POLYCHLORINATED BIPHENYLS (PCBs) CONTAMINATION LEVELS IN CHICKEN EGGS: ENVIRONMENTAL IMPACT

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TÓM TẮT

MỨC ĐỘ NHIỄM POLYCHLORINATED BIPHENYLS (PCBs) TRONG TRỨNG GÀ: TÁC ĐỘNG MÔI TRƯỜNG

Phương pháp phân tích polychlorinated biphenyls (PCB) trong trứng gà đã được phát triển bằng việc kết hợp sử dụng phương pháp chiết QuEChERS cải tiến và kỹ thuật sắc ký khí ghép nối khối phổ (GC-MS/MS). Nồng độ PCB được ghi nhận trong 50 mẫu trứng gà thu thập tại hai nhóm khu vực tái chế, bao gồm: nhóm tái chế kim loại và nhóm tái chế khác. Sau khi phân tích, có đến 20 trong 28 hợp chất PCB (ngoại trừ PCB8, PCB18, PCB44, PCB52 và PCB6) đã được phát hiện với tỷ lệ (DF) lớn hơn 30% trong trứng nguyên quả thu thập tại các khu vực tái chế. PCB123 có hàm lượng ghi nhận cao nhất trong các mẫu trứng thuộc nhóm tái chế kim loại, với khoảng hàm lượng là 0,48–21,60 ng/g-trọng lượng lipid (lw), trong khi đó PCB180 (1,02–5,50 ng/g-lw) được quan sát có hàm lượng cao nhất đối với nhóm mẫu còn lại. Sự phân bố PCB trong trứng gà có mối liên quan với tính chất ưa béo của các PCB và số nguyên tử clo trong cấu trúc hợp chất. Với việc giải thích 72,3% tổng phương sai của bộ dữ liệu nồng độ PCBs trong trứng gà ở hai thành phần chính đầu tiên, kết quả phân tích thành phần chính cho thấy có sự khác biệt rõ rệt về nồng độ PCBs ở các mẫu trứng gà giữa hai nhóm thu thập mẫu. Trên mặt phẳng tạo bởi hai thành phần chính đầu tiên, các điểm mẫu trứng gà thuộc nhóm tái chế khác phân bố tập trung và tách biệt rõ ràng với các điểm mẫu trứng gà thuộc nhóm tái chế kim loại. Kết quả này cho thấy có sự khác biệt trong hồ sơ ô nhiễm PCBs trong môi trường sinh sống của gà đẻ trứng.

Từ khóa: *Polychlorinated biphenyls, GC-MS/MS, trứng gà, Việt Nam*.

1. INTRODUCTION

Polychlorinated biphenyls (PCBs) are a group of halogen aromatic compounds in which at least a hydrogen atom has been substituted by one chlorine atom. Due to their durability, high heat resistance and good dielectric properties, PCBs are frequently utilized in heat transfer systems or as additives to pesticides, and flame retardants [1]. Since PCBs are highly poisonous and persistent in the environment, they have the ability to spread and bioaccumulate in living organisms [2]. PCBs might enter a human's body via air inhalation, dermal pathway, and food consumption [3]. In organisms, PCBs might be harmful to the liver and neurological system [4]. PCBs are believed to impact sperm production and fertility after adult exposure [5]. PCBs have been designated as category 1 human carcinogens by the International Agency for Research on Cancer (1990) and as probable human carcinogens by the U.S. Environmental Protection Agency (2015) [5, 6].

Eggs are frequently included in routine meals due to their essential nutritional value. In Vietnam, people tend to consume free-range chicken eggs over battery-cage chicken eggs. This decision exposes humans to dangerous toxins when consuming free-range chicken eggs in contaminated areas. The lack of monitoring over food quality and living conditions has resulted in the absorption of PCBs during chicken growth and their accumulation in eggs. The previous studies reported notable PCBs concentrated in chicken eggs gathered near former military bases affected by the Vietnamese War [7, 8]. Lambiase *et al.* illustrated the risk of PCBs accumulation in chicken eggs living in recycling and garbage collection areas [9]. Therefore, this study examined chicken eggs obtained from two categories of recycling locations: metal recycling facilities and other recycling sites. The work included: (1) simultaneously analyzing PCBs in chicken eggs; (2) evaluating the correlation between the PCBs contamination profile in chicken eggs and the production characteristics of the recycling sites; and (3) estimating the exposure risk level to human health via chicken egg consumption.

2. EXPERIMENTAL

2.1. Chemicals and reagents

A standard solution consisting of 28 PCBs congeners in isooctane solvent at a concentration of 10 µg/mL was provided by AccuStandard, Inc. (New Haven, USA). The PCBs internal standards (^{13}C, 99% purity) were supplied by Cambridge Isotope Laboratories (Andover, MA, USA). Details about PCBs and PCB internal standards were provided in Table S1. Ultra-pure water (UPW) was obtained by a Milli-Q-Integral system from Merck Millipore (Burlington, MA, USA). Toluene and Acetonitrile (MeCN) were purchased from Merck (Darmstadt, Germany). The primary secondary amine (PSA) and C18 were purchased from Agilent (Santa Clara, CA, USA).

2.2. Sample collection

Fifty chicken egg samples were collected from households raising chickens for eggs in the recycling sites Vietnam in August in 2023, including metal recycling sites (n = 34) and other recycling sites (n=16). Metal recycling sites are the locations where metals such as iron, copper, and aluminum were processed using high-temperature methods. The resultant slag concentrated in nearby residential areas, while pollutants were released directly into the environment. Simultaneously, other recycling facilities encompassed plastic and paper recycling, with pollutants and wastewater were released directly into the residential area. In the laboratory, yolk and albumen parts were separated and put into aluminum foil tarts. All of them were weighted, labeled, and stored at -20 °C until analysis.

2.3. Sample preparation

The PCBs analysis was performed as follows: Firstly, 1 g of frozen yolk/albumin was transferred to a 50-mL centrifuge tube. Then, 50 µL of internal standard (1 µg/mL) was added into the tube. A total of 10 mL of toluene:MeCN mixture (v:v, 6:4), 9 mL of UPW was added into the tube and shaked by hand for 1 min. Secondly, a mixture of 4 g

$MgSO_4$ and 1 g NaCl was added to the tube and vortexed for 5 min. The sample tube was centrifuged at 7000 × *g* for 5 min. Next, 6 mL of the supernatant was transferred into a 15-mL centrifuge tube containing 0.9 g $MgSO_4$, 0.3 g PSA and 0.3 g C18. After three min of vortexing, the mixture was immediately centrifuged at 7000 × *g* for 3 min. After centrifugation, a total of 5 mL of the supernatant was transferred to another 15-mL tube and evaporated by nitrogen to dryness at 1 °C, then reconstituted with 1 mL of *n*-hexane. Finally, the extract was filtered through a 0.22-µm PTFE membrane into a dark vial before analysis on a GC-MS/MS system.

2.4. Gas chromatography-tandem mass spectrometry

The GC-MS/MS system consisted of a Trace GC 1310 gas chromatography, a TriPlus RSH autosampler, and a TSQ Dashboard 9000 mass spectrometer. The DB5-MS column (30 m × 0.25 mm i.d., 0.25 µm film thickness) was employed to separate the PCBs. The temperature gradient program was described as follows: maintain 70 °C for 2 min, raised to 140 °C (20 °C/min), then raised to 180 °C (2 °C/min), and lastly raised to 250 °C (8 °C/min), holding for 10 min. Helium (purity holding of 99.999%) was utilized as a carrier gas at a flow rate of 1 mL/min, argon (purity of 99.999%) was used as collision gas. In splitless mode, the injection volume was 1 µL. The temperatures for the inlet, ion transfer line, and ion source were optimal at 240 °C, 280 °C, and 210 °C, respectively.

2.5. Method validation

The PCBs analytical procedure was evaluated for linearity, recovery, repeatability and reproducibility, limit of detection, and limit of quantification. The linearity range was created over the range of 1-100 ng/mL, with all linear R^2 coefficients achieved being greater than 0.995. The repeatability and reproducibility were assessed by testing the relative standard deviation (RSD). This experiment was performed on blank egg samples, repeated five times at each spiked concentration level (1, 10 and 100 ng/g), and continuously for three days. The obtained RSD value was in the range of 3.3–10.4% (RSD<15%). The limit of detection (LOD) was defined as the PCBs concentration in the egg sample that resulted in 3×SD. Similarly, the limit of quantification (LOQ) was calculated as LOQ = 10×SD. The LOD and LOQ for PCBs in this study were in the range of 0.02–0.06 ng/g-lw and 0.07–0.20 ng/g-lw, respectively. The method validation results were presented in Table S2.

2.6. Health Risk Assessment

For estimation of non-carcinogenic risk, the average daily dose (ADD, mg/kg-day) and hazard quotient (HQ) were calculated as in the equations (1) and (2).

$$ADD = \frac{C \times IR}{BW} \quad (1)$$

$$HQ = \frac{ADD}{RfD} \quad (2)$$

In which, C represented the mean concentration of each PCB (mg/kg); IR was food digestion rate (0.031 kg/day); BW for children was 15 kg and 60 kg for adults; R*f*D was the reference dose (mg/kg-day), which was considered equal to 20 ng/kg-day (USEPA 2005). A value of HQ < 1 represented the daily exposure dose that was not hazardous to human health [10].

For PCBs carcinogenic hazards, the lifetime average daily dose (LADD, mg/kg-day), and the excess lifetime cancer risk (ELCR) were calculated as follows:

$$LADD = \frac{C \times IR \times EF \times ED}{BW \times AT} \qquad (3)$$

$$ELCR = LADD \times CSF \qquad (4)$$

LADD had a meaning similar to ADD. In which, EF was exposure frequency (day/year), assuming 365 days of consumption; ED was exposure duration (years), with 7.0 years for children and 34.5 years for adults; AT was the average time (70 years × 365 days); CSF was the cancer slope factor with a value of 2 mg/kg-day. If ELCR < 1.00E-6, it represented a level that was not risk; if ELCR > 1.00E-4, it represented a level that was of concern or alarming to human health [10].

3. RESULTS AND DISCUSSION

3.1. PCBs in chicken eggs

The PCBs concentration detected in chicken eggs collected in two categories of recycling locations was presented in Table 1. The PCB level in whole eggs was estimated using the weight ratio of yolk and albumen with the PCB concentration in each part. The findings indicated that, except for PCB8, PCB18, PCB44, PCB52, PCB66, PCB101, PCB126 and PCB169, the remaining PCBs had the detection frequency (DF) in chicken eggs greater than 30%. Among them, PCB8, PCB18, PCB44, PCB52, and PCB66 were not detect in all egg samples. Two of them, notably PCB123 and PCB167, exhibiting the highest concentration of 28 PCBs congeners, were identified in eggs in the metal recycling site. Among them, PCB123 had the highest concentration, varying from 0.48 ng/g-lw to 21.60 ng/g-lw for the metal recycling site, followed by PCB167. Particularly, for the other location, PCB189 was observed to have the highest concentration, varying from 0.19 to 6.38 ng/g-lw. Overall, the concentrations of PCBs in the yolk were greater than those in the albumen in all samples (Table S3) and the level of PCBs in eggs was lower than that in eggs from Turkey, which had a range of 10.36–225.62 pg TEQ/g-fat for PCB105 or 33.68–330.52 pg TEQ/g-fat for PCB138 [11]. Besides, it was reported that PCBs contamination was recorded to be significantly lower in egg samples in the Netherlands, where PCB77 concentrations could be up to 2009.9 pg TEQ/g-fat [12]. Nevertheless, PCBs with a greater number of chlorine atoms in their composition had a tendency to accumulate more than other PCBs, which was comparable to the accumulation pattern found in ostrich eggs in Poland [13]. The primary source of exposure to possibly PCB-contaminated environments, such as soil, ambient air, drinking water and animal feed, was considered to be PCBs identification in chicken eggs [14]. The PCBs distribution in the egg fraction and the predominant presence of PCBs with more chlorine atoms suggested a relationship to the higher protein ratio of the yolk and the easier metabolism of PCBs with less chlorine atoms [15].

Table 1: PCBs profile in whole egg samples collected in two categories of recycling locations (ng/g-lw).

PCBs congeners	Metal recycling site (n=34)		Other site (n=16)	
	DF (%)	Range *(Mean)*	DF (%)	Range *(Mean)*
PCB8	0	<MDL	0	<MDL
PCB18	0	<MDL	0	<MDL
PCB28	65	0.16 – 4.29 *(1.56)*	63	0.38 – 1.31 (0.83)
PCB44	0	<MDL	0	<MDL
PCB52	0	<MDL	0	<MDL
PCB66	0	<MDL	0	<MDL
PCB77	74	0.16 – 3.90 *(1.72)*	63	0.19 – 2.56 *(1.17)*
PCB81	71	0.34 – 4.72 *(1.53)*	63	0.16 – 1.38 *(0.74)*
PCB101	3	0.16	6	0.35
PCB105	88	0.06 – 7.13 *(2.45)*	56	0.41 – 3.04 *(1.40)*
PCB114	94	0.27 – 6.05 *(2.20)*	56	0.34 – 2.02 *(1.09)*
PCB118	76	0.16 – 6.20 *(2.32)*	63	0.16 – 3.20 *(0.84)*
PCB123	94	0.48 – 21.60 *(10.87)*	50	0.70 – 4.83 *(2.49)*
PCB126	29	0.10 – 0.64 *(0.22)*	6	0.16
PCB128	91	0.35 – 7.86 *(2.88)*	56	0.27 – 4.32 *(1.58)*
PCB138	88	0.13 – 5.18 *(2.29)*	81	0.26 – 4.58 *(2.00)*
PCB153	74	0.27 – 7.84 *(2.65)*	38	0.19 – 2.56 *(1.39)*
PCB156	88	0.20 – 7.29 *(3.22)*	44	0.27 – 5.89 *(2.09)*
PCB157	91	0.35 – 6.40 *(2.45)*	88	0.16 – 6.18 *(2.09)*
PCB167	97	0.68 – 9.51 *(5.20)*	38	0.20 – 0.82 *(0.50)*
PCB169	41	0.06 – 0.41 *(0.20)*	6	0.20
PCB170	71	0.10 – 5.74 *(2.62)*	44	0.29 – 2.56 *(1.46)*
PCB180	85	0.13 – 6.30 *(2.37)*	56	1.02 – 5.50 *(2.98)*
PCB187	59	0.16 – 1.95 *(0.81)*	38	0.16 – 0.80 *(0.42)*
PCB189	85	0.27 – 7.60 *(3.01)*	44	0.19 – 6.38 *(2.97)*
PCB195	94	0.26 – 9.05 *(3.45)*	63	0.83 – 3.20 *(1.95)*
PCB206	91	0.41 – 5.69 *(2.23)*	75	0.61 – 5.15 *(2.13)*
PCB209	94	0.34 – 4.37 *(1.91)*	75	0.24 – 3.24 *(1.54)*

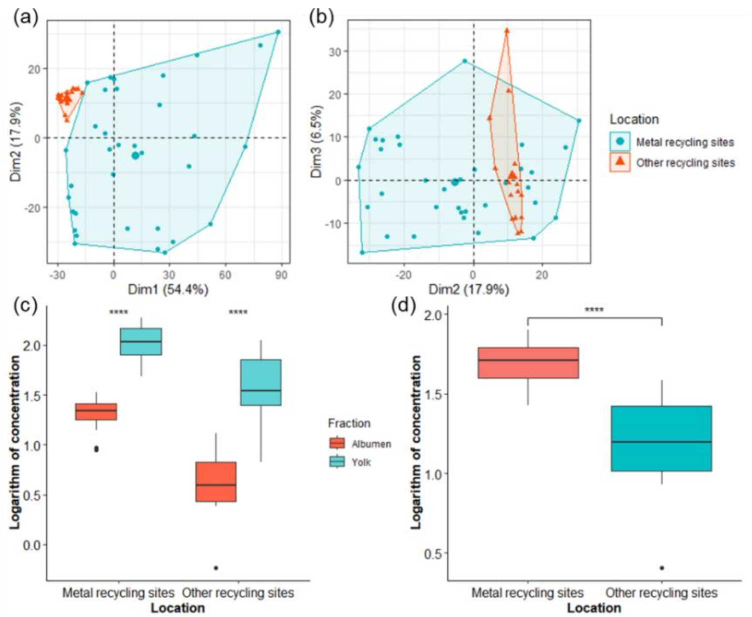

Figure 1. The score plots illustrate the distribution of PCBs in eggs on PC1-PC2 (a) and PC2-PC3 (b). The boxplot illustrates the correlation between PCB concentration and egg fraction (c) and location (d).

To more thoroughly demonstrate the relationship between PCBs congeners and sampling sites, principal component analysis (PCA) was applied to 18 PCBs (DF>50%). The first three principal components (PCs) explained 78.8% of the cumulative total variance; in which PC1, PC2, PC3 accounted for 54.4%, 17.9% and 6.5%, respectively. A significant variation was observed in PCB concentrations in chicken eggs between the metal recycling location and other location in PC1-2 (Fig. 1a). Even so, a notable variation in PCBs contamination was not shown between sampling regions in PC2-3 (Fig. 1b). The predominant key loadings of PCBs for PC1, PC2, PC3 respectively included PCB123, PCB167 and PCB206. The egg samples from the metal recycling sites exhibited more dispersion, indicating that the PCB contamination profile at the sampling locations might be influenced by the properties of the metals. Conversely, the other recycling sites had more concentrated data alongside diminished PCB levels. This indicated that employing lower heating sources in this group led to a decrease in the utilization of high-heat fuels, such as coal or waste oil, which might contain PCBs. PCB123 contamination tendency was also been reported at high levels in a previous study in Dong Nai, which was considered a post-war pollution hotspot in Vietnam, reaching up to 581 pg TEQ/g-fat in chicken eggs [8]. Besides, the discovered PCBs level varied in the sampling areas, perhaps due to the different pollution potential around livestock regions. Previous studies demonstrated a direct correlation between the contamination levels in chicken-rearing environments and the concentration of contaminants presented in hen's eggs. Specifically, poultry eggs raised near e-waste dumps and recycling sites exhibited variations in the concentration of PBDEs, organic halogens and halogenated flame retardants compared to eggs in the control locations [9, 16-18].

The PCBs congeners were shown to correlate with egg fractions (Fig. 1c). There was a significant variation (Mann–Whitney *U* test, p<0.05) that was observed in ΣPCBs concentrations between the yolk and albumen fractions, with ΣPCBs levels in the yolk being higher than that in albumen fractions of both groups. This distribution was deemed appropriate since PCBs with elevated octanol-water partition coefficient (log K_{OW}) were primarily found in the high lipid content fraction (i.e. yolk) [15]. Furthermore, the level of ΣPCBs pollution in chicken eggs varied across the investigated locations, with high ΣPCBs was recorded in egg samples from metal recycling (Fig. 1d, Mann–Whitney *U* test, p<0.05). This proved that surrounding environmental pollution affected the growth and reproduction of hens [19]. The result indicated that metal recycling emissions major amounts of PCBs into the environment relative to other recycling activities. The conventional production process for metal recycling products frequently utilized coal, crude oil, or waste oil as burning fuel, which contain substantial amounts of PCBs. Furthermore, the original recycled materials lack purity and include numerous organic contaminants that readily generated PCBs at elevated temperatures, subsequently being emitted into the environment as exhaust gases. PCBs were progressively released into the environment, such as air, soil and water, leading to their accumulation in living organisms and byproducts [20]. Meanwhile, various recycling activities utilized minimal or no heat in their processes compared to metal recycling. Therefore, the quantity of PCBs released during the recycling process was minimized. The primary factor contributing to the variation in the PCB contamination profile of eggs from chickens residing at metal recycling sites compared to those from other recycling locations was outlined here.

3.2. PCBs exposure via dietary

The average daily dose (ADD) and the lifetime average daily dose (LADD) by age category were described in Table S4. For non-carcinogenic PCBs, the average daily dose for children and adults was 6.35E-09 – 9.59E-07 mg/kg-day and 1.59E-09 – 2.40E-07 mg/kg-day, respectively. Among both children and adults, PCB180 had the highest ADD value, whereas PCB101 showed the lowest. Similarly, for carcinogenic PCBs, the lifetime average daily dose was in the range of 1.98E-09 – 3.82E-07 mg/kg-day for children and 2.44E-09 – 4.71E-07 mg/kg-day for adults. Notably, the ADD values in children consistently exceeded those in adults, contrasting with the LADD values. In general, the Hazard Quotient (HQ) values in this study were all less than 1 and the excess lifetime cancer risk (ELCR) were all less than 1.00E-6, indicating that the PCBs concentration in chicken eggs was acceptable and not at a concerning level.

4. CONCLUSION

A high-accuracy method for simultaneously analyzing 28 PCBs in chicken eggs was revealed in this study. PCBs profiles in 50 chicken egg samples collected in metal and other recycling sites in Vietnam were reported. PCBs containing more than one chlorine atom in their structure were mostly found in the yolk fraction, which was consistent with their poor metabolism abilities and lipophilic properties of PCBs. Moreover, PCBs levels were higher in chicken eggs in metal recycling locations owing to variables such as burning fuel, raw materials, production duration, and temperature. Initial data only focused on chicken eggs, more investigation and an annual update of the PCBs profile remained essential. This study served as a foundation for enhancing the quality management of animal-derived producted and provides a literature for future in-depth study.

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Supplementary Information

Table S1. The information on PCB compounds analyzed in the study.

#	Compound	Abbr.	MW (g/mol)	Log K_{ow}	Internal standards
1	2,4'-Dichlorobiphenyl	PCB8	223.9	5.15	$^{13}C_{12}$-PCB28
2	2,2',5-Trichlorobiphenyl	PCB18	257.5	5.37	$^{13}C_{12}$-PCB28
3	2,4,4'-Trichlorobiphenyl	PCB28	257.5	5.74	$^{13}C_{12}$-PCB28
4	2,2′,3,5′-Tetrachlorobiphenyl	PCB44	291.9	5.79	$^{13}C_{12}$-PCB28
5	2,2',5,5'-Tetrachlorobiphenyl	PCB52	292.0	5.81	$^{13}C_{12}$-PCB52
6	2,3',4,4'-Tetrachlorobiphenyl	PCB66	291.9	-	$^{13}C_{12}$-PCB52
7	3,3',4,4'-Tetrachlorobiphenyl	PCB77	291.9	6.37	$^{13}C_{12}$-PCB101
8	3,4,4',5-Tetrachlorobiphenyl	PCB81	291.9	-	$^{13}C_{12}$-PCB101
9	2,2′,4,5,5′-Pentachlorobiphenyl	PCB101	326.4	6.27	$^{13}C_{12}$-PCB101
10	2,3,3',4,4'-Pentachlorobiphenyl	PCB105	326.4	6.93	$^{13}C_{12}$-PCB105
11	2,3,4,4',5-Pentachlorobiphenyl	PCB114	326.4	-	$^{13}C_{12}$-PCB114
12	2,3',4,4',5-Pentachlorobiphenyl	PCB118	326.4	-	$^{13}C_{12}$-PCB118
13	2',3,4,4',5-Pentachlorobiphenyl	PCB123	326.4	-	$^{13}C_{12}$-PCB118
14	3,3',4,4',5-Pentachlorobiphenyl	PCB126	326.4	-	$^{13}C_{12}$-PCB153
15	2,2',3,3',4,4'-Hexachlorobiphenyl	PCB128	360.8	6.73	$^{13}C_{12}$-PCB128
16	2,2',3,4,4',5'-Hexachlorobiphenyl	PCB138	360.8	6.74	$^{13}C_{12}$-PCB138
17	2,2',4,4',5,5'-Hexachlorobiphenyl	PCB153	360.8	6.74	$^{13}C_{12}$-PCB153
18	2,3,3',4,4',5-Hexachlorobiphenyl	PCB156	360.8	7.53	$^{13}C_{12}$-PCB156
19	2,3,3',4,4',5'-Hexachlorobiphenyl	PCB157	360.8	-	$^{13}C_{12}$-PCB157
20	2,3',4,4',5,5'-Hexachlorobiphenyl	PCB167	360.8	-	$^{13}C_{12}$-PCB167
21	3,3',4,4',5,5'-Hexachlorobiphenyl	PCB169	360.8	7.61	$^{13}C_{12}$-PCB180
22	2,2',3,3',4,4',5-Heptachlorobiphenyl	PCB170	395.3	-	$^{13}C_{12}$-PCB170
23	2,2',3,4,4',5,5'-Heptachlorobiphenyl	PCB180	395.3	-	$^{13}C_{12}$-PCB180
24	2,2',3,4',5,5',6-Heptachlorobiphenyl	PCB187	395.3	-	$^{13}C_{12}$-PCB138
25	2,3,3',4,4',5,5'-Heptachlorobiphenyl	PCB189	395.3	-	$^{13}C_{12}$-PCB189
26	2,2',3,3',4,4',5,6-Octachlorobiphenyl	PCB195	429.7	-	$^{13}C_{12}$-PCB206
27	2,2',3,3',4,4',5,5',6-Nonachlorobiphenyl	PCB206	464.2	7.94	$^{13}C_{12}$-PCB206
28	Decachlorobiphenyl	PCB209	498.6	8.28	$^{13}C_{12}$-PCB209

Table S2. The validated parameters of PCBs analysis method in chicken egg samples by GC-MS/MS.

PCBs	Linear range (ng/mL)	R^2	Recovery (%)			RSD_R (RSD_{wr}, %)			LOD (ng/g-lw)	LOQ (ng/g-lw)
			1 ng/g	10 ng/g	100 ng/g	1 ng/g	10 ng/g	100 ng/g		
PCB8	1-100	0.9993	101.3	99.8	95.2	7.6 (6.5)	6.3 (7.4)	9.3 (5.2)	0.06	0.20
PCB18	1-100	0.9990	85.8	90.3	88.2	7.3 (4.6)	5.1 (3.1)	8.2 (4.0)	0.05	0.17
PCB28	1-100	0.9991	92.0	95.4	96.1	3.1 (8.6)	10 (6.2)	7.4 (4.6)	0.04	0.13
PCB44	1-100	0.9990	87.9	92.1	90.7	4.2 (5.2)	6.3 (8.9)	9.0 (6.0)	0.04	0.13
PCB52	1-100	0.9990	91.5	93.6	87.2	6.3 (2.4)	4.5 (3.6)	7.2 (7.5)	0.05	0.17
PCB66	1-100	1.0000	85.9	90.2	90.4	3.2 (4.5)	5.1 (2.9)	6.8 (4.8)	0.03	0.10
PCB77	1-100	0.0988	100.4	99.6	98.2	4.6 (4.6)	8.7 (7.3)	6.5 (3.6)	0.04	0.13
PCB81	1-100	0.9992	94.4	95.0	98.4	6.2 (2.7)	9.6 (7.1)	9.7 (7.8)	0.03	0.10
PCB101	1-100	0.9993	85.3	90.3	89.2	4.2 (3.5)	6.6 (4.7)	5.2 (7.4)	0.06	0.20
PCB105	1-100	0.9985	91.4	86.4	89.0	3.6 (5.1)	8.9 (9.7)	6.4 (6.3)	0.02	0.07
PCB114	1-100	0.9992	95.3	92.1	98.0	6.0 (8.7)	8.6 (9.4)	8.3 (3.8)	0.02	0.07
PCB118	1-100	0.9999	103.5	99.3	98.0	6.2 (6.8)	8.5 (9.6)	7.6 (7.4)	0.03	0.10
PCB123	1-100	0.9997	95.2	100.4	101.3	9.4 (9.8)	8.5 (4.3)	7.4 (4.0)	0.06	0.20
PCB126	1-100	0.9990	90.5	85.3	83.9	5.4 (8.5)	3.2 (3.4)	8.4 (4.1)	0.04	0.13
PCB128	1-100	0.9989	99.5	104.5	97.3	7.5 (3.3)	3.9 (7.2)	6.8 (3.5)	0.04	0.13
PCB138	1-100	0.9990	90.3	88.3	95.2	3.5 (4.3)	4.0 (6.3)	6.3 (4.1)	0.05	0.17
PCB153	1-100	0.9993	96.9	101.5	98.4	7.9 (9.1)	5.1 (4.4)	5.8 (5.7)	0.03	0.10
PCB156	1-100	0.9998	85.9	95.8	99.9	5 (6.1)	5.8 (6.6)	4.2 (7.7)	0.02	0.07
PCB157	1-100	0.9988	101.1	86.6	94.7	4.3 (3.7)	4 (7.3)	9 (8.2)	0.04	0.13
PCB167	1-100	0.9988	104.2	99.6	96.6	4.5 (9.4)	7.9 (3.3)	9.3 (3.9)	0.03	0.10
PCB169	1-100	0.9995	96.5	102.3	101.3	8.4 (7)	9.2 (9.6)	9.1 (5.4)	0.03	0.10
PCB170	1-100	0.9991	86.4	94.3	96.3	6.9 (3.7)	6.2 (5.3)	3.1 (8)	0.03	0.10
PCB180	1-100	0.9995	86.2	89.7	93.7	9.2 (9.7)	5.6 (5.2)	8.4 (7.2)	0.04	0.13
PCB187	1-100	0.9997	95.5	104.8	99.6	5.9 (7.2)	3.5 (5.9)	4.5 (8.7)	0.05	0.17
PCB189	1-100	0.9990	95.5	99.6	96.2	9.4 (4.6)	8.9 (8.9)	7.3 (8.3)	0.05	0.17
PCB195	1-100	0.9988	90.4	89.3	87.2	4.1 (8.1)	9.3 (6.3)	6.3 (3.8)	0.06	0.20
PCB206	1-100	0.9987	92.8	96.2	86.2	8.8 (3.7)	4.1 (6.3)	3.7 (8.9)	0.06	0.20
PCB209	1-100	0.9991	97.7	86.3	92.5	3.6 (9)	6.7 (9.8)	4.2 (9.3)	0.06	0.20

Table S3. PCBs concentration in chicken egg fractions collected in recycling sites in Vietnam (ng/g-lw).

PCB congeners	Metal recycling sites (n=34)		Other recycling sites (n=16)	
	Yolk	Albumen	Yolk	Albumen
PCB8	<LOD	<LOD	<LOD	<LOD
PCB18	<LOD	<LOD	<LOD	<LOD
PCB28	0.5 – 13.4 *(4.16)*	2.3	1.2 – 4.1 *(2.60)*	<LOD
PCB44	<LOD	<LOD	<LOD	<LOD
PCB52	<LOD	<LOD	<LOD	<LOD
PCB66	<LOD	<LOD	<LOD	<LOD
PCB77	0.5 – 12.2 *(5.21)*	0.3 – 3.0 *(1.00)*	0.6 – 8.0 *(3.53)*	0.9 – 1.4 *(1.15)*
PCB81	0.6 – 10.5 *(3.15)*	0.4 – 2.5 (1.60)	0.5 – 4.3 *(2.26)*	0.5 – 0.9 *(0.70)*
PCB101	0.5	<LOD	1.1	<LOD
PCB105	0.2 – 17.0 *(5.96)*	0.4 – 6.2 *(2.10)*	1.7 – 9.5 *(4.89)*	0.6 – 1.9 *(1.25)*
PCB114	0.9 – 18.9 *(6.35)*	0.3 – 3.5 *(1.60)*	1.6 – 6.3 *(4.07)*	0.3 – 1.3 *(0.75)*

PCB congeners	Metal recycling sites (n=34)		Other recycling sites (n=16)	
	Yolk	Albumen	Yolk	Albumen
PCB118	0.5 – 12.8 *(5.53)*	0.5 – 6.0 *(2.10)*	0.5 – 10 *(2.80)*	0.6 – 1.2 *(0.90)*
PCB123	14.6 – 63.9 *(35.33)*	0.6 – 8.1 *(3.20)*	2.2 – 10.0 *(7.13)*	1.6 – 3.2 *(2.30)*
PCB126	0.3 – 2.0 *(0.69)*	0.3	0.5	<LOD
PCB128	0.9 – 18.4 *(8.14)*	0.4 – 3.2 *(1.50)*	1.4 – 13.5 *(6.49)*	0.4 – 2.4 *(1.43)*
PCB138	0.4 – 13.2 *(6.08)*	0.5 – 6.4 *(1.30)*	0.8 – 14.3 *(6.43)*	0.6 – 0.7 *(0.63)*
PCB153	1.0 – 24.5 *(8.73)*	0.4 – 3.3 *(1.70)*	0.6 – 8.0 *(5.33)*	0.7 – 1.5 *(1.10)*
PCB156	1.3 – 18.8 *(9.79)*	0.3 – 3.1 *(1.51)*	2.7 – 18.4 *(8.74)*	0.4 – 0.5 *(0.45)*
PCB157	1.1 – 18.4 *(6.55)*	0.3 – 4.0 *(1.72)*	0.5 – 19.3 *(6.66)*	0.3 – 1.6 *(0.77)*
PCB167	4.2 – 25.4 *(14.77)*	0.3 – 6.7 *(2.53)*	1.6 – 2.0 *(1.78)*	0.3 – 1.2 *(0.68)*
PCB169	0.2 – 1.0 *(0.45)*	0.2 – 0.6 (0.41)	<LOD	<LOD
PCB170	0.3 – 17.8 *(7.91)*	0.6 – 2.6 *(1.21)*	0.9 – 8.0 *(4.93)*	1.1
PCB180	0.4 – 19.7 *(7.60)*	0.4 – 2.5 *(1.28)*	3.2 – 17.2 *(9.06)*	0.5 – 0.6 *(0.55)*
PCB187	0.5 – 6.1 *(2.11)*	0.5 – 1.6 *(1.00)*	0.5 – 2.5 *(1.30)*	<LOD
PCB189	2.8 – 19.5 *(9.35)*	0.4 – 4.0 *(1.61)*	0.6 – 17.8 *(9.75)*	0.9 – 1.1 *(1.00)*
PCB195	0.8 – 20.8 *(7.35)*	0.4 – 7.2 *(2.71)*	0.3 – 8.0 *(5.00)*	1.7 – 4.7 *(3.30)*
PCB206	1.2 – 11.3 *(5.52)*	0.5 – 3.9 *(2.01)*	2.6 – 16.1 *(6.53)*	0.9 – 2.4 *(1.67)*
PCB209	0.3 – 9.9 *(4.517)*	0.2 – 3.8 *(1.60)*	0.8 – 10.7 *(4.76)*	0.2 – 3.6 *(1.40)*

Table S4. Results of the estimated daily intake (EDI) and hazard quotient (HQ) for detected PCBs compounds.

Non-carcinogenic effects	ADD (mg/kg-day)		HQ		Carcinogenic effects	LADD (mg/kg-day)		ELCR	
	Children	Adult	Children	Adult		Children	Adult	Children	Adult
PCB8	-	-	-	-	PCB77	5.82E-08	7.17E-08	1.16E-07	1.43E-07
PCB18	-		-	-	PCB81	3.33E-08	4.10E-08	6.65E-08	8.20E-08
PCB28	4.67E-07	1.17E-07	2.33E-02	5.84E-03	PCB105	7.77E-08	9.57E-08	1.55E-07	1.91E-07
PCB44	-	-	-	-	PCB114	6.29E-08	7.76E-08	1.26E-07	1.55E-07
PCB52	-	-	-	-	PCB118	4.66E-08	5.74E-08	9.32E-08	1.15E-07
PCB66	-	-	-	-	PCB123	3.82E-07	4.71E-07	7.64E-07	9.42E-07
PCB101	6.35E-09	1.59E-09	3.17E-04	7.94E-05	PCB126	2.68E-09	3.30E-09	5.36E-09	6.61E-09
PCB128	9.52E-07	2.38E-07	4.76E-02	1.19E-02	PCB156	1.11E-07	1.37E-07	2.22E-07	2.73E-07
PCB138	9.59E-07	2.40E-07	4.80E-02	1.20E-02	PCB157	1.02E-07	1.26E-07	2.04E-07	2.52E-07
PCB153	6.42E-07	1.60E-07	3.21E-02	8.02E-03	PCB167	1.49E-07	1.83E-07	2.97E-07	3.66E-07
PCB170	8.09E-07	2.02E-07	4.05E-02	1.01E-02	PCB169	1.98E-09	2.44E-09	3.96E-09	4.88E-09
PCB180	9.59E-07	2.40E-07	4.79E-02	1.20E-02	PCB189	9.77E-08	1.20E-07	1.95E-07	2.41E-07
PCB187	1.49E-07	3.72E-08	7.44E-03	1.86E-03					
PCB195	8.68E-07	2.17E-07	4.34E-02	1.09E-02					
PCB206	6.57E-07	1.64E-07	3.29E-02	8.22E-03					
PCB209	6.59E-07	1.65E-07	3.29E-02	8.23E-03					