor $PM_{2.5}$ was collected between November 2018 and October 2019. All the gyms were nearby the road to gather the indoor dust and the proximities of 4 gyms (3 gyms in Kaohsiung and 1 gym in Pingtung) to the main traffic roads were chosen for the collection of samples for indoor dust and indoor $PM_{2.5}$ and outdoor $PM_{2.5}$.

The samples for indoor dust, indoor $PM_{2.5}$, and indoor $PM_{2.5}$ were simultaneously collected for two weeks in a gym. Indoor dust on the floor was collected by using a vacuum cleaner (Nilfisk Advance Euroclean UZ934 HEPA canister vacuum cleaner) equipped with an independent filter bag as described previously (Gou *et al.*, 2016a). The indoor dust sample was immediately transported to the laboratory at the National Pingtung University of Science and Technology (NPUST) after the daily dust (5–10 g) was gathered in the gym during the sampling period of two weeks. Prior to the chemical analysis, each dust sample was sieved through 100 mesh ($<$ 0.149 mm) by shaking for 10 min, with the removal of hair, trash, leaf, and possibly interfered materials before all the dusts were collected from a gym was pooled together.

The indoor and outdoor $PM_{2.5}$ was followed by TEPA standard methods (NIEA A205.11C). $PM_{2.5}$ samples were gathered on quartz fibre filters under the pre-heated condition at 600°C for 2 h prior to sampling. The $PM_{2.5}$ filter paper was conditioned in an electronic desiccator at the temperature of 20–23°C and humidity of 30–40% and weighed by a balance with an accuracy of 0.1 mg before and after the collection of $PM_{2.5}$ samples. The indoor PM sampler, such as Model 200-Personal Environmental Monitor™ (PEM™) for $PM_{2.5}$ (2.5 μm) (MSP Corporation, Minnesota, USA) was used to collect $PM_{2.5}$ indoors in the gyms based on our previous report with minor modification (Chao *et al.*, 2016). After two-week indoor air sampling with the flow rate of 5.00 L min^{-1} (7.2 m^3 day^{-1} and 100.8 m^3 for two weeks), the $PM_{2.5}$ samples were pooled together from the four continuous 3-day sampling samples by considering the collection of sufficient $PM_{2.5}$-bound PBDD/DF/DEs for further chemical analysis. Collection of the outdoor $PM_{2.5}$ referenced by our previous study was done by using a high-volume air sampler, such as SIBATA HV-1000R (Saitama, Japan) following U.S. EPA Reference Method TO9A (Chung *et al.*, 2019). The outdoor $PM_{2.5}$ in the gyms was gathered for 48 h with a flow rate of 800 L min^{-1} for a triplicate repeat during the two-week sampling and three outdoor $PM_{2.5}$ samplers were pooled for the further chemical analysis. The $PM_{2.5}$ sample to be conditioned in an electronic desiccator after the sampling was immediately transferred into the lab at NPUST.

2.3 Extraction and Clean-up

Soxhlet extraction and multi-clean-up processes, including a multi-layered silica column, alumina column and activated carbon column, were followed based on the previous study (Wu *et al.*, 2014) and our previous report (Chao *et al.*, 2016; Gou *et al.*, 2016a) with minor modification. In brief, the isotopes and surrogate standards were spiked in the $PM_{2.5}$ filter paper for estimating the organobromines loss during the aerosol sampling process before $PM_{2.5}$ sampling indoors and outdoors. To understand the PBDD/DFs and PBDEs loss in the extraction and clean-up procedures, the isotope internal standards were spiked into dust and $PM_{2.5}$ samples were mixed well with toluene before extraction. $PM_{2.5}$ filter samples and 20 g of indoor dust were extracted with 250 mL of toluene by the Soxhlet extractor for 24 h before evaporation. The elute was concentrated to 2 mL for the following multi-clean-up procedures to be eluted by 15 mL hexane, 25 mL dichloromethane/hexane (1/24, v/v), 5 mL toluene/methanol/ethyl acetate/hexane (1/1/2/16, v/v/v/v), and 40 mL toluene. The final elute was concentrated to approximately 1 mL in a vial. The elute was evaporated to near dryness by a gentle stream of gaseous nitrogen to quantity the final volume of 0.2 mL.

2.4 Chemical Analysis of PBDEs and PBDD/DFs

The analytical method used in this study was previously described (Chao *et al.*, 2014b; Gou *et al.*, 2016a). The congeners of 14 PBDEs and 12 PBDD/DFs were analyzed by a high-resolution gas chromatograph (Hewlett–Packard 6970 Series gas, CA) equipped with a high-resolution mass spectrometer (Micromass Autospec Ultima, Manchester, UK) (HRGC/HRMS) installed with a DB-5HT silica capillary column (L = 60, i.d. = 0.25 mm, film thickness = 0.1 μm) (J&W Scientific, CA) and a splitless injector.

The analytical assurance and quality control (QA/QC) of the analytical method used in this study were referenced by U.S. EPA method 1614 and TEPA NIEA M803.00B to be briefly shown as follows. The blanks including field and lab blanks (i.e., solvent or glassware blanks) were regularly tested in each batch of the analyses. Recoveries of spiked blanks, prelabelled internal standards, surrogate, and precision and recovery (PAR) of all the relevant standards were within the acceptable criteria (70–130%). The limits of detection (LODs) were defined as the ratio of signal to noise (S/N) over 3 and method detection limits (MDLs) were obtained from LODs to be calculated as 2.5–5 folds of the estimated LODs. The limit of quantification (LOQ) was defined as the ratio of S/N over 10. MDLs values of PBDEs and PBDD/Fs ranged from 4.33–290 pg g^{-1} and 0.0310–25.6 pg g^{-1}, respectively.

2.5 Risk Assessment and Statistical Analysis

The risk assessments of the gym users and professional staff through a non-dietary pathway were referenced by our previous report with minor modifications (Chou *et al.*, 2016; Gou *et al.*, 2016a; Xu *et al.*, 2016; Zhang *et al.*, 2020). Non-dietary daily intakes of PBDEs and PBDD/Fs in the gyms covered the pathways of inhalation from $PM_{2.5}$ and ingestion from indoor dust. The calculation is done using the following equation; DI (mg kg b.w.$^{-1}$ day^{-1}) = (C × IEF × IR × AB)/(BW) when DI, C,

Table 1. The parameters of risk assessments in this study[a,b].

	Age[c] (years)	Body Weight[c] (kg)	IR for inhalation[c]		IR for ingestion[d]	AT[e] (years)
			Inactive (m^3 day^{-1})	Active (m^3 day^{-1})	Indoor dust (mg)	
Male					30	78.1
	20–24	68.57	9.74	18.42		
	25–34	71.38	9.56	20.01		
	35–54	71.72	9.58	16.57		
	54–64	67.19	9.29	16.81		
Female					30	84.7
	20–24	52.46	7.14	11.86		
	25–34	58.61	7.47	11.79		
	35–54	59.38	7.50	13.72		
	54–64	61.07	7.58	11.54		

[a] DI_{dust} (ng kg b.w.$^{-1}$ day^{-1}) = (C_{dust} × IEF × $IR_{indoor\ dust}$ × $AB_{intestine\ tract}$)/(BW) whereas $AB_{intestine\ tract}$: triBDEs to nonaBDEs = 0.508, BDE-209 = 0.630, and PBDD/Fs = 0.950 and $DI_{PM2.5}$ (ng kg b.w.$^{-1}$ day^{-1}) = ($C_{PM2.5}$ × IEF × $IR_{PM2.5}$ × $AB_{alveoli}$)/(BW) whereas $AB_{alveoli}$ = 1.00.

[b] The IEF was determined as 0.104 (2.5 hours) for the gym users and 0.333 (8 hours) for the gym staff, respectively, based on "The report from surveillance of gym industry in 2021 Trends & Insights" written by Chou and Huang (2021).

[c] The risk factors were referenced by the report of "Compilation of Exposure Factors" by Taiwanese DOH (2008).

[d] The indoor dust daily intake was followed by the report of "Child-specific Exposure Factors Handbook" by U.S. EPA (2008).

[e] AT was from Ministry of The Interior, Taiwan for 2021 (Ministry of The Interior, 2022).

IEF, IR, AB, BW were defined as daily intake, concentration ($PM_{2.5}$ or dust), indoor exposure time (gym user: 0.104 for 2.5 hr day^{-1} and staff: 0.333 for 8 hr day^{-1}), intake rate (inhalation of $PM_{2.5}$ or ingestion of indoor dust), absorption rate of PBDEs (ingestion: triBDEs to nonaBDEs = 0.508 and BDE-209 = 0.630 and inhalation: PBDEs = 1.000) or PBDD/Fs (ingestion = 0.950 and inhalation = 1.000), body weight (Table 1). DI was a summary of $DI_{PM2.5}$ and DI_{dust}. The non-cancer and cancer risks were assessed based on the calculation of chronic daily intake (CDI) (CDI = (DI × EF × ED)/(AT × 365)) as EF = exposure frequency per year of 200 days/year, ED = exposure duration of 44 years at the age of 20–64, and AT = average lifespan. The non-cancer risk (Hazard quotient, HQ) was assessed as the equation of HQ = CDI (chronic daily intake)/RfD (reference dose) and cancer risk (R) was evaluated as the equation of R = CDI × SF (slope factor). RfD was obtained from the U.S. EPA Integrated Risk Information System (IRIS) to express BDE-47, -99, -153, and -209 as 0.0001, 0.0001, 0.0002, and 0.007 mg kg^{-1} day^{-1} (U.S. EPA, 2014), respectively, and 2,3,7,8-TBDD as 0.7 pg kg^{-1} day^{-1} (U.S. EPA, 2012). SF was from for oral 2,3,7,8-TBDD (Simon *et al.*, 2009) and BDE-209 was 0.0001 per pg kg^{-1} day^{-1} and 0.0007 per mg kg^{-1} day^{-1} (U.S. EPA, 2014), respectively.

Measurements of PBDEs and PBDD/Fs below MDLs were recognized as zero for further statistical analysis. Descriptive analysis was used to determine the means and standard deviations (SD) of indoor dust, indoor $PM_{2.5}$, and outdoor $PM_{2.5}$. Mann-Whitney *U* tests were used to determine the differences in levels of PBDD/Fs and PBDEs on $PM_{2.5}$ indoors and outdoors because $PM_{2.5}$-bound PBDEs and PBDD/Fs were not normally distributed and the sample size was small. The correlations or sources of PBDEs and PBDD/Fs in the gyms were examined by the principal component analysis (PCA). For the assessment of risk in the gym users and the staff in the gyms, the Monte Carlo method was used to simulate the non-dietary intakes of PBDEs and PBDD/Fs via ingestion or inhalation. The critical values of HQs and Rs were set as 1.00 and 1.00 × 10^{-6}. All statistical analyses were performed using Statistical Product and Service Solutions, version 12.0.

3 RESULTS AND DISCUSSION

3.1 Levels of PBDD/Fs in the Gyms' Environment

Table 2 shows PBDD/F levels in outdoor $PM_{2.5}$, indoor $PM_{2.5}$, and indoor dust in the gyms located in southern Taiwan. It was found that $\sum_{12}$PBDD/F concentrations (mean ± SD: 0.202 ± 0.200 pg m^{-3}) and PBDD/Fs-TEQ levels (0.00650 ± 0.00340 pg WHO_{2005}-TEQ m^{-3}) in indoor $PM_{2.5}$ were higher than that of those in outdoor $PM_{2.5}$ (PBDD/Fs: 0.163 ± 0.0951 pg m^{-3} vs. PBDD/F-TEQs: 0.00469

Table 2. PBDD/F concentrations on $PM_{2.5}$ and indoor dust collected from the gyms.

	TEF	$PM_{2.5}$ (pg m^{-3})			Indoor Dust (pg g^{-1})
		Outdoor $PM_{2.5}$ Mean ± SD (n = 4)	Indoor $PM_{2.5}$ Mean ± SD (n = 4)	p value[a]	Mean ± SD (n = 6)
Congeners					
2,3,7,8-TeBDF	0.1000	< LOD	< LOD	1.000	2.98 ± 2.58
1,2,3,7,8-PeBDF	0.0300	< LOD	0.000561 ± 0.00112	0.686	3.54 ± 3.35
2,3,4,7,8-PeBDF	0.3000	0.00413 ± 0.00165	0.00388 ± 0.00460	0.042*	8.45 ± 3.90
1,2,3,4,7,8-HxBDF	0.1000	0.0176 ± 0.00800	0.0236 ± 0.0219	0.083	107 ± 49.6
1,2,3,4,6,7,8-HpBDF	0.0100	0.0938 ± 0.0478	0.136 ± 0.108	0.083	2270 ± 942
OctBDF	0.0003	0.0463 ± 0.0370	0.0378 ± 0.0755	0.166	4660 ± 3920
2,3,7,8-TeBDD	1.0000	< LOD	< LOD	1.000	< LOD
1,2,3,7,8-PeBDD	1.0000	< LOD	< LOD	1.000	< LOD
1,2,3,4,7,8-HxBDD	0.1000	< LOD	< LOD	1.000	< LOD
1,2,3,7,8,9-HxBDD	0.1000	< LOD	< LOD	1.000	< LOD
1,2,3,4,6,7,8-HpBDD	0.0100	0.000726 ± 0.00145	< LOD	0.317	6.55 ± 5.57
OctBDD	0.0003	< LOD	< LOD	1.000	27.3 ± 38.0
$\sum_6$ PBDFs		0.162 ± 0.0939	0,202 ± 0.200	1.000	7050 ± 4690
$\sum_6$ PBDDs		0.000726 ± 0.00145	< LOD	0.317	33.8 ± 38.1
$\sum_{12}$ PBDD/Fs		0.163 ± 0.0951	0.202 ± 0.200	1.000	7090 ± 4680
$\sum_6$ PBDFs WHO_{2005}-TEQs[b]		0.00395 ± 0.00176	0.00492 ± 0.00465	0.773	37.8 ± 13.7
$\sum_6$ PBDDs WHO_{2005}-TEQs[b]		0.000007 ± 0.0000145	< LOD	0.317	0.0737 ± 0.0562
$\sum_{12}$ PBDD/Fs WHO_{2005}-TEQs[b]		0.00469 ± 0.00101	0.00650 ± 0.00340	0.248	37.8 ± 13.7

[a] The significant levels were between indoor $PM_{2.5}$ and outdoor $PM_{2.5}$; * $p < 0.05$.
[b] The WHO_{2005}-TEQs were expressed as pg-WHO_{2005}-TEQ m^{-3} and pg-WHO_{2005}-TEQ g^{-1} for $PM_{2.5}$ and dust, respectively.

± 0.00101 pg WHO_{2005}-TEQ m^{-3}) with statistically insignificant differences (n = 4). There were a few articles reported on $PM_{2.5}$-bound PBDD/Fs indoors and outdoors.

The indoor dust level of $\sum_{12}$ PBDD/Fs was 7090 ± 4680 pg g^{-1} and its PBDD/Fs-TEQ level was 37.8 ± 13.7 pg WHO_{2005}-TEQ g^{-1} in the gyms (n = 6). Several studies investigated and reported on PBDD/Fs in indoor dust (Ma *et al.*, 2009; Takigami *et al.*, 2009; Suzuki *et al.*, 2010; Tue *et al.*, 2010, 2013; Gou *et al.*, 2016a). In our previous study (Gou *et al.*, 2016a), the dust PBDD/F levels in the normal and computer classrooms of the elementary schools in southern Taiwan were reported as 4.72–7.51 and 3.60–6.28 ng g^{-1} respectively, while the dust levels of PBDD/F-TEQs were 0.0401–0.0636 ng WHO_{2005}-TEQ g^{-1} in the normal classrooms and 0.0281–0.0474 ng WHO_{2005}-TEQ g^{-1} in the computer classrooms. A comparison between the present work and the previous work reported by us (Gou *et al.*, 2016a), indicated that the indoor dust levels of PBDD/F WHO_{2005}-TEQs (0.0378 pg WHO_{2005}-TEQ g^{-1}) in the gyms were lower when compared with those in the elementary schools from our previous study. Based on the current global data concerned with PBDD/Fs in indoor dust, it was suggested that the PBDD/F concentrations (7.09 ng g^{-1}) in the gyms had a distinctly lower magnitude when compared with those from the floor dust in the e-waste plant of China (89.3–143 ng g^{-1}) (Ma *et al.*, 2009) and house dust in the e-waste sites of Vietnam (7.70–63.0 ng g^{-1}) (Tue *et al.*, 2010) as well as the comparable magnitude with those from the indoor dust in the classrooms (1.46–6.39 ng g^{-1}) (Gou *et al.*, 2016a), house dust in the US (0.33–150 ng g^{-1}) and Japan (1.10–12.1 ng g^{-1}) (Suzuki *et al.*, 2010; Tue *et al.*, 2013), indoor dust in the Japanese offices (1.62–31.3 ng g^{-1}) (Suzuki *et al.*, 2010), and indoor dust in a Japanese hotel (0.740–15-4 ng g^{-1}) (Takigami *et al.*, 2009). Based on the distribution of PBDD/F profiles in $PM_{2.5}$ and in indoor dust, it was observed that $PM_{2.5}$-bound PBDD/Fs were also similarly distributed in the gyms indoors and outdoors, but the indoor dust did not have the similarity of PBDD/F profiles with indoor $PM_{2.5}$ (Fig. S1).

3.2 Levels of PBDEs in the Gyms' Environment

PBDE levels on indoor and outdoor $PM_{2.5}$ and indoor dust in the Taiwanese gyms are presented in Table 3. $\sum_{14}$PBDEs in outdoor $PM_{2.5}$, indoor $PM_{2.5}$, and indoor dust in the gyms were expressed as

Table 3. Levels of PBDEs on $PM_{2.5}$ and indoor dust collected from the gyms.

Congeners	$PM_{2.5}$ (pg m^{-3})			Indoor Dust (pg g^{-1})
	Outdoor $PM_{2.5}$ Mean ± SD (n = 4)	Indoor $PM_{2.5}$ Mean ± SD (n = 4)	*p* value [a]	Mean ± SD (n = 6)
BDE-28	0.00266	0.00845	0.008*	519 ± 923
BDE-47	0.0448 ± 0.0323	0.130 ± 0.0713	0.081	128000 ± 285000
BDE-100	0.0189 ± 0.0133	0.0497 ± 0.0728	1.000	46600 ± 98200
BDE-99	0.122 ± 0.0950	0.264 ± 0.366	0.554	177000 ± 334000
BDE-154	0.0742 ± 0.0551	0.0661 ± 0.0337	0.773	42500 ± 92000
BDE-153	0.211 ± 0.214	0.170 ± 0.0849	0.773	51400 ± 104000
BDE-183	0.349 ± 0.220	0.680 ± 0.470	0.248	13200 ± 11300
BDE-197	0.223 ± 0.105	0.477 ± 0.408	0.564	10300 ± 7700
BDE-203	0.152 ± 0.0711	0.379 ± 0.324	0.564	5180 ± 2960
BDE-196	0.212 ± 0.0941	0.428 ± 0.343	0.773	12700 ± 9270
BDE-208	0.332 ± 0.144	0.361 ± 0.245	0.773	26500 ± 12700
BDE-207	0.920 ± 0.392	0.982 ± 0.696	1.000	106000 ± 52600
BDE-206	0.801 ± 0.351	0.698 ± 0.483	0.564	169000 ± 85100
BDE-209	4.80 ± 1.90	4.85 ± 2.23	0.773	1880000 ± 251000
$\sum_{14}$PBDEs	8.27 ± 3.46	9.54 ± 4.68	0.564	2670000 ± 2330000

mean ± SD, such as 8.27 ± 3.46 pg m^{-3}, 9.54 ± 4.68 pg m^{-3}, and 2670000 ± 2330000 pg g^{-1} (2670 ± 2330 ng g^{-1}), respectively. The results indicated that $PM_{2.5}$-bound PBDEs and BDE-209 (4.85 pg m^{-3}) in indoor $PM_{2.5}$ was higher than that of those in outdoor $PM_{2.5}$ (BDE-209: 4.80 pg m^{-3}), however their difference was found to be not significant. Based on the obtained results, it was suggested that BDE-209 was the predominated congener consisting of 58.0% and 50.8% of the total PBDEs in outdoor and indoor $PM_{2.5}$, respectively. The study conveyed that for indoor dust in the gyms, BDE-209 was also consisting of 70.4% of the total PBDEs. According to the homologue distribution of PBDEs in the gyms including outdoor and indoor $PM_{2.5}$ and indoor dust as shown in Fig. S2, the distribution of $PM_{2.5}$-bound PBDEs in the gyms indoors and outdoors was very similar, but PBDE homologues in indoor dust were different from those in $PM_{2.5}$.

Based on the current global data in Table 4, it was claimed that not many studies were addressed $PM_{2.5}$-bound PBDEs in the outdoor and indoor environment (Beser *et al.*, 2014; Wang *et al.*, 2014; Li *et al.*, 2015; Xu *et al.*, 2015; Chao *et al.*, 2016; Deng *et al.*, 2016; Liu *et al.*, 2016; Xu *et al.*, 2016; Guo *et al.*, 2020; Tames *et al.*, 2020). According to the current data, it is very difficult to conclude whether indoor levels of $PM_{2.5}$-bound PBDEs are higher or lower than outdoor levels of $PM_{2.5}$-bound PBDEs or indoor and outdoor $PM_{2.5}$-bound PBDEs are highly correlated. The results of this present study conveyed that the data of $PM_{2.5}$-bound PBDEs indoors and outdoors in the gyms were not lower when compared with those from the certain outdoor and indoor environments, such as residential houses, rural areas, and urban areas.

A large variation of indoor PBDE concentrations in the gyms was found in this study. Based on the current global data it was emphasized that indeed this was the first report of indoor PBDEs in the gyms. Indoor dust BDE-209 as shown in Fig. S2 was the most abundant congener among PBDEs in the gyms which was very similar to the other microenvironments, such as offices, day-care centres, houses, cars, classrooms, and the public places (Gou *et al.*, 2016a; Brits *et al.*, 2019; Jin *et al.*, 2019; Lee *et al.*, 2020; Al-Harbi *et al.*, 2021; Klinčić *et al.*, 2021). Although the results obtained in the present study were in the same order of magnitude when compared with the other microenvironments (offices, medical and dental clinics, the classrooms of the elementary schools, and residential houses), the pattern of PBDE homologue in indoor dust from the gyms was not similar to the other Taiwanese microenvironments according to our previous studies (Chao *et al.*, 2014c; Shy *et al.*, 2015; Chou *et al.*, 2016; Gou *et al.*, 2016a). It was demonstrated that the unique PBDE homologue pattern in indoor dust of the gyms might be due to three reasons: (1) the electronic equipment used in the gyms was quite different from the one used in other indoor environments; (2) the gyms we chose were established and opened within these 5 years whereas the microenvironments we used for our previous studies were opened before 2015 (Chao *et al.*, 2014c; Shy *et al.*, 2015; Chou *et al.*, 2016; Gou *et al.*, 2016a). (3) Based on the

Table 4. Summary of the current data on $PM_{2.5}$-bound PBDEs.

Region (country)	Source	Reference	∑PBDEs[a]	Mean or mean ± SD
Outdoor				
Region of Valencia Government (Spain)	Households	Beser *et al.*, 2014	$\sum_{12}$ PBDEs	0.213 pg m^{-3}
Beijing (China)	Industrial	Deng *et al.*, 2016	$\sum_{42}$ PBDEs	146 pg m^{-3}
East China Sea (China)	Ocean	Li *et al.*, 2015	$\sum_{11}$ PBDEs	0.97 ± 0.52 pg m^{-3}
Metropolis areas (China)[b]	Urban	Liu *et al.*, 2016	$\sum_{9}$ PBDEs	35 ± 150 pg m^{-3}
Central and southern Taiwan (Taiwan)	Urban	Chao *et al.*, 2016	$\sum_{14}$ PBDEs	67.9 ± 12.9 pg m^{-3}
Central and southern Taiwan (Taiwan)	Industrial	Chao *et al.*, 2016	$\sum_{14}$ PBDEs	112 pg m^{-3}
Central and southern Taiwan (Taiwan)	Rural	Chao *et al.*, 2016	$\sum_{14}$ PBDEs	62.7 pg m^{-3}
Kaohsiung and Pingtung (Taiwan)	Urban	The present study	$\sum_{14}$ PBDEs	8.27 ± 3.46 pg m^{-3}
Indoor				
Guangzhou (China)	Households	Wang *et al.*, 2014	$\sum_{26}$ PBDEs	239 pg m^{-3}
Hong Kong (China)	Households	Wang *et al.*, 2014	$\sum_{26}$ PBDEs	43.8 pg m^{-3}
Shanghai (China)[c]	Households	Xu *et al.*, 2016	$\sum_{18}$ PBDEs	48.5 ± 17.2 pg m^{-3}
Shanghai (China)[c]	Workplaces	Xu *et al.*, 2016	$\sum_{18}$ PBDEs	105 ± 45.5 pg m^{-3}
Hong Kong (China)	Kindergartens	Deng *et al.*, 2016	$\sum_{13}$ PBDEs	453 ± 345 pg m^{-3}
Central and southern Taiwan (Taiwan)[d]	Workplaces	Chao *et al.*, 2016	$\sum_{14}$ PBDEs	116 ± 112 pg m^{-3}
Cordoba (Argentina)	Rural	Tames *et al.*, 2020	$\sum_{7}$ PBDEs	18.28 pg m^{-3}
Harbin (China)	Houses	Guo *et al.*, 2020	$\sum_{10}$ PBDEs	4.19 ± 3.17 pg m^{-3}
Kaohsiung and Pingtung (Taiwan)	Gyms	The present study	$\sum_{14}$ PBDEs	9.54 ± 4.68 pg m^{-3}

[a] The congeners of ∑PBDEs were shown in Table S1 and S2 in the supplementary materials.
[b] The metropolis areas in China including Beijing, Shanghai, Guangzhou, Nanjing, Wuhan, Taiyuan, Chengdu, Lanzhou, Guiyang, and Xinxiang.
[c] Xu *et al.* (2016) did not show the types of workplaces in Shanghai City.
[d] The workplaces in the present study were library, rail station, department store, office, hospital, and supermarket.

latest announcement of persistent organic pollutants on Stockholm Convention in 2019 to list BDE-209 or commercial decaBDE mixture as Annexure A for elimination, the new building materials, electronic equipment, or decoration might be largely used for PBDE-replacement formulation of fire retardants in the gyms.

3.3 Correlations of PBDEs and PBDD/Fs in the Gyms' Environment

Fig. 1 shows the correlations of PBDD/Fs or PBDEs in the gyms indoors and outdoors after examination of PCA tests. Firstly, $PM_{2.5}$-bound PBDD/Fs indoors and outdoors were examined by PCA to classify two groups as follows: $\sum_{12}$PBDD/Fs, PBDDs, PBDFs, and certain PBDD/Fs in outdoor $PM_{2.5}$ in a group and indoor $PM_{2.5}$-bound PBDD/Fs including PBDDs, PBDFs, and certain PBDD/Fs in the other group (Fig. 1(A)) (percentage of variance (σ) = 94.9%). It was stated that outdoor $PM_{2.5}$-bound PBDD/Fs including PBDDs, PBDFs, and certain PBDD/Fs were independent of those in indoor $PM_{2.5}$, indicating that indoor $PM_{2.5}$-bound PBDD/Fs were not associated with outdoor $PM_{2.5}$-bound PBDD/Fs and it could also be explained as the different emission sources of PBDD/Fs between indoors and outdoors. Fig. 1(B) shows the statistically independent correlation of $PM_{2.5}$-bound PBDEs between indoors and outdoors and this result could thus explain the 94.9% of the data (σ = 94.9%). It clearly showed that the outdoor $PM_{2.5}$-bound PBDEs were not related to indoor $PM_{2.5}$-bound PBDEs. According to our previous study (Gou *et al.*, 2016b), airborne PBDEs from Di-BDEs to Nona-BDEs including gas and particle-phase were significantly independent both indoors and outdoors of the vehicle dismantling factories, but the outdoor BDE-209 was significantly correlated with indoor PBDEs from Hexa-BDEs to Deca-BDE.

For the indoor dust of PBDD/Fs and PBDEs, three rotated principal components (RPCs) were displayed (Fig. 2(A)). RPC1 (σ = 61.1%) was composed of BDE-28, 1,2,3,7,8-PeBDF, BDE-47, BDE-154, BDE-206, BDE-100, BDE-153, BDE-208, BDE-207, and BDE-99. RPC 2 (σ = 27.1%) was composed of 1,2,3,4,6,7,8-HpBDD, PBDDs, BDE-203, PBDEs, and BDE-209 and RPC 3 (σ = 11.8%) was composed of PBDD/Fs, PBDFs, BDE-183, 1,2,3,4,7,8-HxBDF, 1,2,3,4,6,7,8-HpBDF, 2,3,4,7,8-PeBDF, and OctBDF. Liang *et al.* (2020) indicated that certain PBDD/Fs were released from the pyrolysis of PBDEs,

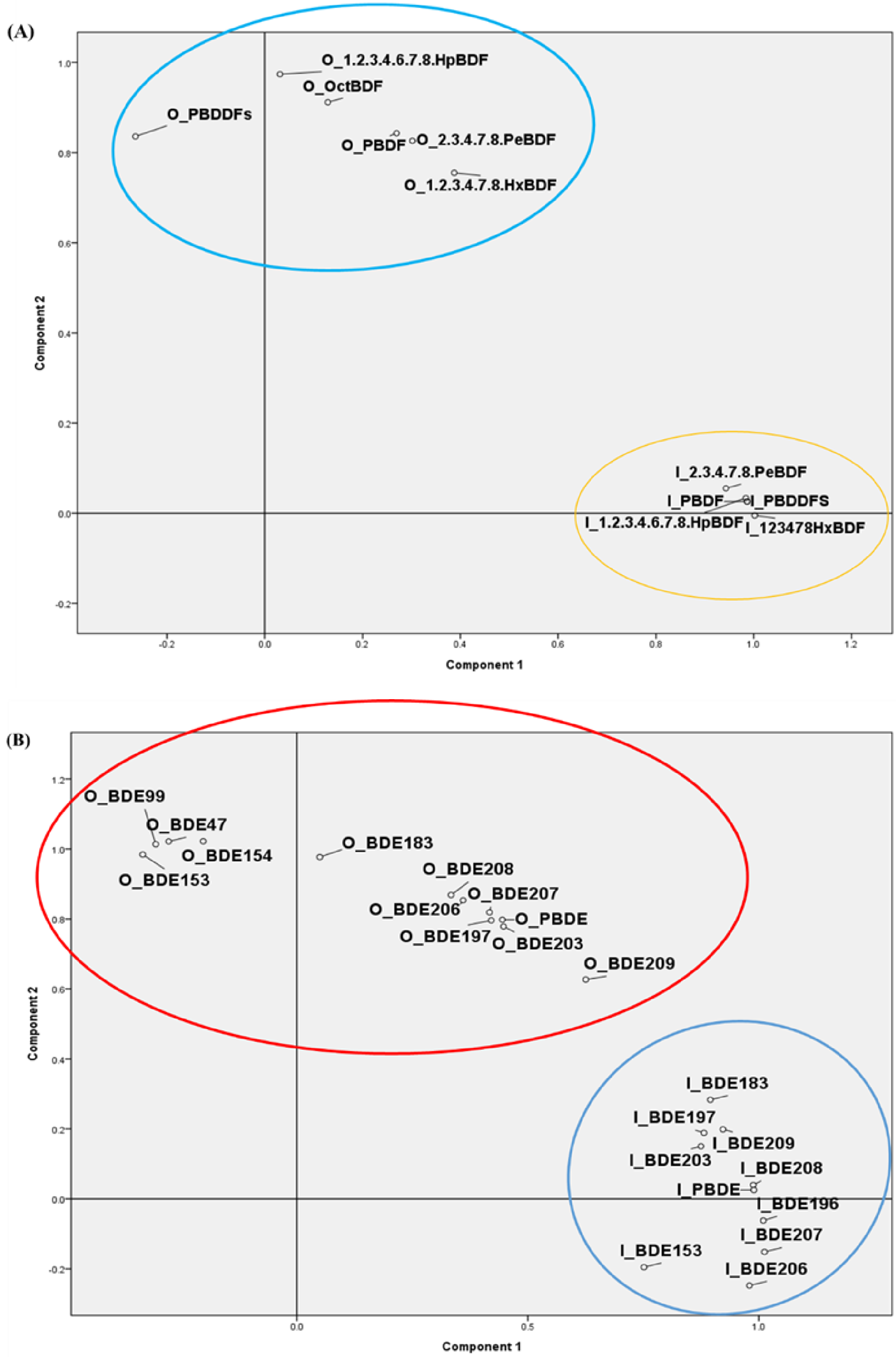

Fig. 1. The relationship between PBDEs and PBDD/Fs in the gyms examined by principal component analysis (PCA). For an example, indoor PBDEs and outdoor PBDD/Fs were expressed as I_PBDEs and O_PBDD/Fs, respectively. The RPCs were shown as follows: (A) $PM_{2.5}$-bound PBDD/Fs indoors and outdoors and (B) $PM_{2.5}$-bound PBDEs indoors and outdoors

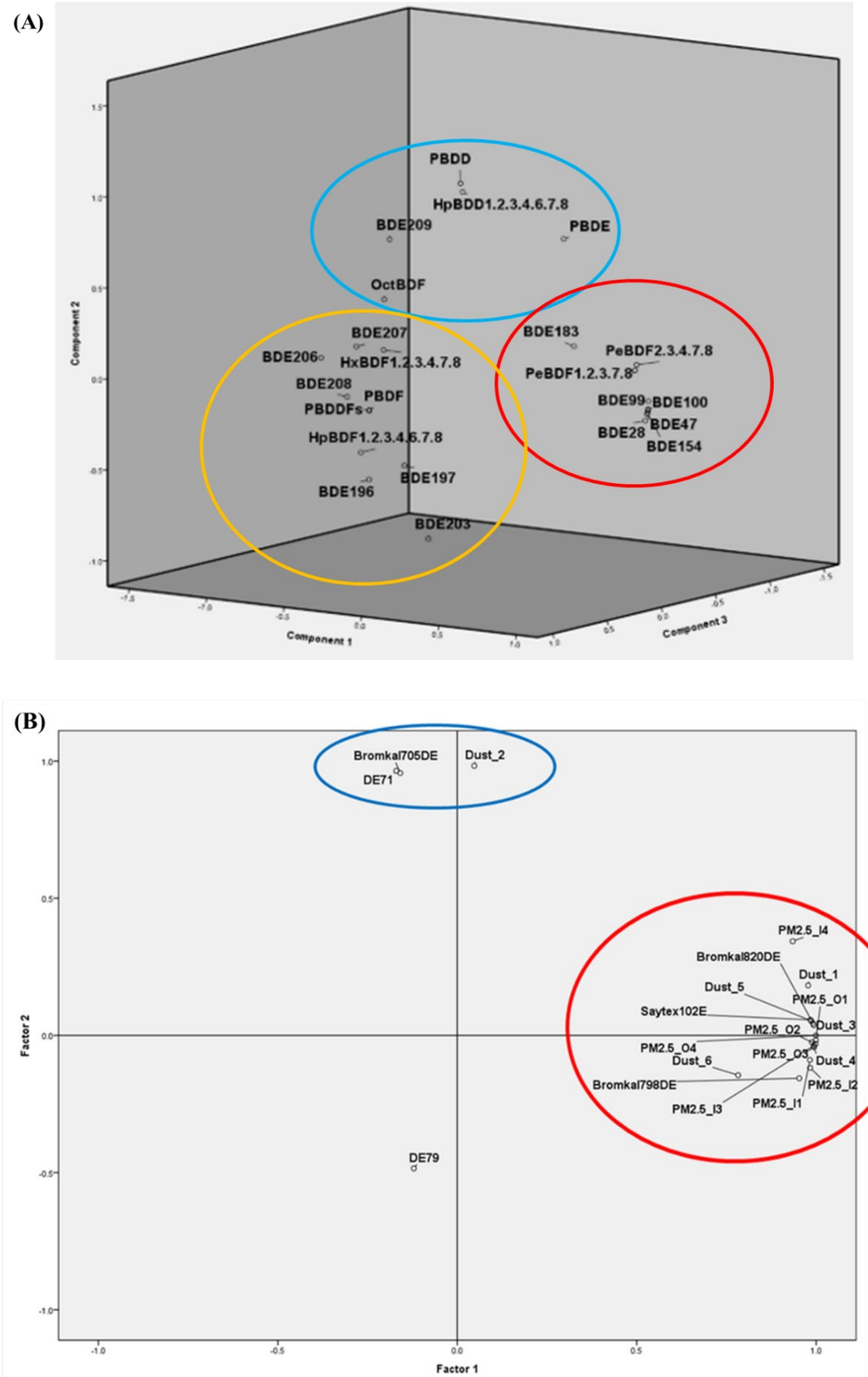

Fig. 2. Principal component analysis was used to examine (A) the relationship between PBDEs and PBDD/Fs in indoor dust and (B) the correlations of PBDEs between indoor $PM_{2.5}$, outdoor $PM_{2.5}$, indoor dust, and commercial formulation of brominated flame retardants (BFRs). $PM_{2.5}$_I, $PM_{2.5}$_O, and Dust were expressed as indoor $PM_{2.5}$, outdoor $PM_{2.5}$, and indoor dust, respectively. Commercial formulations of BFRs are DE-71 (Penta-BDE mixture), Bromkal 70-5DE (Penta), DE-79 (Octa), Bromkal 79-8DE (Octa), Saytex 102E (Deca), and Bromkal 82-0D (Deca). The commercial formula of Bromkal 79-8DE was contained 49.6% of BDE-209.

such as the disruption of the ether bond of the lower brominated numbers of PBDEs would be generated as PBDD/Fs (i.e., BDE-153 converting to 2,3,7,8-tetraBDD); while the higher brominated numbers of PBDEs favored the formation of polybromobenzene by cleavage of ether bond. The previous studies showed a significantly positive correlation between dust PBDD/Fs and dust PBDEs (Ma *et al.*, 2009; Gou *et al.*, 2016a). Based on our findings both in the present and the previous studies (Ma *et al.*, 2009; Gou *et al.*, 2016a; Liang *et al.*, 2020), certain PBDEs and PBDD/Fs were assigned into the same group after PCA tests in the indoor dust of the gyms which suggested that PBDD/Fs and PBDEs might come from the same emission sources. Fig. 2(B) shows the commercial formulation of Saytex 102E, Bromkal 82-0, and Bromkal 79-8DE in relation to indoor and outdoor $PM_{2.5}$-bound PBDEs and indoor dust PBDEs except for an indoor dust sample in a gym located at Kaohsiung to be classified as the groups of Penta-BDE mixtures (DE71 and Bromkal705DE). It is meant that the indoor and outdoor environment of the gyms were mainly contaminated from the Deca-BDE commercial formulations which are released from the surface of consumer or electronic products.

3.4 Risk Assessments in the Gyms' Environment

The risk factors and the exposure levels were used to assess the risk assessments, such as daily intakes, non-cancer risks (HQs), and cancer risks (Rs), via non-dietary routes based on two exposure scenarios including the gym users and employees (Table 1 and Table 5). According to Table 1, the active inhalation rates were 1.69–2.10 times higher than the inactive inhalation rates in Taiwanese. The values of daily intakes, HQs, and Rs for the gym users and staff through ingestion of indoor dust were found to be notably higher than that of those through inhalation of $PM_{2.5}$ as shown in Table 5. The Korean study also announced that the contribution of dust ingestion was still main after the estimation of multiple-exposure assessment of PBDEs (Lee *et al.*, 2020). The summary and individual calculation of HQs and Rs from certain PBDEs and ∑PBDD/Fs for the gym users and the employees were still under the critical values of HQ = 1.00 and R = 1.00×10^{-6}. Thus, it was concluded that no non-cancer and cancer risks were found in the gym users and employees through indoor $PM_{2.5}$ and indoor dust in the gyms. A comparison with our previous report revealed that the school-age children at the age of 7–9 consumed between 9.40×10^{-12} and 1.34×10^{-11} mg kg b.w.$^{-1}$ day^{-1} from the classroom dust (Gou *et al.*, 2016a). However, in the present study, the estimated daily intakes of ∑PBDD/Fs (1.29×10^{-13}–5.42×10^{-13} mg kg b.w.$^{-1}$ day^{-1}) for the adults through the indoor dust of the gyms were found to be low. The gym-dust daily intakes of PBDEs for the male and female employees were found to be 1.61×10^{-7} and 2.11×10^{-7} mg kg b.w.$^{-1}$ day^{-1} (0.161 and 0.211 ng kg b.w.$^{-1}$ day^{-1}), respectively. Several studies reported the estimated daily intakes via indoor dust for adults as BDE-209 of 0.2 ng kg b.w.$^{-1}$ day^{-1} in the South African dust (Brits *et al.*, 2019), PBDEs of 0.56–0.57 ng kg b.w.$^{-1}$ day^{-1} in the Korean dust (Lee *et al.*, 2020), PBDEs of 0.557–0.727 ng kg b.w.$^{-1}$ day^{-1} in the Taiwanese dust (Shy *et al.*, 2015), and PBDEs of 0.283–0.311 ng kg b.w.$^{-1}$ day^{-1} (Xu *et al.*, 2015). The results represented that the data of HQs and Rs in the present study was consistent with our previous study (Shy *et al.*, 2015) and also the Korean report (Lee *et al.*, 2020) suggesting that the non-cancer and cancer risks have not occurred.

4 CONCLUSIONS

This study was suggested to be the first report to announce the levels of PBDEs and PBDD/Fs on indoor and outdoor $PM_{2.5}$ and indoor dust in the gyms. $PM_{2.5}$-bound brominated compounds, such as PBDD/Fs and PBDEs were not correlated in the gyms indoors and outdoors, but the profiles of PBDEs or PBDD/Fs on $PM_{2.5}$ indoors and outdoors are similarly distributed. Certain PBDD/F and PBDE congeners in indoor dust of the gyms were potentially correlated. In the indoor environment, the profiles of PBDEs and PBDD/Fs were not similarly distributed between $PM_{2.5}$ and indoor dust. The assessment of human health risks including the gym users and staff indicated that the daily intakes, non-cancer risks, and cancer risks of PBDEs and PBDD/Fs were still found to be in the acceptable values.

Table 5. Risk assessment of PBDEs and PBDD/Fs in the indoor environment of the gyms.

	Male gym user	Female gym user	Male Staff	Female Staff
Indoor dust[a]				
Daily intake (mg kg b.w.$^{-1}$ day^{-1})				
BDE-47	1.18×10^{-9}	1.54×10^{-9}	9.41×10^{-9}	1.23×10^{-8}
BDE-99	1.62×10^{-9}	2.12×10^{-9}	1.32×10^{-8}	1.73×10^{-8}
BDE-154	3.91×10^{-10}	5.11×10^{-10}	3.14×10^{-9}	4.10×10^{-9}
BDE-209	1.74×10^{-8}	2.27×10^{-8}	1.39×10^{-7}	1.83×10^{-7}
∑PBDEs	5.04×10^{-8}	6.58×10^{-8}	1.61×10^{-7}	2.11×10^{-7}
∑PBDD/Fs-WHO$_{2005}$TEQs	1.29×10^{-13}	1.69×10^{-13}	4.15×10^{-13}	5.42×10^{-13}
Non-cancer risk (HQs)[b]				
BDE-47	6.34×10^{-6}	7.64×10^{-6}	5.06×10^{-5}	6.10×10^{-5}
BDE-99	8.73×10^{-6}	1.05×10^{-5}	7.10×10^{-5}	8.55×10^{-5}
BDE-154	1.05×10^{-6}	1.27×10^{-6}	8.43×10^{-6}	1.02×10^{-5}
BDE-209	1.34×10^{-6}	1.61×10^{-6}	1.07×10^{-5}	1.29×10^{-5}
∑PBDD/Fs-WHO$_{2005}$TEQs	9.93×10^{-6}	1.14×10^{-5}	3.19×10^{-5}	3.84×10^{-5}
Cancer risk (Rs)[b]				
BDE-209	6.55×10^{-12}	7.88×10^{-12}	5.26×10^{-11}	6.34×10^{-11}
∑PBDD/Fs-WHO$_{2005}$TEQ	6.96×10^{-18}	8.38×10^{-18}	2.23×10^{-17}	2.70×10^{-17}
Indoor $PM_{2.5}$[c]				
Daily intake (mg kg b.w.$^{-1}$ day^{-1})				
BDE-47	1.45×10^{-12}	1.23×10^{-12}	6.15×10^{-12}	5.91×10^{-12}
BDE-99	2.96×10^{-12}	2.49×10^{-12}	1.25×10^{-11}	1.20×10^{-11}
BDE-154	7.41×10^{-13}	6.23×10^{-13}	3.15×10^{-12}	3.01×10^{-12}
BDE-209	5.42×10^{-11}	4.56×10^{-11}	2.29×10^{-10}	2.19×10^{-10}
∑PBDEs	1.67×10^{-10}	8.98×10^{-11}	4.51×10^{-10}	4.32×10^{-10}
∑PBDD/Fs-WHO$_{2005}$TEQ	2.96×10^{-13}	3.87×10^{-13}	3.08×10^{-12}	2.95×10^{-12}
Non-cancer risk (HQs)				
BDE-47	7.84×10^{-9}	6.08×10^{-9}	3.32×10^{-8}	2.93×10^{-8}
BDE-99	1.59×10^{-8}	1.24×10^{-8}	6.71×10^{-8}	5.93×10^{-8}
BDE-154	1.99×10^{-9}	1.55×10^{-9}	8.46×10^{-9}	7.47×10^{-9}
BDE-209	4.17×10^{-9}	3.23×10^{-9}	1.76×10^{-8}	1.56×10^{-8}
∑PBDD/Fs-WHO$_{2005}$TEQ	2.27×10^{-8}	2.74×10^{-8}	2.37×10^{-8}	2.09×10^{-8}
Cancer risk (Rs)				
BDE-209	2.04×10^{-14}	1.58×10^{-14}	8.64×10^{-14}	7.63×10^{-14}
∑PBDD/Fs-WHO$_{2005}$TEQ	1.59×10^{-17}	1.92×10^{-17}	1.66×10^{-17}	1.46×10^{-17}

[a] Oral ingestion.
[b] The dimensionless unit.
[c] Inhalation.

ACKNOWLEDGMENTS

This study was supported by the grant (MOST 106-2221-E-020-001-MY3) from the Ministry of Science and Technology, Taiwan and partially from the grant (VHLC-108003) from Kaohsiung Veterans General Hospital Pingtung Branch, Veterans Affair Council, Taiwan. We thanked Prof. Lin-Chi Wang and Prof. Gou-Ping Chang-Chien for their assistance in analyzing PBDEs and PBDD/Fs. We also acknowledge our team members at the National Pingtung University of Science and Technology (NPUST).

DISCLAIMER

The authors declare no conflicts of interest in this study.

SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220264

REFERENCES

Al-Harbi, M., Al-Enzi, E., Al-Mutairi, H., Whalen, J.K. (2021). Human health risks from brominated flame retardants and polycyclic aromatic hydrocarbons in indoor dust. Chemosphere 282, 131005. https://doi.org/10.1016/j.chemosphere.2021.131005

Alves, C.A., Calvo, A.I., Castro, A., Fraile, R., Evtyugina, M., Bate-Epey, E.F. (2013). Indoor air quality in two university sports facilities. Aerosol Air Qual. Res. 13, 1723–1730. https://doi.org/10.4209/aaqr.2013.02.0045

Andrade, A., Dominski, F.H. (2018). Indoor air quality of environments used for physical exercise and sports practice: Systematic review. J. Environ. Manage. 206, 577–586. https://doi.org/10.1016/j.jenvman.2017.11.001

Bai, H., Zheng, Z., Zhang, Y., Huang, H., Wang, L. (2021). Comparison of satellite-based $PM_{2.5}$ estimation from aerosol optical depth and top-of-atmosphere reflectance. Aerosol Air Qual. Res. 21, 200257. https://doi.org/10.4209/aaqr.2020.05.0257

Beser, M.I., Beltrán, J., Yusà, V. (2014). Design of experiment approach for the optimization of polybrominated diphenyl ethers determination in fine airborne particulate matter by microwave-assisted extraction and gas chromatography coupled to tandem mass spectrometry. J. Chromatogr. A 1323, 1–10. https://doi.org/10.1016/j.chroma.2013.10.081

Booth, F.W., Roberts, C.K., Laye, M.J. (2012). Lack of exercise is a major cause of chronic diseases. Compr. Physiol. 2, 1143–1211. https://doi.org/10.1002/cphy.c110025

Brits, M., Brandsma, S.H., Rohwer, E.R., De Vos, J., Weiss, J.M., de Boer, J. (2019). Brominated and organophosphorus flame retardants in South African indoor dust and cat hair. Environ. Pollut. 253, 120–129. https://doi.org/10.1016/j.envpol.2019.06.121

Castro, A., Calvo, A.I., Alves, C., Alonso-Blanco, E., Coz, E., Marques, L., Nunes, T., Fernandez-Guisuraga, J.M., Fraile, R. (2015). Indoor aerosol size distributions in a gymnasium. Sci. Total Environ. 524–525, 178–186. https://doi.org/10.1016/j.scitotenv.2015.03.118

Chao, H.R., Huang, H.L., Hsu, Y.C., Lin, C.W., Lin, D.Y., Gou, Y.Y., Chen, K.C. (2014a). Impact of brominated POPs on the neurodevelopment and thyroid hormones of young children in an indoor environment—A review. Aerosol Air Qual. Res. 14, 1320–1332. https://doi.org/10.4209/aaqr.2013.05.0156

Chao, H.R., Lin, D.Y., Chen, K.Y., Gou, Y.Y., Chiou, T.H., Lee, W.J., Chen, S.J., Wang, L.C. (2014b). Atmospheric concentrations of persistent organic pollutants over the Pacific Ocean near southern Taiwan and the northern Philippines. Sci. Total Environ. 491–492, 51–59. https://doi.org/10.1016/j.scitotenv.2014.03.017

Chao, H.R., Shy, C.G., Huang, H.L., Koh, T.W., Tok, T.S., Chen, S.C.C., Chiang, B.A., Kuo, Y.M., Chen, K.C., Chang-Chien, G.P. (2014c). Particle-size dust concentrations of polybrominated diphenyl ethers (PBDEs) in Southern Taiwanese houses and assessment of the PBDE daily intakes in toddlers and adults. Aerosol Air Qual. Res. 14, 1299–1309. https://doi.org/10.4209/aaqr.2012.12.0342

Chao, H.R., Que, D.E., Gou, Y.Y., Chuang, C.Y., Chang, T.Y., Hsu, Y.C. (2016). Indoor and outdoor concentrations of polybrominated diphenyl ethers on respirable particulate in central and Southern Taiwan. Aerosol Air Qual. Res. 16, 3187–3197. https://doi.org/10.4209/aaqr.2016.11.0472

Chao, H.R., Hsu, J.W., Ku, H.Y., Wang, S.L., Huang, H.B., Liou, S.H., Tsou, T.C. (2018). Inflammatory response and $PM_{2.5}$ Exposure of urban traffic conductors. Aerosol Air Qual. Res. 18, 2633–2642. https://doi.org/10.4209/aaqr.2018.04.0132

Chen, H., Du, R., Ren, W., Zhang, S., Du, P., Zhang, Y. (2021). The microbial activity in $PM_{2.5}$ in indoor air: As an index of air quality level. Aerosol Air Qual. Res. 21, 200101. https://doi.org/10.4209/aaqr.2020.03.0101

Chou, H.M., Kao, C.C., Chuang, K.P., Lin, C., Shy, C.G., Chen, R.F., Tsai, C.C., Chuang, C.Y., Cheng, Y.C., Chen, C.C., Chao, H.R. (2016). Levels of polybrominated diphenyl ethers in air-conditioner filter dust used to assess health risks in clinic and electronic plant employees. Aerosol Air Qual. Res. 16, 184–194. https://doi.org/10.4209/aaqr.2015.09.0541

Chou, T., Huang, S. (2021). The report from surveillance of gym industry in 2021 Trends & Insights. https://www.twtrend.com/trend-detail/gymsurvey01 (accessed April 3 2022).

Chung, M.C., Tsai, M.H., Que, D.E., Bongo, S.J., Hsu, W.L., Tayo, L.L., Chao, H.R., Lin, Y.H., Lin, S.L., Gou, Y.Y., Hsu, Y.C., Hou, W.C., Huang, K.L. (2019). Fine particulate matter-induced toxic effects in an animal model of *Caenorhabditis elegans*. Aerosol Air Qual. Res. 19, 1068–1078. https://doi.org/10.4209/aaqr.2019.03.0127

Chung, M.C., Huang, K.L., Avelino, J.L., Tayo, L.L., Lin, C.C., Tsai, M.H., Lin, S.L., Mansor, W.N.W., Su, C.K., Huang, S.T. (2020). Toxic assessment of heavily traffic-related fine particulate matter using an in-vivo wild-type caenorhabditis elegans model. Aerosol Air Qual. Res. 20, 1974–1986. https://doi.org/10.4209/aaqr.2020.05.0192

Deng, C., Chen, Y., Li, J., Li, Y., Li, H. (2016). Environmental pollution of polybrominated diphenyl ethers from industrial plants in China: A preliminary investigation. Environ. Sci. Pollut. Res. Int. 23, 7012–7021. https://doi.org/10.1007/s11356-015-5902-8

Gou, Y.Y., Que, D.E., Chuang, C.Y., Chao, H.R., Shy, C.G., Hsu, Y.C., Lin, C.W., Chuang, K.P., Tsai, C.C., Tayo, L.L. (2016a). Dust levels of polybrominated diphenyl ethers (PBDEs) and polybrominated dibenzo-p-dioxins/furans (PBDD/Fs) in the Taiwanese elementary school classrooms: Assessment of the risk to school-age children. Sci Total Environ 572, 734–741. https://doi.org/10.1016/j.scitotenv.2016.07.044

Gou, Y.Y., Hsu, Y.C., Chao, H.R., Que, D.E., Tayo, L.L., Lin, C.H., Huang, S.M., Tsai, C.H., Shih, S.I. (2016b). Pollution characteristics and diurnal variations in polybrominated diphenyl ethers in indoor and outdoor air from vehicle dismantler factories in Southern Taiwan. Aerosol Air Qual. Res. 16, 1931–1941. https://doi.org/10.4209/aaqr.2016.06.0249

Guo, J.Q., Li, Y.F., Liu, L.Y., Huo, C.Y., Sun, Y., Ma, W.L., Zhang, Z.F., Li, Y.F. (2020). Occurrence and partitioning of brominated flame retardants (BFRs) in indoor air and dust: A 15-month case study in a test home. Enviro. Sci. Pollut. Res. Int. 27, 35126–35136. https://doi.org/10.1007/s11356-020-09788-9

Hsu, H.Y., Tsai, M.C., Yeh, T.L., Hsu, L.Y., Hwang, L.C., Chien, K.L. (2021). Association of baseline as well as change in lipid levels with the risk of cardiovascular diseases and all-cause deaths. Sci. Rep. 11, 7381. https://doi.org/10.1038/s41598-021-86336-6

Jin, M.T., Li, L.J., Zheng, Y.X., Shen, X.Y., Wang, D.R. (2019). Polybrominated diphenyl ethers (PBDEs) in dust in typical indoor public places in Hangzhou: Levels and an assessment of human exposure. Ecotoxicol. Environ. Saf. 169, 325–334. https://doi.org/10.1016/j.ecoenv.2018.10.043

Klinčić, D., Tariba Lovaković, B., Jagić, K., Dvoršćak, M. (2021). Polybrominated diphenyl ethers and the multi-element profile of house dust in Croatia: Indoor sources, influencing factors of their accumulation and health risk assessment for humans. Sci. Total Environ 800, 149430. https://doi.org/10.1016/j.scitotenv.2021.149430

Lee, H.K., Kang, H., Lee, S., Kim, S., Choi, K., Moon, H.B. (2020). Human exposure to legacy and emerging flame retardants in indoor dust: A multiple-exposure assessment of PBDEs. Sci. Total Environ. 719, 137386. https://doi.org/10.1016/j.scitotenv.2020.137386

Li, Y., Chen, L., Wen, Z.H., Duan, Y.P., Lu, Z.B., Meng, X.Z., Zhang, W. (2015). Characterizing distribution, sources, and potential health risk of polybrominated diphenyl ethers (PBDEs) in office environment. Environ. Pollut. 198, 25–31. https://doi.org/10.1016/j.envpol.2014.12.024

Liang, J., Lu, G., Wang, R., Tang, T., Huang, K., Jiang, F., Yu, W., Tao, X., Yin, H., Dang, Z. (2020). The formation pathways of polybrominated dibenzo-*p*-dioxins and dibenzofurans (PBDD/Fs) from pyrolysis of polybrominated diphenyl ethers (PBDEs): Effects of bromination arrangement and level. J. Hazard. Mater. 399, 123004. https://doi.org/10.1016/j.jhazmat.2020.123004

Liu, D., Lin, T., Shen, K., Li, J., Yu, Z., Zhang, G. (2016). Occurrence and concentrations of halogenated flame retardants in the atmospheric fine particles in Chinese cities. Environ. Sci. Technol. 50, 9846–9854. https://doi.org/10.1021/acs.est.6b01685

Ma, J., Addink, R., Yun, S., Cheng, J., Wang, W., Kannan, K. (2009). Polybrominated dibenzo-p-dioxins/ dibenzofurans and polybrominated diphenyl ethers in soil, vegetation, workshop-floor dust, and electronic shredder residue from an electronic waste recycling facility and in soils from a chemical industrial complex in eastern China. Environ. Sci. Technol. 43, 7350–7356. https://doi.org/10.1021/es901713u

Ministry of The Interior (2022). The new Average lifespan of Taiwanese in 2021. https://www.moi.gov.tw/News_Content.aspx?n=4&s=235543 (in Chinese)

Navinya, C.D., Vinoj, V., Pandey, S.K. (2020). Evaluation of $PM_{2.5}$ surface concentrations simulated by NASA's MERRA Version 2 aerosol reanalysis over india and its relation to the air quality index. Aerosol Air Qual. Res. 20, 1329–1339. https://doi.org/10.4209/aaqr.2019.12.0615

Salonen, H., Salthammer, T., Morawska, L. (2020). Human exposure to air contaminants in sports environments. Indoor Air 30, 1109–1129. https://doi.org/10.1111/ina.12718

Shen, H., Cheng, P.H., Yuan, C.S., Yang, Z.M., Hung, C.M., Yen, P.H., Ie, I.R. (2020). Chemical characteristics, spatiotemporal distribution, and source apportionment of $PM_{2.5}$ surrounding industrial complexes in Southern Kaohsiung. Aerosol Air Qual. Res. 20, 557–575. https://doi.org/10.4209/aaqr.2020.01.0007

Shy, C.G., Hsu, Y.C., Shih, S.I., Chuang, K.P., Lin, C.W., Wu, C.W., Chuang, C.Y., Chao, H.R. (2015). Indoor level of polybrominated diphenyl ethers in the home environment and assessment of human health risks. Aerosol Air Qual. Res. 15, 1494–1505. https://doi.org/10.4209/aaqr.2015.05.0291

Simon, T., Aylward, L.L., Kirman, C.R., Rowlands, J.C., Budinsky, R.A. (2009). Estimates of cancer potency of 2,3,7,8-tetrachlorodibenzo(p)dioxin using linear and nonlinear dose-response modeling and toxicokinetics. Toxicol. Sci. 112, 490–506. https://doi.org/10.1093/toxsci/kfp232

Siudek, P., Ruczyńska, W. (2021). Simultaneous measurements of $PM_{2.5}$- and PM_{10}-bound benzo(a)pyrene in a coastal urban atmosphere in Poland: Seasonality of dry deposition fluxes and influence of atmospheric transport. Aerosol Air Qual. Res. 21, 210044. https://doi.org/10.4209/aaqr.210044

Slezakova, K., Peixoto, C., Oliveira, M., Delerue-Matos, C., Pereira, M.D.C., Morais, S. (2018). Indoor particulate pollution in fitness centres with emphasis on ultrafine particles. Environ. Pollut. 233, 180–193. https://doi.org/10.1016/j.envpol.2017.10.050

Suzuki, G., Someya, M., Takahashi, S., Tanabe, S., Sakai, S., Takigami, H. (2010). Dioxin-like activity in japanese indoor dusts evaluated by means of in vitro bioassay and instrumental analysis: Brominated dibenzofurans are an important contributor. Environ. Sci. Technol. 44, 8330–8336. https://doi.org/10.1021/es102021c

Taiwanese Department of Health (Taiwanese DOH) (2008). Compilation of Exposure Factors. Center of Health Risk Assessment and Policy Evaluation, College of Public Health, National Taiwan University (Project ID: DOH96-HP-1801). (in Chinese)

Takigami, H., Suzuki, G., Hirai, Y., Ishikawa, Y., Sunami, M., Sakai, S. (2009). Flame retardants in indoor dust and air of a hotel in Japan. Environ. Int. 35, 688–693. https://doi.org/10.1016/j.envint.2008.12.007

Tames, F., Miglioranza, K.S.B., Rodriguez Nuñez, M., Carreras, H. (2020). Indoor persistent organic pollutants in agricultural areas from Argentina. Indoor Air 30, 725–734. https://doi.org/10.1111/ina.12649

Tue, N.M., Suzuki, G., Takahashi, S., Isobe, T., Trang, P.T.K., Viet, P.H., Tanabe, S. (2010). Evaluation of dioxin-like activities in settled house dust from vietnamese e-waste recycling sites: Relevance of polychlorinated/brominated dibenzo-p-dioxin/furans and dioxin-like PCBs. Environ. Sci. Technol. 44, 9195–9200. https://doi.org/10.1021/es102505j

Tue, N.M., Suzuki, G., Takahashi, S., Kannan, K., Takigami, H., Tanabe, S. (2013). Dioxin-related compounds in house dust from New York State: Occurrence, in vitro toxic evaluation and implications for indoor exposure. Environ. Pollut. 181, 75–80. https://doi.org/10.1016/j.envpol.2013.06.010

U.S. Environmental Protection Agency (U.S. EPA) (2008). Child-Specific Exposure Factors Handbook, Chapter 6 - Inhalation Rate, (2008, Final Report). U.S. Environmental Protection Agency, Washington, DC. https://ordspub.epa.gov/ords/eims/eimscomm.getfile?p_download_id=484738 (accessed Febuary 2015).

U.S. Environmental Protection Agency (U.S. EPA) (2012). EPA's Reanalysis of Key Issues Related to Dioxin Toxicity and Response to NAS Comments. U.S. Environmental Protection Agency, Washington, DC. https://yosemite.epa.gov/sab/sabproduct.nsf/0/9DE6A0825A9C050F85257412005EA22A/$File/Dioxin+-+Main+Text+-+SAB-ERD.pdf (accessed June 2022).

U.S. Environmental Protection Agency (U.S. EPA) (2014). Technical Fact Sheet – Polybrominated

Diphenyl Ethers (PBDEs) and Polybrominated Biphenyls (PBBs). U.S. Environmental Protection Agency, Washington, DC. https://www.epa.gov/sites/production/files/2014-03/documents/ffrrofactsheet_contaminant_perchlorate_january2014_final_0.pdf (accessed June 2022).

Vega, E., López-Veneroni, D., Ramírez, O., Chow, J.C., Watson, J.G. (2021). Particle-bound PAHs and chemical composition, sources and health risk of $PM_{2.5}$ in a highly industrialized area. Aerosol Air Qual. Res. 21, 210047. https://doi.org/10.4209/aaqr.210047

Wang, W., Zheng, J., Chan, C.Y., Huang, M.J., Cheung, K.C., Wong, M.H. (2014). Health risk assessment of exposure to polybrominated diphenyl ethers (PBDEs) contained in residential air particulate and dust in Guangzhou and Hong Kong. Atmos. Environ. 89, 786–796. https://doi.org/10.1016/j.atmosenv.2014.01.030

Wu, E.M.Y., Wang, L.C., Lin, S.L., Chang-Chien, G.P. (2014). Validation and characterization of persistent organic pollutant emissions from stack flue gases of an electric arc furnace by using a long-term sampling system (AMESA®). Aerosol Air Qual. Res. 14, 185–196. https://doi.org/10.4209/aaqr.2013.09.0285

Xu, F., Liu, Y., Wang, J., Zhang, G., Zhang, W., Liu, L., Wang, J., Pan, B., Lin, K. (2015). Characterization of heavy metals and brominated flame retardants in the indoor and outdoor dust of e-waste workshops: implication for on-site human exposure. Environ. Sci. Pollut. Res. 22, 5469–5480. https://doi.org/10.1007/s11356-014-3773-z

Xu, F., Tang, W., Zhang, W., Liu, L., Lin, K. (2016). Levels, distributions and correlations of polybrominated diphenyl ethers in air and dust of household and workplace in Shanghai, China: Implication for daily human exposure. Environ. Sci. Pollut. Res. 23, 3229–3238. https://doi.org/10.1007/s11356-015-5559-3

Yu, T.Y., Chao, H.R., Tsai, M.H., Lin, C.C., Lu, I.C., Chang, W.H., Chen, C.C., Wang, L.J., Lin, E.T., Chang, C.T., Chen, C., Kao, C.C., Wan Mansor, W.N., Yu, K.L.J. (2021). Big data analysis for effects of the COVID-19 outbreak on ambient $PM_{2.5}$ in areas that were not locked down. Aerosol Air Qual. Res. 21, 210020. https://doi.org/10.4209/aaqr.210020

Zhang, T., Chen, Y., Xu, X. (2020). Health risk assessment of $PM_{2.5}$-bound components in Beijing, China during 2013–2015. Aerosol Air Qual. Res. 20, 1938–1949. https://doi.org/10.4209/aaqr.2020.03.0108