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Health risk assessment of polychlorinated biphenyls (PCBs) in baby clothes. A preliminary study☆

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ABSTRACT

Clothes may contain a large range of chemical additives and other toxic substances, which may eventually pose a significant risk to human health. Since they are associated with pigments, polychlorinated biphenyls (PCBs) may be especially relevant. On the other hand, infants are very sensitive to chemical exposure and they may wear some contact and colored textiles for a prolonged time. Consequently, a specific human health risk assessment is required. This preliminary study was aimed at analyzing the concentrations of PCBs in ten bodysuits purchased in on-line stores and local retailers. The concentrations of 12 dioxin-like and 8 non-dioxin-like PCB congeners were determined by gas chromatography coupled to high resolution mass spectrometry, with detection limits ranging between 0.01 and 0.13 pg/g. The dermal absorption to PCBs of children at different ages (6 months, 1 year and 3 years old) was estimated, and the non-cancer and cancer risks were evaluated. Total levels of PCBs ranged from 74.2 to 412 pg/g, with a mean TEQ concentration of 13.4 pg WHO-TEQ/kg. Bodysuits made of organic cotton presented a total mean PCB concentration substantially lower than clothes made of regular cotton (11.0 vs. 15.8 pg WHO-TEQ/kg). The dermal absorption to PCBs for infants was calculated in around $3 \cdot 10^{-5}$ pg WHO-TEQ/kg·day, regardless the age. This value is > 10,000-fold lower than the dietary intake of PCBs, either through breastfeeding or food consumption. Furthermore, this exposure value would not pose any health risks for the infants wearing those bodysuits. Anyhow, as it is a very preliminary study, this should be confirmed by analyzing larger sets of textile samples. Further investigations should be also focused on the co-occurrence of PCBs and other toxic chemicals (i.e., formaldehyde, bisphenols and aromatic amines) in infant clothes.

1. Introduction

People are permanently exposed to cocktails of environmental and food contaminants. In non-occupationally exposure populations, dietary intake is the most important exposure pathway for many chemicals, including a wide variety of semi-volatile organic compounds (SVOCs), such as polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), bisphenol A, polybrominated diphenyl ethers (PBDEs) or per- and polyfluoroalkyl substances (PFASs) (Domingo and Nadal, 2017; Trabalón et al., 2017; González et al., 2018; Fan et al., 2021; Martínez et al., 2021; Sun et al., 2021). However, the contribution of other pathways, such as air inhalation and dermal absorption, cannot be disregarded (Melymuk et al., 2016), since they can be potentially significant, especially for some specific vulnerable populations. While the number of scientific studies on health risk assessment of air inhalation of chemical pollutants is very extensive, investigations on the risks associated to dermal absorption are more limited, being only focused to some specific substances.

Recent studies have indicated that dermal absorption to air contaminants, especially indoors, may be also a significant pathway for some SVOCs (Bekö et al., 2013; Weschler and Nazaroff, 2012; Kolarik and Morrison, 2021). Even for non-occupational environments, wearing clothing exposed to indoor air pollution can substantially increase the dermal uptake of SVOCs (Morrison et al., 2016). In addition, the simple

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Table 1
Characteristics of the 10 purchased bodysuits whose PCB levels were determined.

Nº	Place	Materials	Made in	Color	Official certification	Density (mg/cm^2)
1	Chain Store	100% Organic Cotton	China	White		18.9
2	Chain Store	100% Cotton	Bangladesh	Beige and brown		19.1
3	Chain Store	100% Cotton	Bangladesh	Mustard and brown		18.6
4	Chain Store	100% Organic Cotton	Cambodia	Green		19.3
5	Chain Store	100% Organic Cotton	Cambodia	White		19.5
6	Chain Store	100% Organic Cotton	Cambodia	Grey		20.6
7	Chain Store	100% Cotton	Bangladesh	Pink and white	OEKO-TEX® Standard 100	16.1
8	Chain Store	100% Cotton	Bangladesh	Pink	OEKO-TEX® Standard 100	18.5
9	Chain Store	100% Cotton	Bangladesh	White	OEKO-TEX® Standard 100	18.0
10	Shop	100% Organic Cotton	EU	White, black and yellow	GOTS[a]	17.7

[a] GOTS: Global Organic Textile Standard.

act of bringing home clothes of former occupationally exposed employees may become a key pathway for the contamination of the residential environment (Kaifie et al., 2019), ultimately exposing children to air pollutants from outdoors. Unfortunately, the lack of understanding may lead to wrong assumptions, either considering that dermal absorption on body locations covered by clothing could be neglected or that clothing has no influence on dermal exposure (Gong et al., 2016).

In recent years, the occurrence of some specific SVOCs (e.g., phthalates, bisphenol A) in textile materials, including fabrics designed for newborns and infants (Rovira et al., 2015; Freire et al., 2019; Li et al., 2019; Rovira and Domingo, 2019; Tang et al., 2020) and even in diapers (Ishii et al., 2015; Park et al., 2019; Makoś-Chełstowska et al., 2021) has been extensively studied. Other studies have shown that washing clothes before wearing them could reduce the exposure to some of these chemicals, such as SVOCs (Morrison et al., 2016) or formaldehyde (De Groot et al., 2010).

In turn, information about the presence of other SVOCs like PCDD/Fs is more limited (Klasmeier, 1998; Križanec and Le Marechal, 2006). Horstmann and McLachlan (1994) analyzed the levels of PCDD/Fs in several pieces of new clothing from different manufactures, highlighting that these contaminants might be also transferred from textiles to human skin during wearing (Horstmann and McLachlan, 1994; Klasmeier et al., 1999). Despite their potential toxicity, data on other polychlorinated biphenyls (PCBs) are even scarcer, with only very few recent studies focused on the sorption of PCBs from contaminated air to clothing (Morrison et al., 2018; Kolarik and Morrison, 2021).

The early-life stages are critical for the further development of newborns and infants, who are especially vulnerable population groups. Therefore, their exposure to environmental toxicants and food contaminants must be strictly controlled and minimized. The chemical exposure may occur through different pathways whose contribution may vary. In this study, the content of PCBs in several commercial bodysuits was determined. Furthermore, the dermal absorption to PCBs for children aged <3 years old who might wear those clothing was evaluated and compared with other exposure sources. Finally, the health risks associated to that exposure were assessed.

2. Materials and methods

2.1. Chemicals and reagents

All solvents and reagents used were suitable for residue analysis. The standard solutions of dioxin-like PCBs (dl-PCBs) and non-dioxin-like PCBs (ndl-PCBs) in nonane, used for calibration (P48-W-CS1 to CS5 and P48-M-CS0.1 to CS3), quantification (P48–W-ES and MBP-MXE) and analytical recovery (P48-RS), were purchased from Wellington Laboratories Inc. (Guelph, ON, Canada).

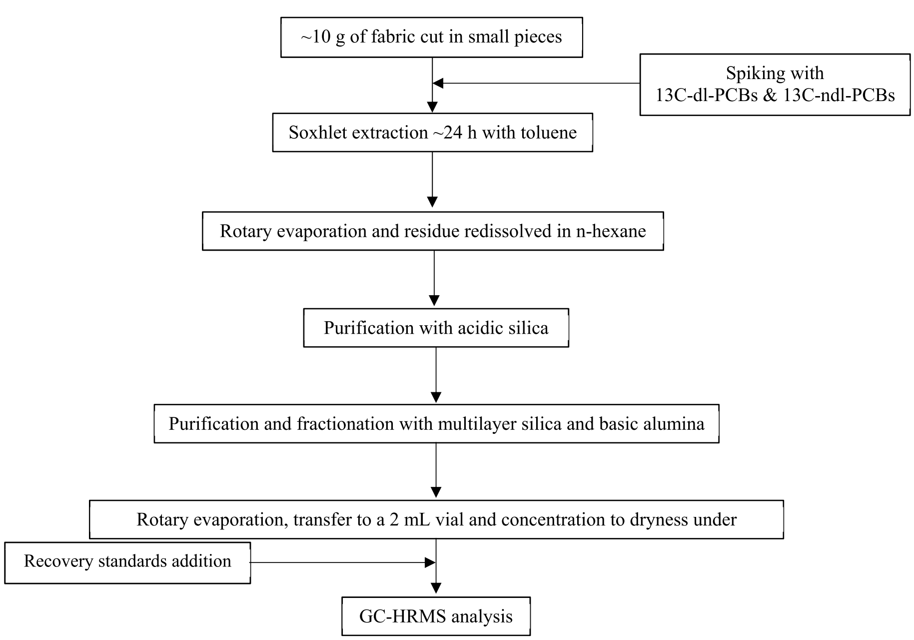

Fig. 1. Schematic representation of the PCB extraction process in clothing.

Table 2
Parameters for exposure assessment and risk evaluation.

Variable	Description	Value	Reference
C_{cloth}	Concentration of each PCB congener	Cloth specific mg/mg	Present study Table 3
d_{cloth}	Cloth density	Cloth specific mg/cm^2	Present study Table 1
F_{mig}	Fraction of substance migrating to skin	0.005	Bundesinstitut für Risikobewertung, 2012
F_{pen}	Fraction of penetration inside the body	0.14	US EPA, 2014
$F_{contact}$	Fraction of contact area for skin	1	Bundesinstitut für Risikobewertung, 2012
$T_{contact}$	Contact duration between skin-textile	1/day	Assumed
BW	Body weight of a 6 months old infant	6 kg	Schuhmacher et al. (2013)
	Body weight of a 1 year old toddler	8.4 kg	ACSA, (2020)
	Body weight of a 3 years old toddler	12.3 kg	ACSA, (2020)
A_{skin}	Skin-cloth contact area for a 6 months old infant	1630 cm^2	US EPA, 2011
	Skin-cloth contact area for a 1 year old toddler	2230 cm^2	
	Skin-cloth contact area for a 3 years old toddler	3380 cm^2	
n	mean number of events per day	1	Assumed
GIABS	Gastrointestinal absorption factor	1	US EPA, 2021

2.2. Sampling

In 2021, ten bodysuits were bought in different Spanish big stores, retailers and on-line shops. The samples were classified according to their labelling: 5 samples were made with organic cotton, while the remaining 5 clothes were made with regular cotton. Additionally, the bodysuits were classified according to the country of manufacture, color and the dyeing/printing. In turn, samples with the OEKO-TEX® Standard 100 label were identified. Table 1 summarizes the characteristics of each item.

2.3. PCB determination

A portion of each unwashed bodysuit was cut in small pieces of approximately 1–2 cm^2 and placed in a glass thimble for Soxhlet extraction. About ¾ of the total volume of the thimble was filled with these pieces (i.e., 8–13 g of textile material depending on the sample). Then, the bodysuits were Soxhlet extracted for ~24 h with toluene after being spiked with known amounts of mixtures of ^{13}C-dl-PCBs (P48–W-ES) and ^{13}C-ndl-PCBs (MBP-MXE) (Fig. 1).

Afterwards, the extracts were rotary evaporated and the residues were dissolved in 5 mL of *n*-hexane. Then, any organic components and other interfering substances were removed by using a silica gel column modified with sulfuric acid (44%, w/w). Further sample purification and fractionation were carried out by means of multilayer silica and basic alumina. For each sample, all PCBs were collected in a single fraction that was rotary concentrated and transferred into a 2 mL vial. The remaining solvent was subsequently reduced to dryness by a gentle stream of nitrogen. The final extract for instrumental analysis was obtained by adding 50 μL of a nonane solution containing known amounts of the recovery standards.

Samples were analyzed by gas chromatography coupled to high resolution mass spectrometry (GC-HRMS) on an Agilent Technologies 6890N gas chromatograph (Agilent, Palo Alto, CA, USA) coupled to a Micromass AutoSpec Ultima NT (Waters, Manchester, UK) high resolution mass spectrometer (EBE geometry) controlled by a Masslynx data system. All samples, as well as standards, were injected with a CTC combiPAL autosampler (CTC Analytics AG, Zwingen, Switzerland) under data control system. Chromatographic separation was achieved with a DB-XLB (Agilent, Folsom, CA, USA) fused-silica capillary column (60 m × 0.25 mm I.D. × 0.25 μm film thickness). Electron ionization (EI) mode was used with an electron energy of 32 eV, trap current of 500 μA and an acceleration voltage of 8000 V, operating in the selected ion monitoring (SIM) mode at a resolving power of 10,000 (10% valley definition).

Separate injections were performed for the analysis of dl-PCBs and ndl-PCBs, using two different chromatographic and MS programs, as well as the appropriate calibration standards. Quantification was carried out by the isotopic dilution method. A procedural blank was also carried out following the same analytical method than for the samples in order to ensure solvents and other reagents do not give a significant contribution to the determined PCB values in the bodysuits.

The laboratory performing the analysis is accredited according to the ISO/IEC 17025 norm for the analysis of dioxins and PCBs in abiotic and abiotic samples (e.g. soils, sediments, ambient air, food and feed). In this sense, the laboratory regularly participates with satisfactory performance in proficiency test for different kind of these matrices. Although the fabric matrix is not included in the accreditation, the same methodology was applied with good performance and optimal analytical recoveries of the labelled compounds added as quantification standards.

2.4. Dermal absorption and human health risk assessment

The exposure to PCBs for children wearing the bodysuits was estimated in a worst-case scenario (unwashed clothes). A typical exposure assessment procedure, previously applied for other chemicals (Rovira et al., 2015), was conducted. The dermal absorption was calculated by applying Eq. (1), which is based on the European Chemical Agency (ECHAEuropean Chemicals Agency,) guidance on information requirements and chemical safety assessment (ECEuropean Commission,).

$$Exp_{derm} = C_{cloth} \cdot 10^{-6} \cdot d_{cloth} \cdot A_{skin} \cdot F_{mig} \cdot F_{contact} \cdot F_{pen} \cdot T_{contact} \cdot n / BW \quad \text{(Eq.1)}$$

Exp_{derm} is the dermal exposure (in mg/kg·day) and the remaining dermal exposure parameters are summarized in Table 2. As there is no available information regarding PCB migration from textiles to skin, a migration factor of 0.0005 was used, following the criteria of the Bundesinstitut für Risikobewertung (Bundesinstitut für Risikobewertung, 2012). In any case, more studies on the migration of PCBs and other chemical additives are required.

The children exposure to PCBs through dermal contact was compared with data corresponding to the contribution of other potential exposure pathways. For infants <6 months old, the estimated intake of PCBs was considered only through breastfeeding, according to data from a population living in the same area of study (Schuhmacher et al., 2013). In turn, for toddlers aged 1 and 3 years, the dietary intake of PCBs was calculated taking into account the results of a previous total dietary study performed in Catalonia (ACSA, 2020).

The dermal absorption to PCBs through clothing was used to assess the non-cancer and cancer risks. Non-carcinogenic risks were evaluated by calculating the Hazard Quotient (HQ), this is, comparing the dermal exposure with the reference dose (RfD) of each PCB congener, obtained from the Regional Screening Levels (Formerly PRGs) (United States Environmental Protection Agency, 2011). The cancer risk (CR) was assessed by multiplying the dermal absorption with the respective slope factor (SF) (Eq. (2)). Dermal values of RfD (RfD_d) and SF (SF_d) were calculated by using the oral slope factor (SFo) and oral reference dose (RfDo) of PCBs and the gastrointestinal absorption factor (GIABS), which was established as the unity (United States Environmental Protection Agency, 2021). Although no safety values may be applied to carcinogenic substances, CR values below 10^{-6} are considered as

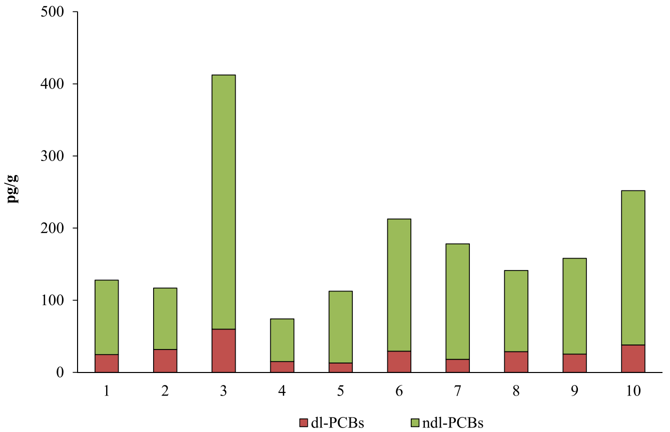

Fig. 2. Concentration of dl- and ndl-PCBs in 10 bodysuits. List of dl-PCB congeners: 81, 77, 123, 118, 114, 105, 126, 167, 156, 157, 169, 189; list of ndl-PCB congeners: 28, 52, 101, 153, 138, 180.

Table 3
Mean concentrations (in pg/g) of 18 PCB congeners in 10 bodysuits.

n = 10	Mean	St. Dev.	MIN	MAX	% detected
dl-PCBs					
PCB-81	0.084	0.06	<0.070	0.241	20
PCB-77	2.18	1.33	0.503	5.02	100
PCB-123	1.12	0.91	<0.098	3.10	90
PCB-118	15.8	7.04	6.93	31.4	100
PCB-114	0.212	0.28	<0.074	0.941	30
PCB-105	6.29	3.22	2.79	13.8	100
PCB-126	0.104	0.05	<0.093	0.203	10
PCB-167	0.646	0.32	0.288	1.15	100
PCB-156	1.47	0.83	0.601	3.10	100
PCB-157	0.318	0.45	<0.047	1.28	20
PCB-169	0.066	0.07	<0.048	0.253	20
PCB-189	0.082	0.03	<0.077	0.128	10
ndl-PCBs					
PCB-28	27.2	19.50	<0.085	71.3	90
PCB-52	42.0	30.17	0.97	106	100
PCB-101	29.1	19.04	9.13	71.3	100
PCB-153	24.0	13.08	11.6	47.3	100
PCB-138	19.8	10.07	10.2	40.5	100
PCB-180	8.14	4.48	4.50	17.3	100
Total dl-PCBs (pg/g)	**28.4**	**13.48**	**13.0**	**59.8**	
Total ndl-PCBs (pg/g)	**150**	**85.09**	**59.2**	**352**	
Total PCBs (pg/g)	**179**	**96.95**	**74.2**	**412**	
Total PCBs (pg WHO-TEQ/kg)	**13.4**	**6.54**	**2.34**	**28.8**	

acceptable according to international standards (Mahfooz et al., 2020). Data for the exposure assessment and risk evaluation are summarized in Table 2.

$$CR = Exp_{derm} \cdot SF \tag{Eq.2}$$

2.5. Data treatment

The statistics was performed by means of the statistical software package SPSS 27.0 (IBM Corp. Released, 2020). Samples with PCB values below their respective limit of detection (LODs) were assumed to contain one-half of the LOD (ND = ½ LOD). Total PCB concentrations were also expressed as WHO toxic equivalents (WHO-TEQ) by using the toxicity equivalency factors (WHO-TEF) assigned to the 12 dl-PCBs (Van den Berg et al., 2006).

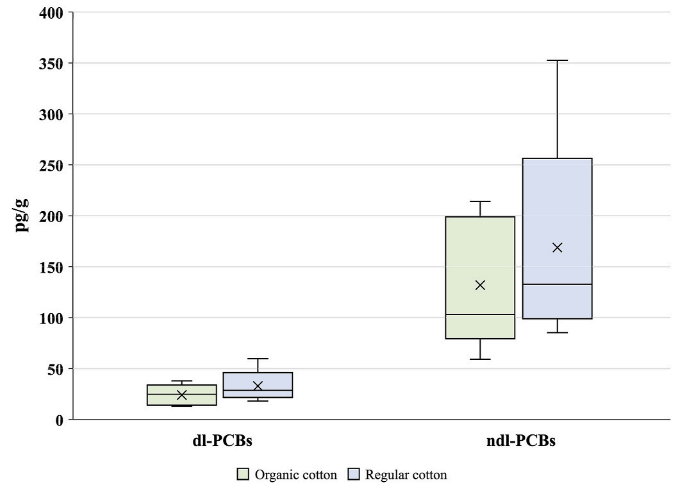

Fig. 3. Boxplots of dl- and ndl-PCB levels in 10 bodysuits, according to the cotton production.

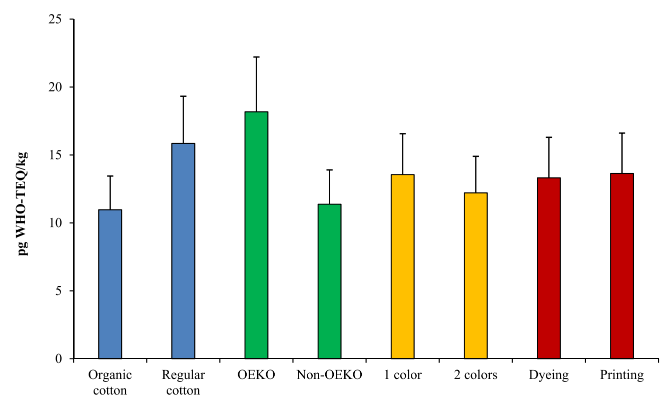

Fig. 4. PCB concentrations in 10 bodysuits according to the (a) cotton production, (d) OEKO-TEX® Standard 100, (c) number of colors, and (d) painting process. Error bars indicate standard deviation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Results and discussion

3.1. PCB levels in clothing

The total concentrations of PCBs in each one of the 10 analyzed bodysuits are depicted in Fig. 2. Total levels of PCBs ranged from 74.2 pg/g, corresponding to a sample with organic cotton, to 412 pg/g, found in bodysuit of regular cotton. The mean concentration of total PCBs was 179 pg/g, with a standard deviation of 96.9 pg/g. When comparing the contribution of both, dl-PCBs and ndl-PCBs, it can be seen that ndl-PCBs were the predominant congeners, with contribution percentages ranging from 73% to 90%. The mean concentration of dl-PCBs in the 10 textile samples was 28.4 pg/g (range: 13.0–59.8 pg/g) or, in terms of toxic equivalents, 13.4 pg WHO-TEQ/kg (range: 2.34–28.8 pg WHO-TEQ/kg). Regarding the individual PCB congeners, maximum and minimum mean concentrations corresponded to PCB-52 and PCB-169, respectively (Table 3).

PCB burdens of each fabric according to a number of factors (e.g., cotton production, colors, dying/painting, OEKO-TEX® Standard 100) were compared. Bodysuits made of organic cotton presented a total mean PCB concentration of 156 pg/g, while those made of conventional cotton showed a mean level of 201 pg/g (Fig. 3). In percentage terms, it means that samples with regular cotton contained 29% more PCBs than

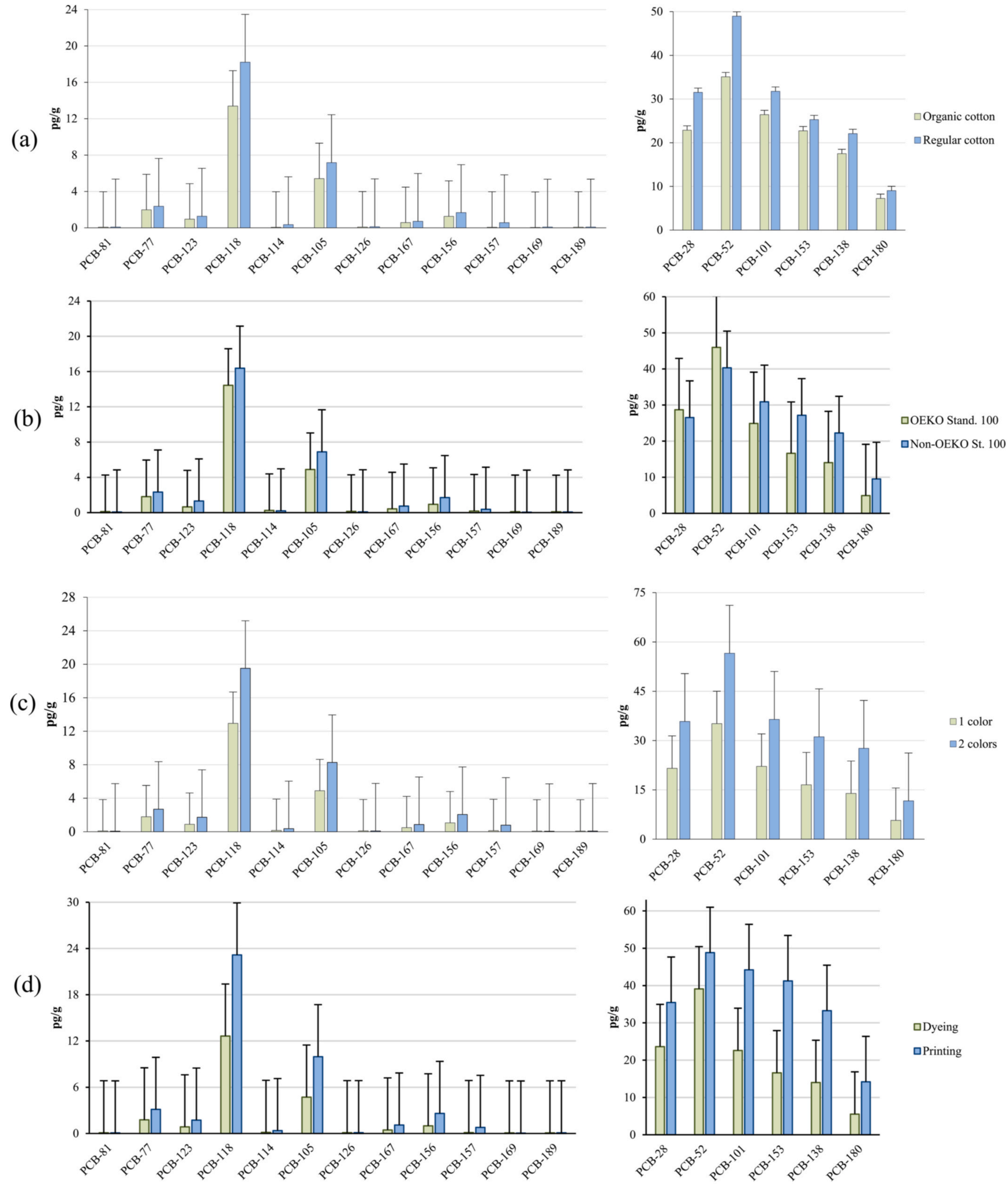

Fig. 5. PCB congener profile according to the (a) cotton production, (b) OEKO-TEX® Standard 100, (b) number of colors, and (d) painting process. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

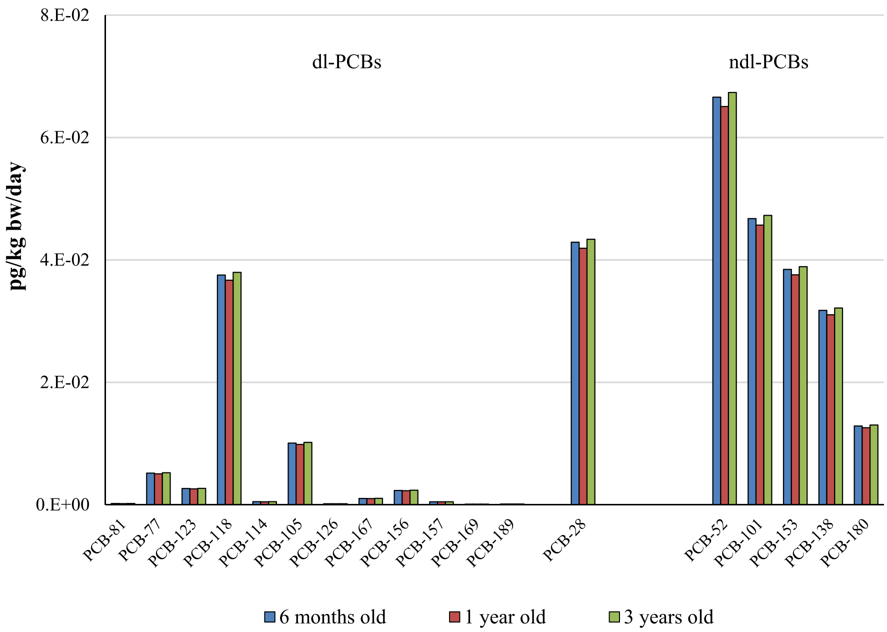

Fig. 6. Mean exposure to dl-PCBs and ndl-PCBs through clothing for children aged 6 months, 1 year and 3 years.

clothes with organic cotton. This difference was especially relevant for dioxin-like congeners, for which samples with regular cotton showed an amount 36% higher than organic cotton fabrics (32.7 vs. 24.0 pg/g). When considering the TEFs, the difference between conventional and organic cotton clothes was even more notorious, of up to 45% (15.8 and 11.0 pg WHO-TEQ/kg, respectively). Similarly, ndl-PCBs were also more abundant in bodysuits of regular cotton with respect to those made of organic cotton (167 and 132 pg/g, respectively).

Eco-labelling in the textile industry entails environmental friendly practices and the promotion of products with a low environmental impact throughout their lifetime (Ţigan et al., 2018) and a low generation of toxic waste (Ranasinghe and Jayasooriya, 2021). It means improving the sustainability of the production process (e.g., use of environmental efficient raw materials and less water, discharge less effluents, etc.), but also minimizing the presence of dangerous chemicals in textile products (Hayat et al., 2020). However, Rovira et al. (2015) reported higher levels of aluminum and strontium in conventional clothes than in eco-labelled and organic cotton items. Unfortunately, although one-half of the samples were made with organic cotton, only one of the 10 analyzed bodysuits (sample No. 10) had an eco-label certification: Global Organic Textile Standard (GOTS). Surprisingly, this sample showed the second highest amount of PCBs (Fig. 2).

Despite bodysuits made of organic cotton showed lower levels of PCBs, they were not toxic-free. In an investigation on the release to water of toxic chemicals from various textiles, including eco-labelled clothes, Dave and Aspegren (2010) stated that eco-labelled products were evenly distributed on a toxicity scale, so eco-labelling in its present form does not necessarily protect users or the environment from exposure to toxic chemicals. Moreover, Herrero et al. (2019) found significantly higher levels of copper in eco-labelled jeans than in conventional items.

In addition to the cotton production, PCB concentrations according to the number of colors, as well as the fact of being labelled with an OEKO-TEX® Standard 100 certificate and the painting process, were compared (Fig. 4). Dyed and painted clothes presented very similar PCB mean concentrations (13.3 and 13.6 pg WHO-TEQ/kg, respectively). Besides, no correlations were found between fabrics concentrations and the number of colors. The presence of PCBs in consumer products may be associated with their color (Anh et al., 2021). In this study, the concentrations of dl-PCBs and ndl-PCBs in white colored bodysuits (21.0 and 111.8 pg/g, respectively) were lower than in colored samples (31.5 and 166.7 pg/g for dl-PCBs and ndl-PCBs, respectively). Sample #53, mustard and brown colored, showed the highest level of PCB-101 (71.3 pg/g), while sample #60, tri-colored (white, black and yellow) presented the greatest value of PCB-153 (47.3 pg/g). Both PCB congeners are directly related to yellow pigments (Anezaki and Nakano, 2014). In turn, very surprisingly the samples certified with the OEKO-TEX® Standard 100 presented higher concentrations of PCBs than non-certified items (18.2 vs. 11.4 pg WHO-TEQ/kg, respectively). PCBs are not currently listed as one of the target chemicals of the OEKO-TEX® Standard 100. In the EC regulation of establishing the ecological criteria for the award of the Community Ecolabel for textile products, it is stated that PCBs and other biocides (i.e., chlorophenols and organotin compounds) shall not be used during transportation or storage of products and semi-manufactured products.

The PCB congener profiles in the 10 textile samples according to the same factors are depicted in Fig. 5. All the analyzed PCB congeners presented higher values in bodysuits made with regular cotton. According to their OEKO-TEX® Standard 100 certification, there was not a homogenous profile, as some PCB congeners (81, 114,126, 169, 189, 28 and 52) showed slightly higher burdens in certified clothes, while the remaining analyzed congeners were more abundant in non-certified textile samples. Regarding the coloring, the levels of most PCB congeners, except for PCBs 81, 169 and 189, were higher in bodysuits with two colors than those single-colored. Finally, printing process had an evident effect on the quantity of PCBs found in textile samples, as samples subject to dyeing presented substantially lower levels of all the PCB congeners than those subject to dyeing (105, 167, 156, and 157).

3.2. Human health risk assessment

The dermal exposure to PCBs through clothing was estimated for children at different stages of development (Fig. 6). Taking into account the total concentrations of PCBs, expressed in terms of WHO-TEQ, the dermal absorption at the age of 6 months, 1 year and 3 years was calculated in $3.19 \cdot 10^{-5}$, $3.11 \cdot 10^{-5}$ and $3.22 \cdot 10^{-5}$ pg WHO-TEQ/kg·day. In conclusion, the exposure to PCBs through clothing was very similar irrespective of the age. The mean exposure to each one of the 12 dl-PCBs and 6 ndl-PCBs here analyzed is summarized in Table 4. Non-dioxin-like PCBs showed a higher contribution to the total exposure to PCBs than dl-

Table 4
Non-cancer and cancer risks of dermal absorption to PCBs through clothing.

	PCB-81	PCB-77	PCB-123	PCB-118	PCB-114	PCB-105	PCB-126	PCB-167	PCB-156	PCB-157	PCB-169	PCB-189	
RfD_o (mg/kg bw/d)	2.30E-06	7.00E-06	2.30E-05	2.30E-05	2.30E-05	2.30E-05	7.00E-09	2.30E-05	2.30E-05	2.30E-05	2.30E-08	2.30E-05	
SF_o (mg/kg bw/d)$^{-1}$	39.0	13.0	3.9	3.9	3.9	3.9	13000	3.9	3.9	3.9	3900	3.9	
RfD_d	2.30E-06	7.00E-06	2.30E-05	2.30E-05	2.30E-05	2.30E-05	7.00E-09	2.30E-05	2.30E-05	2.30E-05	2.30E-08	2.30E-05	
SF_d	3.90E+01	1.30E+01	3.90E+00	3.90E+00	3.90E+00	3.90E+00	1.30E+04	3.90E+00	3.90E+00	3.90E+00	3.90E+03	3.90E+00	
Hazard Quotient (non-cancer risk)													Hazard Index
6 months old	8.63E-08	2.25E-06	1.16E-06	1.63E-05	2.18E-07	4.38E-06	7.29E-08	4.49E-07	1.02E-06	2.14E-07	4.61E-08	5.74E-08	2.63E-05
1 year old	8.44E-08	2.20E-06	1.13E-06	1.59E-05	2.13E-07	4.28E-06	7.12E-08	4.39E-07	9.96E-07	2.09E-07	4.51E-08	5.61E-08	2.57E-05
3 years old	8.73E-08	2.27E-06	1.17E-06	1.65E-05	2.21E-07	4.43E-06	7.37E-08	4.54E-07	1.03E-06	2.17E-07	4.66E-08	5.80E-08	2.66E-05
Cancer risk													Total cancer risk
6 months old	3.32E-12	2.88E-11	4.44E-12	6.27E-11	8.40E-13	1.69E-11	9.34E-10	1.73E-12	3.92E-12	8.24E-13	1.77E-10	2.21E-13	1.24E-09
1 year old	3.24E-12	2.81E-11	4.34E-12	6.13E-11	8.21E-13	1.65E-11	9.13E-10	1.69E-12	3.83E-12	8.05E-13	1.73E-10	2.16E-13	1.21E-09
3 years old	3.36E-12	2.91E-11	4.49E-12	6.35E-11	8.50E-13	1.70E-11	9.45E-10	1.75E-12	3.96E-12	8.34E-13	1.79E-10	2.23E-13	1.25E-09

RfD_o: Oral reference dose; SF_o: Oral slope factor; GIABS: Gastrointestinal absorption factor; RfD_d: Dermal reference dose; SF_d: Dermal slope factor.

PCBs. The congener profile was dominated by PCB-52, with a contribution percentage of up to 22.2% of the total. Regarding dl-PCBs, PCB-118 was the predominant congener (mean percentage: 12.5%). Ingestion and inhalation have been identified as the main routes of exposure to PCBs (Ravenscroft and Schell, 2018; Weitekamp et al., 2021). However, the role of other potential exposure pathways should not be neglected. Zhao et al. (2021) highlighted the importance of the dermal route, especially for waste workers. Other recent studies have pointed out the important role of textiles in the transmission of air pollutants, for which dermal exposure also has a special significance (Morrison et al., 2017; Kolarik and Morrison, 2021; Yu et al., 2022).

Dermal uptake of PCBs was compared with the contribution of other exposure pathways. It has been large reported that food intake, including breastfeeding for newborns, is the main route of exposure to PCBs. For infants aged 6 months living in Tarragona County (Catalonia, Spain), the daily intake of PCBs through breastfeeding has been estimated in 1.58 pg WHO-TEQ/kg·day (Schuhmacher et al., 2013). In turn, the PCB dietary intake by Catalan toddlers of 1 year and 3 years old has been calculated in 0.82 and 1.52 pg WHO-TEQ/kg·day (ACSA, 2020). These values confirm that contact clothes is a negligible exposure pathway in comparison to the intake of PCBs through food and/or breast milk, with contribution percentages of 0.002%–0.004%. The importance of the dietary intake as entrance route of PCBs to the human body, in front of other potential exposure pathways, has been largely reported (Harrad et al., 2006; Linares et al., 2010; Ampleman et al., 2015; Nadal et al., 2020).

Since data on RfD and SF have been derived for dl-PCBs but not for ndl-PCBs, both carcinogenic and non-carcinogenic risks were calculated for the 12 dl-PCBs (Table 4). As the dermal exposure did not differ according to the age, health risks of PCBs through clothing were also very similar in children who are 6 months, 1 year and 3 years old. The HQ associated to the dermal absorption through contact textiles was very low for all the PCB congeners, ranging from $4.59 \cdot 10^{-8}$ to $1.63 \cdot 10^{-5}$ (PCB-169 and PCB-118, respectively). The Hazard Index, calculated as the sum of HQ of the 12 evaluated dl-PCBs, was found to be $2.63 \cdot 10^{-5}$, $2.57 \cdot 10^{-5}$ and $2.66 \cdot 10^{-5}$ for children aged 6 months, 1 year and 3 years, respectively. These levels are far below the threshold, set at the unity. On the other hand, cancer risks were estimated in levels ranging $2.20 \cdot 10^{-13}$ to $9.31 \cdot 10^{-10}$ for PCB-189 and PCB-126, respectively. Some studies suggest that the cancer risk profile in chemical mixtures of PCBs may be dominated by PCB-126 (Besis et al., 2021), due to its relatively higher SF compared with the other dl-PCB congeners. In any case, cancer risks are clearly lower than the value 10^{-6}, an internationally recognized threshold level. In conclusion, the current exposure to PCBs due to the use of bodysuits does not pose any non-cancer and cancer risks to infants, even when they wear clothes not made of organic cotton.

4. Conclusions

Data on the occurrence of some non-regulated chemical additives and environmental pollutants in clothes are very limited. To the best of our knowledge, this is one of the first experimental studies reporting the levels of PCBs in children's clothing and assessing the health risks associated to the dermal absorption to these chemicals through bodysuits, as contact materials. Despite the results are very preliminary, bodysuits made of organic cotton presented a total mean PCB concentration substantially lower than samples made with regular cotton (15.8 and 11.0 pg WHO-TEQ/kg, respectively). Use of organic cotton is an appropriate method to reduce the dermal absorption of PCBs. Nevertheless, traces of PCBs were also found in most bodysuits, so even organic cotton textile samples are not toxic-free, at least in terms of PCB burdens. The PCB congener profile showed a higher contribution of ndl-PCBs, being PCB-52 the most abundant congener. Notwithstanding, the current levels of PCBs do not mean an important health risks for the infants and toddlers, as the dermal absorption to PCBs through clothing was estimated to be more than 4 orders of magnitude lower than their dietary intake. Furthermore, wearing those bodysuits, even for the whole day, was not associated to adverse health effects.

As this is very preliminary investigation, our conclusions should be confirmed by analyzing a larger set of textile samples of different characteristics. Future studies should be also focused on evaluating the co-occurrence of other organic toxic substances, such as formaldehyde, bisphenols or aromatic amines, in children's clothing. Health risks should be eventually assessed by considering an aggregated exposure, this is, estimating the dermal absorption of all the toxicants and not only of a single substance. Moreover, the potential contribution of other exposure pathways, such as dust ingestion and air inhalation, must be considered.

Credit author statement

Marta Herrero: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Writing – original draft, Neus González: Investigation; Resources; Writing – review & editing, Joaquim Rovira: Conceptualization; Supervision; Writing – original draft, Montse Marquès: Conceptualization; Writing – review & editing, José L. Domingo: Supervision; Writing – review & editing, Manuela Abalos: Formal analysis; Investigation; Resources; Writing – review & editing, Esteban Abad: Formal analysis; Investigation; Resources; Writing – review & editing, Martí Nadal: Conceptualization; Funding acquisition; Project administration; Writing – original draft

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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