Environ Geochem Health (2019) 41:93–123
https://doi.org/10.1007/s10653-018-0176-y

ORIGINAL PAPER

Air pollution and body burden of persistent organic pollutants at an electronic waste recycling area of China

Qilin Qin · Xijin Xu · Qingyuan Dai · Kai Ye · Chenyang Wang · Xia Huo

Received: 2 April 2018 / Accepted: 15 August 2018 / Published online: 31 August 2018

Abstract This paper reviews the concentrations of persistent organic pollutants (POPs) in atmosphere of an electronic waste (e-waste) recycling town, Guiyu, in Southeast China, focusing on polybrominated diphenyl ethers (PBDEs), polychlorinated dibenzo-p-dioxin and dibenzofurans (PCDD/Fs), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs). We assess the evidence for the association between air pollution and human body burden, to provide an indication of the severity of respiratory exposure. Compared with standards and available existing data for other areas, it clearly shows that four typical POPs, derived from recycling processes, lead to serious atmospheric pollution and heavy body burden. From published data, the estimated respiratory exposure doses of Guiyu adults and children, varied between 2.48–10.37 and 3.25–13.6 ng kg^{-1} body weight (bw) day^{-1} for PBDEs, 2.31–7.6 and 4.09–13.58 pg World Health Organization-Toxic Equivalent Quantity (WHO-TEQ) kg^{-1} bw day^{-1} for PCDD/Fs, 5.57 and 20.52 ng kg^{-1} bw day^{-1} for PCBs, and 8.59–50.01 and 31.64–184.14 ng kg^{-1} bw day^{-1} for PAHs, respectively. These results show that air pollution is more harmful to children. Furthermore, except for PBDEs, the hazard quotient (HQ) of the other three pollutants was rated more than 1 by respiratory exposure only, and all of them are at risk of carcinogenesis. So we speculate these pollutants enter the body mainly through air inhalation, making respiratory exposure may be more important than dietary exposure in the Guiyu e-waste recycling area. Effective management policies and remediation techniques are urgently needed to prevent the deterioration of ambient air quality in the e-waste recycling area.

Keywords POPs · Atmospheric pollution · Human pollution burden · Respiratory exposure · E-waste

Q. Qin · Q. Dai · K. Ye · X. Huo (✉)
Laboratory of Environmental Medicine and Developmental Toxicology, Guangdong Key Laboratory of Environmental Pollution and Health, School of Environment, Jinan University, 855 East Xingye Avenue, Guangzhou 511486, Guangdong, China
e-mail: xhuo@jnu.edu.cn

X. Xu · C. Wang
Laboratory of Environmental Medicine and Developmental Toxicology, and Provincial Key Laboratory of Infectious Diseases and Molecular Immunopathology, Shantou University Medical College, Shantou 515063, Guangdong, China

X. Xu
Department of Cell Biology and Genetics, Shantou University Medical College,
Shantou 515063, Guangdong, China

Abbreviations

POP	Persistent organic pollutant
E-waste	Electronic waste
PBDE	Polybrominated diphenyl ether
PCDD/F	Polychlorinated dibenzo-p-dioxin and dibenzofuran

PCB	Polychlorinated biphenyl
PAH	Polycyclic aromatic hydrocarbon
WHO-TEQ	World Health Organization-Toxic Equivalent Quantity
bw	Body weight
HQ	Hazard quotient
UCB	Umbilical cord blood
TSP	Total suspended particulate
I-TEQ	International Toxic Equivalent Quantity
dw	Dry weigh
DEDair	Daily exposure dose by air inhalation
ILCR	Incremental lifetime cancer risk

Introduction

Electronic waste (e-waste) is electrical or electronic equipment that is no longer used, such as refrigerators, air conditioners, washing machines, television sets, computers, printers, and mobile phones. With the progress of information technology, the rapid growth of e-waste has become a serious problem. It is estimated 41.8 and 65.4 million tons of e-waste are generated globally in 2014 and 2017, respectively, mainly in Europe, the USA, and Australia (Breivik et al. 2014; Michelle et al. 2016). Approximately 70% of the world's e-waste has been sent to China (Schwarzer et al. 2005). Moreover, the domestic production of e-waste in China has also increased year by year. In a report released by the United Nations Environment Program in 2010, e-waste production in China has reached approximately 2.3 million tons, making it the world's second largest e-waste producer after the USA (3 million tons) (Dooley 2010). Much of the e-waste recycling in China is a conglomeration of processes carried out in the informal sector, while domestically generated and illegally imported e-wastes are destined to Guiyu, Longtang, and Dali towns in Guangdong Province; the Taizhou region in Zhejiang Province; Huanghua city in Hebei Province; and Hunan and Jiangxi Province (Chan et al. 2013). Among these areas, Guiyu and Taizhou are the most prominent areas for informal e-waste recycling within the country (Chi et al. 2011; Huo et al. 2007). Guiyu is the most studied area of domestic and foreign scholars, so this review focuses on the Guiyu area.

Guiyu (23°N latitude and 116°E longitude) is a town in the Chaoyang district of Shantou city, along the southeastern coast of Guangdong Province in China. It enjoys the tropical climate region of South Asia, with an annual mean temperature 21.4 °C and an annual precipitation of 13,864 mm. Guiyu is well known for its e-waste dismantling industry and has been described as "the world's most toxic place" and "Junk town." Guiyu has more than 30-year history of e-waste recycling, where the "recycling" is comprised of several small-scale enterprises and family-run workshops.

More than 6000 small-scale family-run workshops (nearly 60–80% of families in the town) comprised of 160,000 workers lacking protective measures are involved in the business of e-waste dismantling and recycling (Huo et al. 2007; Wu et al. 2010). Guiyu mainly uses raw methods, including open burning of e-waste, de-soldering of printed circuit boards over coal grills, acid leaching to retrieve gold, and physical dismantling e-waste by hammer, chisel, screwdriver, and bare hands, to disassemble e-waste (An et al. 2014).

Each of these original e-waste dismantling processes not only produces large amounts of particulate matter and heavy metal, but also releases large amounts of persistent organic pollutants (POPs), such as polybrominated diphenyl ethers (PBDEs), polychlorinated dibenzo-p-dioxin and dibenzofurans (PCDD/Fs), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) into the atmosphere (Cong et al. 2018; Deng et al. 2006; Zeng et al. 2018a). These POPs are highly toxic, bioaccumulative, and persistent, migrate over long distances, and may enter the body attached to particles (Roscales et al. 2013). Particulate matter, such as PM2.5, can directly enter the lung alveoli to damage lung function, causing asthma, bronchitis, and various respiratory diseases (Jung et al. 2017). Organic pollutants can be stored in human tissue, such as hair, serum, human milk, and placenta, as well as circulate in umbilical cord blood (UCB) (Yu et al. 2011), causing morbidity. Under the strict laws and regulations of Guangdong Province, Guiyu began to centralize the dismantling of e-waste in 2010. However, it only changed the decentralized disassembly into centralized, fixed-point dismantling, but did not change the original methods of disassembly that resulted in pollution. Local Guiyu residents continued to be exposed to atmospheric pollutants, with the especially vulnerable groups (pregnant women and children), being under threat. However, people mainly focus on the health effects of heavy metal pollution on vulnerable groups of Guiyu, with relatively little attention paid to POPs (Cao et al. 2017; Liu et al. 2017b; Lu et al. 2018; Zeng et al. 2018b; Zhang et al. 2018). Therefore, in recent years there has been an urgent need to quantify and understand the behavior of POPs in the Guiyu atmosphere, understand the major sources and metabolism of POPs in human body, and then compare the data with previous studies or other regions, to provide a theoretical basis to enable the government to make more effective policies and take precautions to eliminate or minimize the adverse effects of POPs on the human body (Fig. 1).

Pollution levels of POPs in the atmosphere

PBDEs

PBDEs are used in acrylonitrile butadiene styrene plastic, high-impact polystyrene, epoxy resins, and rubber and may appear in obsolete e-waste products or end-of-life printed circuit boards, cables, and television sets (Rahman et al. 2001). In the process of extensive disposal of e-waste such as comminution, heating, and combustion, brominated flame retardants cause serious air pollution in e-waste recycling areas (An et al. 2011), especially from the heating of printed circuit boards inside recycling workshops or open burning of e-waste containing PBDEs (An et al. 2011; Leung et al. 2006).

As shown in Table 1, in 2004, Deng et al. (2007) measured the PBDE concentrations of total suspended particulate (TSP) and PM2.5 in the Guiyu atmosphere. They found that the mean PBDE concentration in TSP was 140 times higher than that the same period in Hong Kong and 70 times higher than that in Guangzhou, both relatively polluted cities in China. Furthermore, high concentrations of PBDEs have also been detected in PM2.5, at levels 180 and 100 times higher than that of Hong Kong and Guangzhou. The total PBDE concentration at Guiyu was even two to three times higher than that near an electronic product recycling facility at Örebro, Sweden (Julander et al. 2005), showing that uncontrolled recycling activities at Guiyu release large amounts of PBDEs into the atmosphere. Afterward, Chen et al. (2009a) reported the diurnal variation of PBDEs in the Guiyu atmosphere. They found that the average concentration of 11 BDE homologs in the atmosphere was 11.7 ng m^{-3} in the daytime and 4.8 ng m^{-3} at night, slightly lower than that of a previous report (Deng et al. 2007). This does not mean that pollution has decreased, since the newer sampling points were farther from the pollution source. The pollutant concentrations in the atmosphere are easily affected by meteorological conditions and distance from the source of pollution (Zickus et al. 1997). Although the atmosphere has self-purifying activity, the atmospheric PBDE concentrations of Guiyu reported by Chen et al. (2009a) were also 30 times higher than that of Chendian, a reference area mainly based on the underwear industry and located in 9 km downwind of Guiyu. Moreover, the atmospheric PBDE concentrations of Chendian were just slightly below that of Taizhou, one of the largest e-waste recycling areas in China (Li et al. 2008). This shows that PBDE concentrations in the Guiyu atmosphere were clearly higher than that in Taizhou. This may be because of the different types of e-waste dismantling. Taizhou mainly dismantles cable and electrical equipment, whereas Guiyu mainly deals with personal computers and televisions. At the same time, it indicated that e-waste recycling creates serious air pollution also for the neighboring vicinity.

Chen et al. (2011b) also studied the phase partitioning, seasonal variation of PBDEs in Guiyu atmosphere. They found that the PBDE concentrations in gaseous phase of the summer and winter atmosphere were 4.6 and 5.3 ng m^{-3}, respectively, and were 2.5 and 38.9 ng m^{-3} in particle phase, respectively, and both measurements indicated the atmospheric PBDE concentration in winter was higher than that in summer. In addition, An et al. (2011) studied the atmospheric PBDE pollution at different e-waste dismantling sites of Guiyu during work time and off work time. They found that during work time, the atmospheric PBDE pollution of the inside e-waste dismantling workshop was the most serious, followed by the waste incineration plant, the plastic recycling workshop, the pollution of the outside e-waste dismantling workshop which was relatively light. However, during off work time, even if the total atmospheric PBDE concentrations have declined at each e-waste dismantling sites, the PBDE concentrations in gas increased in plastic recycling workshop

Fig. 1 Some e-waste exposure (included **Guiyu**) and control areas referenced in China. The figure from a literature (Song and Li 2014)

and outside e-waste dismantling workshop, but decreased significantly in waste incineration plant and inside e-waste dismantling workshop. Nevertheless, their pollution levels were still higher than those in residential areas and reference areas. It indicates that the e-waste dismantling workers in Guiyu were seriously polluted by PBDEs in the atmosphere. Compared with the PBDE data recorded in the literature, the PBDE concentration in the residential areas of Guiyu during work time was the highest concentration yet reported in the outdoor atmosphere. So not only the workers, but also the ordinarily residents were living under severe atmospheric PBDE pollution. Although showing high PBDE concentrations, BDE-209 was not the only dominant congener. The highest percentage of BDE-209 in residential areas of Guiyu was only 56% of the total PBDEs (An et al. 2011; Chen et al. 2011b). This was lower than the other air studies in Asia, such as Kyoto, Japan, and Guangzhou, China (BDE-209 in these urban atmosphere accounts for over 70% of the total PBDEs) (Chen et al. 2006; Hayakawa et al. 2004), and in Europe, such as e-waste dismantling workshop of Sweden (where BDE-209 was shown to be the only dominant congener), and the UK (BDE-209 accounts for 59% of total PBDE) (Cahill et al. 2007; Wilford

Table 1 Comparison of Guiyu atmospheric PBDE concentrations (ng m^{-3}) with some other locations

Location	Concentration	Sample type	Sampling point type	Sampling time	References
Guiyu	21.5/16.6	TSP/PM2.5	E-waste source	August–September, 2004	Deng et al. (2007)
Hong Kong	0.2/0.1	TSP/PM2.5	Urban	August–September, 2004	Deng et al. (2007)
Guangzhou	0.3/0.2	TSP/PM2.5	Urban	August–September, 2004	Deng et al. (2007)
Örebro, Sweden	33.4	Total dust	Inside e-waste recycling factory	January, 2002	Julander et al. (2005)
Örebro, Sweden	214.3	Inhalable dust	Inside e-waste recycling factory	January, 2002	Julander et al. (2005)
Örebro, Sweden	6.2	Respirable dust	Inside e-waste recycling factory	January, 2002	Julander et al. (2005)
Guiyu	8.9, 11.7/4.8	Gas plus particle, day/night	E-waste source	September, 2005	Chen et al. (2009a)
Chendian	0.3, 0.4/0.2	Gas plus particle, day/night	Underwear industry	September, 2005	Chen et al. (2009a)
Taizhou	0.9	Gas plus particle	E-waste source	October, 2005	Li et al. (2008)
Guiyu	4.6/5.3	Summer, Gas/particle	E-waste source	September, 2005	Chen et al. (2011b)
Guiyu	2.5/39	Winter, Gas/particle	E-waste source	December, 2005	Chen et al. (2011b)
Guiyu	320/2656, 35/83	Gas/particle, work time, off work time	Inside e-waste dismantling workshop	October, 2007	An et al. (2011)
Guiyu	80/576, 44/62	Gas/particle, work time, off work time	Waste incineration plant	October, 2007	An et al. (2011)
Guiyu	23/303, 27/141	Gas/particle, work time, off work time	Plastic recycling workshop	October, 2007	An et al. (2011)
Guiyu	48/254, 95/83	Gas/particle, work time, off work time	Outside e-waste dismantling workshop	October, 2007	An et al. (2011)
Guiyu	15/82, 13/15	Gas/particle, work time, off work time	Residential area	October, 2007	An et al. (2011)
Guiyu	5/63, 5/37	Gas/particle, work time, off work time	Park	October, 2007	An et al. (2011)

et al. 2008). In addition, compared with another e-waste recycling area Taizhou in China (Li et al. 2008), Guiyu also showed much higher PBDE concentrations and lower BDE-209 percentage. However, different from the distribution of PBDE homologs in the atmosphere in other region, Guiyu atmosphere mainly contains light PBDEs, with three main congeners of BDE-28, 47, and 99 alone contributing to approximately 31–53% of the total PBDEs (Chen et al. 2011b). In particular, the average concentration of atmospheric BDE-47 in Guiyu was two to five times than that of the dismantling hall of the recycling electrical plant in Sweden (Andreas et al. 2001).

PCDD/Fs

The atmospheric PCDD/Fs resulting from e-waste recycling are mainly released from the open burning of waste wire (Ren et al. 2015). The average emission of

PCDD/Fs from simulated open burning of insulated wires is 11,900 ng World Health Organization$_{98}$-Toxic Equivalent Quantity (WHO$_{98}$-TEQ) kg^{-1} (Gullett et al. 2007).

As shown in Table 2, Wong et al. (2007) measured 17 PCDD/F concentrations (particulate and gas phase) in the air from Guiyu, Guangzhou, and Hong Kong. The Guiyu atmospheric total PCDD/F concentration was 6.52 pg m^{-3}, which was one point five times than that of Guangzhou and three times higher than that of Hong Kong. Subsequently, Li et al. (2007a) also found high concentrations of PCDD/Fs in the Guiyu atmosphere, especially in winter. The total native PCDD/F concentrations in the Guiyu atmosphere were 10 and 29 times greater than that of Chendian and the Tianhe district, Guangzhou, respectively. The high levels of PCDD/F contamination in Chendian may be due to atmospheric transport from Guiyu. The TEQ of PCDD/Fs in the Guiyu winter atmosphere was the highest level even reported for a documented concentrations of PCDD/Fs in the ambient air (nd-12.0 pg International Toxic Equivalent Quantity (I-TEQ) m^{-3}) (Assunção et al. 2005; Moon et al. 2005; Raun et al. 2005; Yu et al. 2006). Compared with other e-waste recycling areas, the average atmospheric PCDD/F concentration of Guiyu was also much higher than that of other e-waste recycling areas in the same period, such as Taizhou, Longtang, and Fengjiang, one of the largest e-waste recycling sites in Taizhou (Li et al. 2008; Ren et al. 2015; Wen et al. 2011) (Table 2).

Xiao et al. (2012) also detected high concentrations of PCDD/Fs in the atmospheric TSP from Guiyu, similar to the results of Li et al. (2007a), and were significantly higher than in summer. Compared with other regions at home and abroad, the I-TEQ of PCDD/Fs in the atmospheric TSP from Guiyu was 39 and more than 100 times higher than that of Guangzhou and Hong Kong, respectively (Yu et al. 2006; Department 2004). It also was 2–3 orders of magnitude higher than Taiwan (Lee et al. 2004) and other Western European cities (Catalonia, Spain; New Jersey, USA; Houston, USA) (Abad et al. 2004; Lohmann et al. 2003; Correa et al. 2004) (Table 2). Fortunately, the atmospheric PCDD/F pollution has improved in Guiyu after centralized dismantling of e-waste in 2010. Zhang et al. (2017) measured the PCDD/F concentrations in the ambient Guiyu atmosphere around plastic recycling workshops, circuit board baking activities, and remote small villages. The atmospheric total TEQ concentrations (TSP plus gas phase) in the studied recycling sites of Guiyu were 13 times lower than that in 2007 (1.2 vs 16.3 pg I-TEQ m^{-3}) (Xiao et al. 2012). Nevertheless, the contribution of e-waste dismantling activities to PCDD/F ambient air pollution was still very large. The PCDD/F content in the ambient atmosphere around the plastic recycling workshops and circuit board baking activities was higher than that of remote small villages (Table 2) and was nearly at or already exceeded the safety limit (0.6 pg TEQ m^{-3}). Compared with Qingyuan, which was under strict and standardized management at the same time by Guangdong Province, the concentrations of PCDD/Fs in Guiyu were much higher, indicating that better regulation for the Guiyu e-waste dismantling industry is still needed.

PCBs

PCBs were present in old transformers and capacitors before their ban in the 1970 s, so e-waste recycling areas that dealt with these devices may have high PCB levels (Wong et al. 2007). Contemporary computers and cell phones do not contain PCBs. Guiyu has been predominantly processing computers and cell phones (Chen et al. 2011a). Measurements of PCB concentrations in air samples from Guiyu open burning sites, a residential area, and a reservoir revealed Guiyu atmospheric PCBs mainly come from the open burning of circuit boards and cable wires (Xing et al. 2009) (Table 3). At open burning sites, the mean concentration of total PCBs in gas and particles was 414.8 ng m^{-3} and 57.3 ng m^{-3}, respectively, which was significantly higher than that of the residential area and reservoir. The concentration of PCB at open burning sites was far lower than the average concentration of PCB in indoor dust samples collected from workshops at Luqiao (Wen et al. 2008). The PCB concentrations of dust in the workshop may overestimate the outdoor atmospheric PCB concentrations of workshops in Luqiao, but it also reflects that the outdoor atmospheric PCB concentrations of workshops in Luqiao are higher than that in the atmosphere of Guiyu open burning sites, possibly due to processing predominantly old transformers and capacitors in Luqiao workshops (Wen et al. 2008). Nevertheless, the seriousness of atmospheric PCB pollution at Guiyu can still be shown, especially at open burning sites. The PCB concentrations at open burning sites of

Table 2 Comparison of Guiyu atmospheric PCDD/F concentrations (pg m^{-3}) with some other locations

Location	Concentration	Sample type	Sampling point type	Sampling time	References
Guiyu	6.5, 0.7[a]	Gas plus particle	Near e-waste open burning sites	September, 2004	Wong et al. (2007)
Guiyu	872/891.4, 127.3[c]/253.0[c], 8.4[a]/15.2[a], 8.8[b]/16.0[b]	Gas plus TSP, summer/winter	E-waste source	Sept/December, 2005	Li et al. (2007a)
Chendian	130.2/87.5, 22.4[c]/23.4[c], 0.9[a]/1.3[a], 1.1[b]/1.3[b]	Gas plus TSP, summer/winter	Underwear industry	Sept/December, 2005	Li et al. (2007a)
Guangzhou	26.2/30.7, 6.5[c]/6.8[c], 0.3[a]/0.4[a], 0.3[b]/0.4[b]	Gas plus TSP, summer/winter	Urban	Sept/December, 2005	Li et al. (2007a)
Taizhou	14.3, 1.1[b]	Gas plus particle	E-waste source	October, 2005	Li et al. (2008)
Longtang	237.0, 13.6[a]	Gas plus particle	Near e-waste open burning sites	January, 2006	Ren et al. (2015)
Fengjiang	280.6/223.3, 3.4[a]/3.2[a]	TSP/PM2.5	Near e-waste open burning sites	July, 2006–January, 2007	Wen et al. (2011)
Guiyu	317.4, 16.3[b]	TSP	E-waste source	September, 2007	Xiao et al. (2012)
Guangzhou	0.1–1.3[b]	Particulate	Urban	2004	Yu et al. (2006)
Hong Kong	5.5×10^{-2}–7.3×10^{-2}[b]	Particulate	Urban	2004	Department (2004)
Taiwan	0.6×10^{-2}–1.5×10^{-1}[b]	Particulate	Urban	Not available	Lee et al. (2004)
Catalonia, Spain	1.6×10^{-2}–9.5×10^{-1}[b]	Particulate	Industrial	Not available	Abad et al. (2004)
Catalonia, Spain	1.0×10^{-2}–35.7×10^{-2}[b]	Particulate	Urban/suburban	Not available	Abad et al. (2004)
Catalonia, Spain	0.5×10^{-2}–12.5×10^{-2}[b]	Particulate	Rural	Not available	Abad et al. (2004)
New Jersey, USA	0.6×10^{-3}–5.5×10^{-2}[b]	Particulate	Urban	Not available	Lohmann et al. (2003)
Houston, USA	0.4×10^{-2}–5.5×10^{-2}[b]	Particulate	Urban	Not available	Correa et al. (2004)
Guiyu	24.3, 1.2[b]	Gas plus TSP	E-waste source	August, 2013	Zhang et al. (2017)
Qingyuan	19.0, 0.4[b]	Gas plus TSP	E-waste source	August, 2013	Zhang et al. (2017)
Guiyu	22.6/26.0/5.1, 0.6[b]/0.8[b]/0.9[b]	PM2.5/TSP/gas	Neighborhoods of plastic recycling workshops	August, 2013	Zhang et al. (2017)
Guiyu	7.6/14.9/2.7, 0.1[b]/0.3[b]/0.5[b]	PM2.5/TSP/gas	Neighborhoods of circuit board baking activities	August, 2013	Zhang et al. (2017)
Guiyu	0.6/0.5/0.6, 2.2×10^{-3}[b]/1.9×10^{-3}[b]/2.1×10^{-2}[b]	PM2.5/TSP/gas	Remote villages	August, 2013	Zhang et al. (2017)
Qingyuan	10.8/31.0/2.9, 0.1[b]/0.3[b]/0.3[b]	PM2.5/TSP/gas	Neighborhoods around green recycling centers	August, 2013	Zhang et al. (2017)
Qingyuan	2.2/4.2/0.8, 0.1[b]/0.2[b]/0.1[b]	PM2.5/TSP/gas	Neighborhoods of family dismantling workshop	August, 2013	Zhang et al. (2017)

Table 2 continued

Location	Concentration	Sample type	Sampling point type	Sampling time	References
Qingyuan	1.3/2.4/0.5, 3.6 × 10^{-2b}/ 8.1 × 10^{-2b}/5.8 × 10^{-2b}	PM2.5/TSP/gas	Remote villages	August, 2013	Zhang et al. (2017)

[a]pg WHO-TEQ m^{-3}

[b]pg I-TEQ m^{-3}

[c]2,3,7,8-PCDD/F content

Table 3 Comparison of Guiyu atmospheric PCB concentrations (ng m^{-3}) with some other locations

Location	Concentration	Sample type	Sampling point type	Sampling time	References
Guiyu	414.8/57.3	Gas/particle	E-waste open burning site	April, 2006	Xing et al. (2009)
Guiyu	4.7/14.8	Gas/particle	Residential area	April, 2006	Xing et al. (2009)
Guiyu	1.1/17.9	Gas/particle	Reservoir	April, 2006	Xing et al. (2009)
Luqiao	1.6 × 10^6	Dust	E-waste dismantling workshop	Not available	Wen et al. (2008)
Taizhou	12.4	TSP	E-waste dismantling industrial park	January, 2007	Han et al. (2010)
Qingyuan	25.6	Gas plus TSP	E-waste site	July, 2007–June, 2008	Chen et al. (2014)
North Carolina	2.0	Indoor gas	Urban	September 2003–November, 2005	And and Harrad 2006)
Bursa, Turkey	0.5	Gas plus TSP	Urban	August 2004–May, 2005	Cindoruk and Tasdemir 2007)
Izmir, Turkey	1.4/3.1	Gas plus TSP, winter/summer	Industrial area	March–April/June, 2005	Cetin et al. (2007)
Izmir, Turkey	0.9/0.3		Urban	March–April/June, 2005	Cetin et al. (2007)
Guangzhou	0.9	Gas plus TSP	Urban	June, 2004	Chen et al. (2006)
Shanghai	0.0–14.2	PM10	Industrial area	March, 2005–January, 2006	Ma et al. 2007)
Luqiao	2.5/0.8	Gas/particle	Residential area	August, 2006	Xing et al. (2011)
Fengjiang	8.5/0.2	Gas/particle	Residential area	August, 2006	Xing et al. (2011)
Qingyuan	2.2	Gas plus TSP	Rural area	July, 2007–June, 2008	Chen et al. 2014)
Longtang	0.4/0.1	Winter, gas/particle	E-waste open burning site	December, 2011	Wang et al. (2017)
Longtang	7.0/0.8	Summer, gas/particle	E-waste open burning site	June, 2012	Wang et al. (2017)
Taizhou	21.5/5.3	Gas/particle	Residential area	October–November, 2014	Wang et al. (2016)
Taizhou	37.8/65.8	Gas/particle	Industrial area	October–November, 2014	Wang et al. (2016)

Guiyu were far higher than that at 400 meters downwind of an e-waste dismantling industrial park at Fengjiang of Taizhou and an e-waste site of Qingyuan (Han et al. 2010; Chen et al. 2014).

The high level of PCB pollution was not only found at open burning sites, but also in the residential area. Compared with PCB concentrations in other regions, average atmospheric PCB concentrations of residential Guiyu were higher than those in a number of cities, such as North Carolina, USA; Bursa and Izmir, Turkey; and Guangzhou, China, and were similar to Shanghai (And and Harrad 2006; Cindoruk and Tasdemir 2007; Cetin et al. 2007; Chen et al. 2006; Ma et al. 2007). Compared with other typical e-waste recycling area, the PCB concentration in particles of residential Guiyu was also higher than that of Luqiao, Fengjiang, and Qingyuan (Xing et al. 2011; Chen et al. 2014). These data show that the high concentration of PCB in the residential area near Guiyu was probably due to atmospheric transport from the open burning sites, and Guiyu residents had a higher risk of exposure. Unfortunately, there is a lack of data for Guiyu atmospheric PCB concentrations in recent years. However, some recent studies have reported the atmospheric PCB content in Taizhou and Qingyuan. Wang et al. (2017) reported that the concentrations of atmospheric gaseous and particulate PCBs, in an e-waste open burning site in a village of Longtang, were 0.4 and 0.1 ng m^{-3} in summer and 7.0 and 0.8 ng m^{-3} in winter, respectively. These values are lower than a previous study (Chen et al. 2014) and could be attributed to the effective implementation of environmental regulations and control measures. However, the air PCB pollution in Taizhou has not significantly improved. Wang et al. (2016) measured indoor air PCB concentrations from recycling workshops at 37.8 and 65.8 ng m^{-3} in gaseous and particulate phases, respectively, compared to 21.5 and 5.3 ng m^{-3} in gaseous and particulate phases of indoor air from a residential area, respectively. Based on these data, we can infer atmospheric PCB pollution in Guiyu may still be a serious problem. So, there is an urgent need for more recent determinations of the atmospheric PCBs in Guiyu to assess the effectiveness of e-waste centralized dismantling policy, and ongoing monitoring of the situation to better improve the policy.

PAHs

PAHs are well-known persistent, bioaccumulative, carcinogenic, and mutagenic contaminants (Lapviboonsuk and Loganathan 2007; Ramesh et al. 2011) that could be released into the atmosphere by the uncontrolled combustion process of waste, especially burning of plastics or polymers (Qiu et al. 2004). Once PAHs are released into the atmosphere, they distribute between gas and particle phases (Bi et al. 2003). High concentration of PAH which exists in the atmosphere, especially the carcinogenic PAH compounds, will impose serious environmental and health problems (Park et al. 2002; Ramesh et al. 2011).

Only a few studies have reported the severity of atmospheric PAH pollution in Guiyu. As shown in Table 4, Wong et al. (2007) studied the levels of PAHs in atmospheric TSP and PM2.5 at the roof of a 3-story high building near open burning sites of Guiyu. The mean concentration of total PAH associated with TSP was 10 times more than that of Hong Kong and twice as high as that of Guangzhou (Sin et al. 2003; Duan et al. 2007). Similarly, the concentrations of total PAHs associated with PM2.5 were also higher than in some developed cities in China, such as more than 20 times higher than that of Hong Kong residential/industrial/commercial areas in summer, two times higher than that of Guangzhou, and two to three times greater than that of Shanghai (Fang et al. 2003; Li et al. 2005; Gu et al. 201b). Compared to some regions abroad, it was far higher than that of Atlanta and Los Angles, USA; Montelibretti RM, Italy; Crete, Greece and CCA-UNAM, Mexico (Li et al. 2009; Eiguren-Fernandez et al. 2004; Balducci 2008; Tsapakis and Stephanou 2007; Saldarriaga et al. 2008). These data suggest e-waste recycling activities may be an additional source of PAHs, especially open burning.

In addition, Zhang et al. (2011) also researched the concentration and distribution of sixteen PAHs in gas and TSP samples collected from an e-waste dismantling workshop, a plastic recycling workshop, a waste incineration field, and a large residential area in Guiyu during the daytime and nighttime. They found that the total atmospheric PAH concentrations (gas plus particle) of the outside e-waste dismantling workshop were 580.2 ng m^{-3} in the daytime (work hours) and 744.0 ng m^{-3} at night (rest hours), higher than that inside the e-waste dismantling workshop, and approximately twofold higher than that of the plastic recycling workshop (Table 4). The highest concentration of PAH (1040.7 ng m^{-3}) was found in samples from the waste incineration field during the daytime. However, the concentration dropped to 501.3 ng m^{-3} at night due to ceasing of the operation. Normally, the concentration of PAH in the residential area was higher at night, due to transportation, deposition, and other processes of atmospheric pollutants along with particulate matter. The concentration at night was almost six times higher than that in the daytime in the residential area. It was similar to or slightly higher than the results of Wong et al. (2007), which were sampled from the roof of a 3-story high building near open burning sites. Compared with other e-waste recycling areas in China, the atmospheric concentrations of total PAHs at night in the residential area were higher than that in an industrial complex area and an

Table 4 Comparison of Guiyu atmospheric PAH concentrations (ng m^{-3}) with some other locations

Location	Concentration	Sample type	Sampling point type	Sampling time	References
Guiyu	148.0	TSP	E-waste open burning site	August–September, 2004	Wong et al. (2007)
Guiyu	102.0	PM2.5	E-waste open burning site	August–September, 2004	Wong et al. (2007)
Hong Kong	12.2	Gas plus TSP	Urban	January–December, 2000	Sin et al. (2003)
Guangzhou	60.2	TSP	Urban	August, 2003–April, 2004	Duan et al. (2007)
Hong Kong	3.7	Summer, PM2.5	Urban	Not available	Fang et al. (2003)
Guangzhou	47.3	PM2.5	Urban	November, 2002	Li et al. (2005)
Shanghai	38.8	PM2.5	Urban	December, 2006–January, 2008	Gu et al. 2010b)
Atlanta, USA	3.9/1.3	PM2.5	Urban/suburban	January–December, 2004	Li et al. (2009)
Los Angles, USA	1.0	PM2.5	Urban	May, 2001–July, 2002	Eiguren-Fernandez et al. (2004)
Montelibretti RM, Italy	8.7	PM2.5	Rural	July, 2005–2006	Balducci 2008)
Crete, Greece	1.2	PM2.5	Suburban	August, 2001	(Tsapakis and Stephanou 2007)
CCA-UNAM, Mexico	4.9	PM10	Urban	February–April, 2004	Saldarriaga et al. (2008)
Guiyu	580.2/744.0	Gas plus particle, day/night	Outside electronic waste dismantling workshop	October, 2007	Zhang et al. (2011)
Guiyu	558.9/580.7	Gas plus particle, day/night	Inside electronic waste dismantling workshop	October, 2007	Zhang et al. (2011)
Guiyu	313.5/378.6	Gas plus particle, day/night	Plastic recycling workshop	October, 2007	Zhang et al. (2011)
Guiyu	1040.7/501.3	Gas plus particle, day/night	Waste incineration field	October, 2007	Zhang et al. (2011)
Guiyu	50.1/291.7	Gas plus particle, day/night	Residential area	October, 2007	Zhang et al. (2011)
Qingyuan	29.6/16.7	Summer, PM2.5, day/night	Industrial complex area	August, 2009	Wei et al. (2012)
Qingyuan	93.4/113.0	Winter, PM2.5, day/night	Industrial complex area	January–February, 2010	Wei et al. (2012)
Qingyuan	7.4/33.1	Summer, PM2.5, day/night	E-waste dismantling plant	August, 2009	Wei et al. (2012)
Qingyuan	42.2/87.9	Winter, PM2.5, day/night	E-waste dismantling plant	January–February, 2010	Wei et al. (2012)
Fengjiang	22.4/248.5	PM2.5, Summer/winter	E-waste dismantling industrial park	July, 2006–January, 2007	Gu et al. (2010a)
[a]Guiyu monthly average	8.9/15.4	PM2.5/TSP	E-waste open burning site	August–September, 2004	Wong et al. (2007)
[a]Guiyu highest	18.9/29.9	PM2.5/TSP	E-waste open burning site	August–September, 2004	Wong et al. (2007)
[a]Guangzhou	3.9	PM2.5	Urban	November, 2002	Li et al. (2005)
[a]São Paulo, Brazil	0.2	TSP	Urban	2000	Vasconcellos et al. (2003)

Table 4 continued

Location	Concentration	Sample type	Sampling point type	Sampling time	References
[a]Melbourne, Australia	0.2	TSP	Urban	2000	Vasconcellos et al. (2003)
[b]Guiyu	9.1/71.1	Gas plus particle, day/night	Outside electronic waste dismantling workshop	October, 2007	Zhang et al. (2011)
[b]Guiyu	13.7/6.0	Gas plus particle, day/night	Inside electronic waste dismantling workshop	October, 2007	Zhang et al. (2011)
[b]Guiyu	138.6/86.8	Gas plus Particle, day/night	Waste incineration field	October, 2007	Zhang et al. (2011)
[b]Guiyu	6.4/64.6	Gas plus particle, day/night	Plastic recycling workshop	October, 2007	Zhang et al. (2011)
[b]Guiyu	2.9/48.6	Gas plus particle, day/night	Residential area	October, 2007	Zhang et al. (2011)
[c]Fengjiang	2.2/25.8	PM2.5, Summer/winter	E-waste dismantling industrial park	July, 2006–January, 2007	Gu et al. (2010a)
[c]Luqiao	0.9/13.2	PM2.5, Summer/winter	Urban	July, 2006–January, 2007	Gu et al. (2010a)

[a]Concentration of BaP

[b]TEQ concentration of BaP

[c]Concentration of BaP-equivalent carcinogenic power, BaPE = BaA × 0.06 + BbkF × 0.07 + BaP + DahA × 0.6 + IcdP × 0.08, Approximate to its TEQ

e-waste dismantling plant both in Qingyuan (Wei et al. 2012), and also slightly higher than that in Fengjiang, which was sampled near an e-waste dismantling industrial park (Gu et al. 2010a). These data are sufficient to show that the Guiyu atmosphere was seriously polluted by PAHs and has not improved, and the level of air PAH pollution in the residential areas of Guiyu is comparable to that of industrial complex area or e-waste dismantling plant.

Benzopyrene (BaP) is the most toxic homolog of PAHs in the atmosphere, with both carcinogenic and mutagenic properties, so we usually pay more attention to the concentration of BaP rather than the total PAH concentration in the atmosphere. The WHO also regards BaP as an indicator of carcinogenic risk (Health 2000). Wong et al. (2007) measured the mean atmospheric BaP concentration of Guiyu. The monthly average concentration of BaP was 8.9 and 15.4 ng m^{-3}, and the highest concentration reached 18.9 and 29.9 ng m^{-3} in PM2.5 and TSP, respectively, higher than Guangzhou (Li et al. 2005), São Paulo, Brazil, and Melbourne, Australia (Vasconcellos et al. 2003). Zhang et al. (2011) also estimated the TEQ of atmospheric BaP in five typical regions of Guiyu, including the outside and inside of an e-waste dismantling workshop, a waste incineration field, plastic recycling workshop and large residential area. The lowest level was detected in the residential area. However, it still was higher than that of an e-waste dismantling industrial park in Fengjiang (Gu et al. 2010a). These data show that the local government was gradually implementing the standardized management of the e-waste dismantling industry in Guiyu, but the severe atmospheric PAH pollution of Guiyu has not decreased in recent years.

Body burden and health implications

The monitoring of pollutant concentrations in the air indicates the presence and levels of the pollutions at the e-waste processing areas in China. However, the presence of pollutants in the environment does not necessarily indicate significant human exposure (Esteban and Castaño 2009). Assessing the contaminant level in human tissues can provide direct information about the exposure levels, body burden, and potential health risks (Ma et al. 2008). People are exposed to contaminants through several pathways, such as inhalation, dermal contact, and ingestion (Liu et al. 2016). The pollutants will accumulate into the human body and further harm human health. There were high concentrations of POPs in the Guiyu atmosphere, which should accumulate in the body via air inhalation. Therefore, there is an urgent need to understand the pollutant content in the human body and assessment human health risk. So we summarize the exposure of Guiyu residents to POPs (PBDEs, PCDD/Fs, PCBs, and PAHs) based on existing studies, with a particular focus on internal doses of POPs (e.g., hair, serum, human milk, placenta, and UCB) (Wu et al. 2010, 2011; Xu et al. 2013, 2015a; Zheng et al. 2011).

Body burden of PBDEs

Higher PBDE concentrations observed in the air at Guiyu e-waste recycling areas were consistent with elevated concentrations of these compounds observed in the population samples compared with the other cities and countries, as shown in human hair. Contaminants enter the hair mainly through internal accumulation and atmospheric deposit. Therefore, hair has been identified as a suitable indicator to reflect exposure of atmospheric pollutants. As shown in Table 5, the mean PBDE concentration found in hair samples from e-waste recycling workers of Guiyu (Zheng et al. 2011) was lower than that of Luqiao, Fengjiang, and Bui Dau, Vietnam (Wen et al. 2008; Jing et al. 2011; Muto et al. 2012), but more than Xinqiu, which had the highest PBDE level in informal recycling operations workers hair of four minor e-waste pollution areas in Zhejiang Province (Zhao et al. 2008). However, compared with the general population at home and abroad, the levels in hair of Guiyu e-waste recycling workers were far higher than that of Shanghai, Guangzhou, Yunnan, Hangzhou, Northern Poland, and Spain (Jing et al. 2011; Zheng et al. 2011; Yuan et al. 2016; Leung et al. 2010; Król et al. 2014; Tadeo et al. 2009). Moreover, the level of e-waste recycling workers' hair was close to that of pregnant women living in the vicinity of an e-waste recycling area, Luqiao, Philippines, and Wen'an, a waste plastic recycling area in Hebei Province (Leung et al. 2010; Malarvannan et al. 2013; Tang et al. 2014). These data show that the PBDE pollution in the hair of Guiyu e-waste recycling workers was significantly higher than that of the general population of many other parts of the world, and similar to the comparison results of atmospheric PBDE levels, indicating severe air pollution can also be reflected in human tissues. We can see that children and pregnant women in e-waste polluted areas were affected as much as workers.

It was not just hair that was the only indicator. Other human tissues of Guiyu residents also showed severe PBDE pollution. As shown in Table 5, the median PBDE concentration in serum from residents of Guiyu was three times higher than that of Haojiang, located at the wind directly direction below Guiyu and dominated by aquaculture (Bi et al. 2007). Similarly, Yuan et al. (2008) measured serum PBDE concentrations to be 382 ng g^{-1} lipid of Guiyu e-waste workers and 158 ng g^{-1} lipid of Haojiang residents. The PBDE concentrations in serum of Guiyu residents were no less than that of occupational workers in other regions under the highly polluted environment and were higher than that of Luqiao, Wenling, and e-waste workers from Guangdong (Zhao et al. 2010; Qu et al. 2007). Even Haojiang residents were also at high risk of exposure, with PBDE concentrations being higher than Dalian, China, USA, Mexico, Sweden, UK, and Japan (Chen et al. 2009b; Leung et al. 2010; Pérez-Maldonado et al. 2009; Fängström et al. 2005; Thomas et al. 2006; Inoue et al. 2006).

Furthermore, the most important concern is the number of PBDEs in human milk, placenta, and UCB, which reflects the maternal body burden and infant's antenatal and postpartum exposure. Xu et al. (2013) showed the total PBDE concentrations were significantly higher in UCB from Guiyu than the reference area and were more than four times higher compared with a previous study (Wu et al. 2010) (Table 5). A recent study showed that PBDE concentrations in the UCB of Guiyu residents were not reduced and were five times higher than those in Haojiang (Li et al. 2017). A similar result was found in the placenta samples, which also had nearly five times more PBDE concentrations than that of Haojiang (Xu et al. 2015a), even the placental level of Haojiang was far higher than that of Taizhou (Zhao et al. 2013), and both areas have instituted centralized disassembly. Unfortunately, there was a lack of data for human milk samples. However, according to the data in placenta and UCB samples, we could infer the content of PBDE in Guiyu human milk samples may be far higher than in other parts of the world, such as some Asian countries (China (Guangzhou and Tianjin), Philippines, Japan, Korea, Vietnam, India) (Jing et al. 2011; Bi et al. 2006; Zhu et al. 2009; Malarvannan et al. 2013; Inoue et al. 2006; Haraguchi et al. 2009; Tue

Table 5 Comparison of the PBDE body burden of residents in Guiyu with some other locations

Sample type	Location	Concentration	Date	Study population	References
Hair[a]	Guiyu	125	2008	E-waste dismantling workers	Zheng et al. (2011)
	Luqiao	870.8	July, 2006	Male e-waste dismantling workers	Wen et al. (2008)
	Fengjiang	157	2007	E-waste dismantling workers	Jing et al. (2011)
	Bui Dau, Vietnam	276	2007–2008	E-waste dismantling workers	Muto et al. (2012)
	Xinqiu	29.6	April, 2007	E-waste dismantling workers	Zhao et al. (2008)
	Xiazheng	11.1	April, 2007	E-waste dismantling workers	Zhao et al. (2008)
	Tongshan	7.4	April, 2007	E-waste dismantling workers	Zhao et al. (2008)
	Panlang	4.7	April, 2007	E-waste dismantling workers	Zhao et al. (2008)
	Yandang	4.5	April, 2007	General population	Zhao et al. (2008)
	Shanghai	40.3	September, 2007	General population	Jing et al. (2011)
	Guangzhou	16.6	Not available	General population	Zheng et al. 2011)
	Yuantan	10.0	Not available	General population	Zheng et al. (2011)
	Yunnan	5.2	January, 2014	General population	Yuan et al. (2016)
	Hangzhou	3.6	2005	General population	Leung et al. (2010)
	Poland	17	2012	General population	Król et al. (2014)
	Spain	20	Not available	Adults	Tadeo et al. (2009)
	Spain	8.3	Not available	Children	Tadeo et al. (2009)
	Luqiao	110	2005	Pregnant women living in the vicinity of an e-waste recycling center	Leung et al. (2010)
	Philippines	78	2008	Mothers living at a waste disposal site	Malarvannan et al. 2013)
	Philippines	57	2008	Mothers living at a non-dumpsite site	Malarvannan et al. (2013)
	Philippines	71	2008	All mothers	Malarvannan et al. 2013)
	Wen'an	89.6	November, 2011	Children living in waste plastic recycling area	Tang et al. (2014)
	Wen'an	133	November, 2011	Young living in waste plastic recycling area	Tang et al. (2014)
	Wen'an	108	November, 2011	Middle-aged living in waste plastic recycling area	Tang et al. (2014)
Serum[b]	Guiyu	580	August, 2005	Inhabitants	Bi et al. (2007)
	Haojiang	190	August, 2005	Inhabitants	Bi et al. (2007)
	Guiyu	382	Not available	E-waste dismantling workers	Yuan et al. (2008)
	Haojiang	158	Not available	Inhabitants	Yuan et al. (2008)
	Luqiao	117.6	November, 2006	Residents in an e-waste recycling area	Zhao et al. (2010)
	Wenling	357.4	November, 2006	Residents in an e-waste recycling area	Zhao et al. (2010)
	Guangdong	126	Not available	E-waste dismantling workers	Qu et al. (2007)
	Dalian	31.6	2006	Children	Chen et al. (2009b)
	USA	59.6	2006–2007	Children	Leung et al. (2010)
	Mexico	29.5	2006–2009	Children	Pérez-Maldonado et al. (2009)
	Sweden	5	2002–2006	Children	Fängström et al. (2005)
	UK	5.6	June-July, 2003	General population	Thomas et al. (2006)
	Japan	3.3	2005	Mothers	Inoue et al. (2006)
UCB[b]	Guiyu	57.6	Not available	Pregnant women	Xu et al. (2013)
	Chaoan	8.2	Not available	Pregnant women	Xu et al. (2013)

Table 5 continued

Sample type	Location	Concentration	Date	Study population	References
	Guiyu	13.8	May–July, 2007	Pregnant women	Wu et al. (2010)
	Chaonan	5.2	May–July, 2007	Pregnant women	Wu et al. (2010)
	Guiyu	71.9	March–August, 2012	Pregnant women	Li et al. (2017)
	Haojiang	15.5	March–August, 2012	Pregnant women	Li et al. (2017)
Placenta[b]	Guiyu	61.4	August-12	Pregnant women	Xu et al. (2015a)
	Haojiang	13.0	August-12	Pregnant women	Xu et al. (2015a)
	Taizhou	7.9	October, 2009–May, 2011	Pregnant women	Zhao et al. (2013)
Human milk[b]	China	7.8	2007	Mothers	Jing et al. (2011)
	Guangzhou	3.5	2006	Mothers	Bi et al. (2006)
	Tianjin	2.8	March–May, 2006	Mothers	Zhu et al. (2009)
	Beijing	1.9	December, 2007	Mothers	Haraguchi et al. (2009)
	Philippines	2.6	2008	Mothers	Malarvannan et al. (2013)
	Japan	1.7	2005	Mothers	Inoue et al. (2006)
	Korea	3.7	October, 2007	Mothers	Haraguchi et al. (2009)
	Vietnam	2.3	2007	Mothers	Tue et al. (2010)
	India	2.2	2009	Mothers	Devanathan et al. (2012)
	Germany	2	2005	Mothers	Raab et al. (2008)
	France	3.7	2004–2006	Mothers	Antignac et al. (2009)
	Belgium	3	2006	Mothers	Roosens et al. (2010)
	Ghana	4.5	2009	Mothers	Asante et al. (2011)

[a]ng g^{-1} dry weigh (dw), [b]ng g^{-1} lipid

et al. 2010; Devanathan et al. 2012), European countries (Germany, France, Belgium) (Raab et al. 2008; Antignac et al. 2009; Roosens et al. 2010) and North America, Ghana (Asante et al. 2011). These data indicate that even with centralized e-waste dismantling, Guiyu residents were still exposed to a high PBDE pollution, especially susceptible pregnant women and infants. In addition, BDE-28, 47, 153, 209 were the main homologs in UCB and placenta samples of Guiyu residents, which contributed approximately 80% of the total PBDEs and BDE-209 contributing the most, possibly due to its higher lipophilicity (Wu et al. 2010; Xu et al. 2015a). However, the frequencies of other congeners (BDE-28, 47, 183, 153) were all higher in UCB and placenta samples from Guiyu than from the reference area, except for BDE-209. This shows that UCB and placenta samples from mothers involved in e-waste recycling showed higher concentrations of PBDE congeners than that from women in the reference area, especially for low-brominated congeners such as BDE-28, 47, and 99. The exposure pattern of the main PBDE congeners in UCB and placenta was the same as in previous results of examining atmosphere. This suggests the high PBDE body burdens of Guiyu residents may be mainly due to air inhalation exposure, but further proof is needed.

Exposure to PBDEs can have multiple adverse health effects. PBDEs have been shown to interact as antagonists or agonists at androgen, progesterone, and estrogen receptors and can be combined with hormone receptors in the organism, affecting the synthesis, secretion, transport, metabolism, and combination of hormones and interfering with normal hormone levels in the human body to disrupt the endocrine system (Hamers et al. 2006). Endocrine disturbances are associated with various human diseases, such as obesity, heart disease, diabetes, infertility, cancer, and neurological defects (Landrigan et al. 2016). Many studies showed that in utero exposure to BDE-99 reduces sperm counts in adult rats and alters the ultrastructure of the ovary cells in females, and exposure to BDE-47 can result in impaired reproductive system function in female mice (Kuriyama et al. 2005; Talsness et al. 2005; Talsness et al. 2008). Only one human study showed a significant negative correlation between sperm count and BDE-153 concentration in Japanese men's semen (Akutsu et al.

2008). In addition, animal studies of PBDEs strongly suggest an increased risk of thyroid hormone disruption (PBDEs and thyroxine (T4) are structurally similar), and the thyroid gland of mice is affected by BDE-209 exposure and that the exposure of PBDEs can reduce the total T4 and free T4, affecting the normal function of thyroid (Darnerud 2004; Tseng et al. 2008; Kuriyama et al. 2007). A recent epidemiologic study of PBDEs suggests a slight decrease in thyroid-stimulating hormone in exposed pregnant women, which could affect children's growth and intellectual development (Chevrier et al. 2010; Liu et al. 2017a). Moreover, PBDE exposure also showed neurodevelopmental toxicity, leading to hyperactivity, cognitive deficits, and impaired memory (Costa and Giordano 2007). In a word, studies have associated adverse effects of PBDEs with neurodevelopmental toxicity, decreased birth outcomes, hormone imbalances, and tumors (Chao et al. 2007; Siddiqi et al. 2003; Vuong et al. 2017), and DNA damage (Pellacani et al. 2012).

Body burden of PCDD/Fs

A prior report suggested that e-waste recycling was the most significant source of PCDD/F contamination in China (Ma et al. 2008). Therefore, e-waste recycling should be regarded as possibly the major contributor to human exposure to PCDD/Fs in China. It is notable that non-dietary intake of PCDD/Fs accounts for approximately 85% of total daily intake for e-waste recycling workers, which is much higher than that in the general population (< 30%) (Ma et al. 2008). Therefore, compared with other Guiyu environmental media, PCDD/Fs in the atmosphere may be the most harmful factor affecting resident health. Aerial contamination with PCDD/Fs at Guiyu has resulted in levels of human exposure to 15–56 times the WHO recommended maximum intake (4 pg WHO-TEQ kg^{-1} day^{-1}) (Li et al. 2007a). Therefore, it is necessary to understand the body burden of PCDD/Fs in different human tissues, to understand the main pathways of PCDD/F exposure for Guiyu inhabitants, and to take preventive measures in the direction.

As shown in Table 6, Luksemburg (2002) collected hair samples from barber shops of Guiyu and reported that the total PCDD/F concentrations ranged between 16.4 and 25.6 pg WHO-TEQ g^{-1} dw with an average of 21.0 pg WHO-TEQ g^{-1} dw. This was markedly higher than hair samples from Shanghai, Hangzhou, and general population in China and was five times greater than found in municipal solid waste incineration workers of China (Jing et al. 2011; Chan et al. 2007; Nakao et al. 2005). In contrast to other e-waste recycling area samples in China, the PCDD/F concentrations from hair sampling in Guiyu barber shops were just slightly below than that from e-waste recycling workers in Fengjiang (Jing et al. 2011). This shows that Guiyu residents were also exposed to considerably high levels of PCDD/Fs in the atmosphere, and the exposure level of residents was almost equal with the e-waste dismantling workers in Taizhou. To date, data are lacking for PCDD/Fs accumulated in the human body of Guiyu residents, but this does not mean that PCDD/Fs were not absorbed by the body. The high concentrations of PCDD/Fs have been detected in human milk, placenta, and hair from mothers and serum samples from children of Taizhou (Chan et al. 2007; Shen et al. 2010), where the air pollution levels of PCDD/Fs were lower than that of Guiyu. These values from Taizhou showed higher concentrations than those samples from reference area, Hangzhou (Chan et al. 2007). The accumulation of PCDD/Fs in the bodies of Taizhou residents could be explained by personal characteristics and dietary intake, but cannot exclude air exposure.

A pervious study indicated that Guiyu residents are also exposed to considerably high levels of PCDD/Fs (Li et al. 2007a). The daily intake of PCDD/Fs in Guiyu was between 68.9 (summer) to 126 and 122 (summer) to 223 pg WHO-TEQ kg^{-1} day^{-1} for adults and children, respectively. These values far exceed the WHO (1998) tolerable daily intake limits (1–4 pg WHO-TEQ kg^{-1} day^{-1}) and daily intake limits in regions around medical solid waste incineration (Domingo et al. 2002; Nouwen et al. 2001). In addition, the daily intake dose for children was approximately twice as much as those for adults (Zhao et al. 2007). Thus, it could be interpreted that infants and children absorb PCDD/Fs at a faster rate than adults due to their high growth rate (Gies et al. 2007), suggesting that children are particularly vulnerable to the impact of improper e-waste disposal practices, especially air pollution caused by e-waste recycling. In addition, there may be serious PCDD/F pollution in the vicinity of the e-waste recycling area

Table 6 Comparison of the PCDD/F body burdens of residents in Guiyu with some other locations

Sample type	Location	Concentration	Date	Study population	References
Hair[a]	Guiyu	21.0	Not available	General population	Luksemburg (2002)
	Shanghai	2.2	September, 2007	General population	Jing et al. (2011)
	Hangzhou	5.6	August–December, 2005	Mothers	Chan et al. (2007)
	China	1.7	Not available	General population	Nakao et al. (2005)
	China	4.4	Not available	Municipal solid waste incineration workers	Nakao et al. (2005)
	Fengjiang	36.1	September, 2007	E-waste workers	Jing et al. (2011)
	Taizhou	33.8	August–December, 2005	Mothers	Chan et al. (2007)
Serum[b]	Taizhou	10.3	April–July 2008	Children	Shen et al. (2010)
Human milk[b]	Taizhou	21.0	August–December, 2005	Mothers	Chan et al. (2007)
	Hangzhou	9.4	August–December, 2005	Mothers	Chan et al. (2007)
Placenta[b]	Taizhou	35.2	August–December, 2005	Mothers	Chan et al. (2007)
	Hangzhou	11.9	August–December, 2005	Mothers	Chan et al. (2007)

[a] pg WHO-TEQ g^{-1} dw

[b] pg WHO-TEQ g^{-1} lipid

due to atmospheric transport, resulting in increased health risk to local residents (Zhao et al. 2007).

A large number of studies have found that PCDD/F exposure showed immune toxic and has some effects on cellular and humoral immunity. The entry of PCDD/Fs into human body can inhibit the CD16 + T lymphocytes and damage the T cell/monocyte interaction in the blood environment, which is beneficial to the T cell response of specific antigen, and 20 years after long-term exposure to PCDD/Fs, the body's CTL function remains suppressed (Van Den Heuvel et al. 2002; Ernst et al. 1998). At the same time, PCDD/F exposure showed reproductive and developmental toxicity. Numerous studies have found that PCDD/Fs in the body can inhibit human prostate growth, reduces ovulation in female rats, and inhibit the proliferation of zebrafish heart cells and cardiovascular formation in birds (Gupta et al. 2006; Hsu et al. 2007; Antkiewicz et al. 2005; Ivnitski-Steele et al. 2005). In addition, the elevated body burden of PCDD/Fs may impose health implications for the next generation. A small number of studies found that postnatal exposure to PCDD/Fs affects thyroid hormone system and immunological functions of infants and children (Nagayama et al. 2007; Weisglas-Kuperus et al. 2000). It is urgent to know the body burden of PCDD/Fs for Guiyu residents in recent years, and the relationship between PCDD/F exposure and disease prevalence.

Body burden of PCBs

PCBs are known to cause developmental neurotoxicity, and these compounds may affect a variety of neuropsychological functions in children, including general cognition, visual-spatial function, memory, attention, executive functions, and motor function (Boucher et al. 2009; Schantz et al. 2003). Therefore, it is necessary to understand the body burden of in different human tissues, to understand the main pathways of PCB exposure for Guiyu inhabitants, and to take preventive measures in the direction.

Unfortunately, there was a lack of PCB data in the hair samples of Guiyu residents. High levels of PCB pollution were found in the hair of residents from other electronic waste dismantling areas. As shown in Table 7, the highest concentration of PCB in hair

Table 7 Comparison of the PCB body burdens of resident in Guiyu with some other locations

Sample type	Location	Concentration	Date	Study population	References
Hair[a]	Luqiao	1600	July, 2006	E-waste recycling workers	Wen et al. (2008)
	Longtang	894	July, 2011	E-waste recycling workers	Zheng et al. (2016)
	Xinqiu	182.0	April, 2007	E-waste recycling workers	Zhao et al. (2008)
	Xiazheng	68.4	April, 2007	E-waste recycling workers	Zhao et al. (2008)
	Tongshan	32.8	April, 2007	E-waste recycling workers	Zhao et al. (2008)
	Panlang	28.2	April, 2007	E-waste recycling workers	Zhao et al. (2008)
	Taizhou	386	December, 2005	Breastfeeding mothers	Man et al. (2017)
	USA	47.5	2004	General people	Altshul et al. (2004)
	Philippines	29	2008	General people	Malarvannan et al. (2013)
	China	91	2004	Urban people	Zhang et al. (2007a)
	China	19	2004	Rural people	Zhang et al. (2007a)
	Iran	17	2007–2008	Pregnant women	Behrooz et al. (2012)
Human milk[b]	Guiyu	9.5	2006	Mothers	Xing et al. (2009)
	Dalian	42	November–December, 2002	Mothers	Kunisue et al. (2004)
	Shengyang	28	November–December	Mothers	Kunisue et al. (2004)
	South Africa	10	2006	Mothers	Darnerud et al. (2006)
	Indonesia	27	2001–2003	Mothers	Sudaryanto et al. (2006)
	Vietnam	33	2007	Mothers	Tue et al. (2010)
	India	30	2009	Mothers	Devanathan et al. (2012)
	Philippines	65	2008	Mothers	Malarvannan et al. (2013)
	Korea	60	2007	Mothers	Haraguchi et al. (2009)
	Japan	61	2007–2008	Mothers	Haraguchi et al. (2009)
	Ghana	62	2009	Mothers	Asante et al. (2011)
	Italy	240	200–2001	Mothers	Ingelido et al. (2007)
	Poland	152	2004	Mothers	Jaraczewska et al. (2006)
	Belgium	90	2006	Mothers	Colles et al. (2008)
	Luqiao	163.9	November, 2006	Mothers	Ling et al. (2008)
Serum[b]	Guiyu	69	August, 2005	Residents	Bi et al. (2007)
	Haojiang	65	August, 2005	Residents	Bi et al. (2007)
	Luqiao	443.7	September, 2008	E-waste recycling workers	Ma et al. (2017)
	Luqiao	204.2	November, 2006	Residents	Zhao et al. (2010)
	Luqiao	190.4	November, 2006	Mothers	Ling et al.. (2008)
	Luqiao	222.0	November, 2006	Boys	Ling et al.. (2008)
	Luqiao	152.9	November, 2006	Girls	Ling et al.. (2008)
	Wenling	83.8	November, 2006	Residents	Ling et al.. (2008)
UCB[b]	Guiyu	338.6	May–July, 2007	Newborns	Wu et al. (2011)
	Chaonan	140.2	May–July, 2007	Newborns	Wu et al. (2011)

Table 7 continued

Sample type	Location	Concentration	Date	Study population	References
\	Luqiao	566.8	November, 2006	Newborns	Ling et al.. (2008)
	A lightly polluted site of Taizhou	168.2	November, 2006	Newborns	Ling et al. (2008)

[a] $ng\ g^{-1}$ dw

[b] $ng\ g^{-1}$ lipid

samples was found in e-waste recycling workers of Luqiao, followed by Longtang, Xinqiu, Xiazheng, Tongshan, and Panlang (Wen et al. 2008; Zheng et al. 2016; Zhao et al. 2008). This paralleled the atmospheric PCB concentrations. The higher concentrations of PCBs were found in hair samples from areas with severe atmospheric PCB pollution. Therefore, we could speculate that there was also a high concentration of PCB in the hair samples of Guiyu e-waste recycling workers. It was not only the e-waste recycling workers, but also the local residents of the e-waste recycling area who were exposed to the highly polluted PCB environment. PCB concentrations in the hair of breastfeeding mothers in Taizhou (Man et al. 2017) were much higher than those in the rest of the world, such as the USA, Philippines, China, and Iran (Altshul et al. 2004; Malarvannan et al. 2013; Zhang et al. 2007a; Behrooz et al. 2012). The data suggest that Guiyu residents may be also exposed to a highly polluted PCB environment as a result of local e-waste dismantling activities.

Other tissues of Guiyu residents did not have higher PCB levels than seen in other areas in China. PCB levels in human milk samples have been studied to determine the exposure levels of PCBs for Guiyu local residents (Xing et al. 2009). Total PCB concentrations in human milk ranged from 0 to 57.6 $ng\ g^{-1}$ lipid, with an average of 9.5 $ng\ g^{-1}$ lipid and 0.9 pg WHO-TEQ g^{-1} lipid. This was similar to findings for Dalian, Shenyang (Kunisue et al. 2004), South Africa (Darnerud et al. 2006), and some southeast Asian countries (Indonesia, Vietnam, India) (Sudaryanto et al. 2006; Tue et al. 2010; Devanathan et al. 2012). However, higher values have been found in the Philippines (Malarvannan et al. 2013), Korea, Japan (Haraguchi et al. 2009), Ghana (Asante et al. 2011), and some Western European countries (Italy, Poland, Belgium) (Ingelido et al. 2007; Jaraczewska et al. 2006; Colles et al. 2008), especially Luqiao (Ling et al. 2008) (Table 7). The result of this comparison was different from that of atmosphere samples. It may be due to the different distribution of PCB homologs between Guiyu and Luqiao, and the homologs were difference in lipid content and molecular size. The concentrations of higher molecular weight PCBs tend to accumulate in human milk (Schecter et al. 1998). The most predominant PCB congeners contributing to WHO-TEQs in human milk samples from Guiyu were PCB-105 and 157, with their concentrations accounting for more than 80% of the total WHO-TEQs. Usually, the concentration of PCB in breast milk is related to the frequency of fish consumption of the donors (Deng et al. 2012). However, the correlation of PCB concentrations between Guiyu residents breast milk and fish samples was not significant ($p > 0.05$), due to the fact that Guiyu residents have a low living standard resulting in the low frequency of fish consumption (Xing et al. 2009). In addition, the major congeners in airborne particles in the residential area of Guiyu were light PCBs, e.g., PCB-28, 37, 49, and 77 (Xing et al. 2009). Therefore, that would explain why PCB levels in human milk were not as high as expected, as levels were related to the distribution of homologs of PCBs in the atmosphere. This finding was similar to the results for PCB concentrations in the serum and UCB of Guiyu residents. The concentration of PCB in serum of Guiyu residents was only slightly higher than that for Haojiang residents (Bi et al. 2007), and the value was also far below the PCB levels in serum of e-waste workers and residents in Luqiao (Ma et al. 2017; Zhao et al. 2010; Ling et al. 2008) and just slightly lower than Wenling (Ling et al. 2008). In addition, Wu et al. (2011) assessed the median PCB concentration to be 338.6 $ng\ g^{-1}$ lipid in UCB samples from Guiyu, vs 140.2 $ng\ g^{-1}$ lipid in samples from Chaonan, and 2.5 $ng\ g^{-1}$ lipid and 2.1 $ng\ g^{-1}$ lipid for TEQ level, respectively. The value was also lower than that of Luqiao, but twice as high as that of the lightly polluted area in Taizhou (Ling et al. 2008). The relative concentration of PCB congeners in human milk was not significantly different from that of UCB, and all were not as high as expected. This shows that internal exposure of human milk and UCB was no different in the same area, and was due to a lesser content of heavy PCBs, e.g., PCB-105 and 157 in airborne particles in the residential area of Guiyu (Xing et al. 2009). Such a finding lends further support to the notion that the body burden of PCBs of Guiyu residents was mainly due to air pollution, but this still lacks direct evidence.

Many studies have shown that PCB exposure is usually shows reproductive, cytotoxic, and other toxicity. It has been found that PCB exposure can damage ovarian function, affect female reproductive organs, decrease the weight of male testis, affect spermatogenesis, and decrease the activity of spermatozoa (Ruby et al. 2003; Gupta 2010). In addition, PCB-101 and 118 exposures induced oxidative stress and antioxidant stress and affected the activity and content of reactive oxygen species, malondialdehyde, superoxide dismutase, and glutathione in cells (Hashmi et al. 2018). PCB exposure also showed estrogenic activity to organisms, causing endocrine disorders in the body. A study suggested a lower T4 level in maternal serum in relation to exposure to PCDD/Fs and PCBs (Zhang et al. 2010a). They are also associated with adverse effects on motor development in infants (Berghuis et al. 2013). A lower birth weight was associated with the increase in PCB-153 in cord serum (150 g per 1 ug L^{-1}) (Govarts et al. 2012). In addition, some study suggested that exposure to PCB was associated with increased incidence of hypertension and diabetes (Frithsen 2008; Kim et al. 2014), and impaired repair ability of DNA damage (Wang et al. 2018).

Body burden of PAHs

A variety of PAH exposure will lead to several toxic effects, such as DNA damage, gene mutation and chromosome aberration (Bocskay et al. 2005; Stowers and Anderson 1985), and cancer of the respiratory, digestive, and reproductive systems (Carl-Elis et al. 2002; Rybicki et al. 2004; Tang et al. 1995). Embryonic developmental toxicity and endocrine disrupting toxicity have also been observed (Binkova et al. 2001; Kizu et al. 2000). A number of epidemiological studies have indicated that several occupational groups with potential exposure to complex mixtures containing PAHs are at significantly increased risk of developing lung cancer and bladder cancers (Mastrangelo et al. 1996). In addition to elevated cancer risk and disruption of hormonal equilibrium, growing evidence supports developmental toxicity from prenatal or early postnatal exposure to PAHs (Archibong et al. 2002; Belpomme et al. 2007). Animal experiments show that some PAHs can pass through the placenta to cause liver, lung, lymph tissue, and nervous system tumor in pups (Bulay and Wattenberg 1971; Rice and Ward 1982; Vesselinovitch et al. 1979). So it is important to characterize the body burden of PAHs for Guiyu residents, to determine whether residents have a high incidence of related diseases, especially newborns and children who are considered to be more susceptible than adults. In addition, it is necessary to understand the main pathways of PAH exposure in Guiyu inhabitants and take precautions to eliminate or minimize the adverse effects of PAHs on the human body.

Knowledge of the body burden of PAHs in Guiyu is badly lacking. Only a few studies have appeared. Guo et al. (2012) studied the median Σ7 carcinogenic PAH concentration in UCB samples of Guiyu and Chaonan (108.1 vs. 79.4 ppb). Xu et al. (2013) also studied the PAH values in UCB samples of Guiyu and Chaonan (14.4 vs. 10.1 ppb). The individual values for the seven carcinogenic PAHs (BaA, Chr, BbF, BkF, BaP, IP, DA) were lower compared with a previous study (Guo et al. 2012), but higher than values reported for these PAHs in UCB from Taiyuan city, except for BaA (Dong et al. 2009). In addition, the distribution patterns of PAHs were similar to the studies of Guo et al. (2012), with 3-, 5-, and 6-ring PAHs being the most abundant, and Σ7 carcinogenic PAHs contributing to most of the Σ16-PAHs. This phenomenon was also observed in a study for serum of children from e-waste recycling areas, where within the 68.5 ppb of Σ16-PAHs, 60.3 ppb was comprised of the Σ7 carcinogenic PAHs, and levels were significantly higher than that from the reference area (Σ16-PAHs: 26.9 ppb; Σ7 carcinogenic PAHs: 21.3 ppb) (Xu et al. 2015b). All the predominant PAH congeners in UCB and serum samples from Guiyu were three-, five-, and six-ring compounds, with IP occupying the highest percentage, followed by BP, BbkF, and Phe. The distribution patterns were similar to the previous studies about environmental atmosphere samples in Guiyu, in which five-ring and six-ring PAHs accounted for 73% of the total PAHs, mainly IP, BP, BbkF, Phe, and Chr (Wong et al. 2007; Zhang et al. 2011). This was strong evidence showing that POPs in the body of Guiyu residents entered mainly through inhalation.

PAH has been a serious air pollution problem in Guiyu and has posed a serious health hazard, especially to pregnant women and children. Recent studies have suggested that PAH-contaminated air may cause neonatal UCB lymphocyte DNA damage and, importantly, that female neonatal UCB lymphocytes are more susceptible than male newborn lymphocytes to DNA damage (Xu et al. 2013). PAH-caused DNA damage may also result in the activation of apoptosis pathways, interference of transcription, DNA replication, or protein synthesis (Gurbani et al. 2013; Kuang et al. 2013; Wei et al. 2010).

Respiratory exposure and health risk assessment

People are exposed to contaminants mainly through principal pathways (e.g., inhalation, dermal contact, and ingestion). Dietary intake is generally accepted to be the primary exposure route for some organic compounds (Curl 2014; Nadal and Domingo 2013; Zhang et al. 2010b). Nevertheless, in some highly polluted areas, inhalation may become the main route due to its severe air pollution. For example, in China's PBDE production area, air inhalation accounts for 71% of the total exposure dose (Jin et al. 2010). Especially in the e-waste recycling areas, residents are exposed to PCDD/Fs mainly through direct inhalation of polluted air (Kouimtzis et al. 2002; Xiao et al. 2012) and e-waste workers conducting open burning activities and residents; both are exposed to PCBs through air inhalation accounts for 87.8 and 59.6% of the total exposure dose, respectively (Xing et al. 2009). These organic compounds are mainly attached to particles, enter the body, and aggravated the damage of respiratory exposure although some amount of protective measures can be used to obstruct a portion of the organic particles. However, some fine particles, such as PM2.5, can still enter the body and deposit.

Generally, the risk of potential adverse health effects was calculated using the mean measured concentrations. Here, we only assess the risks to human health caused by inhalation air containing pollutants, which are classified as carcinogens and non-carcinogens. The daily exposure dose by air inhalation (DEDair), health risk assessment of non-carcinogens, and carcinogens of POPs was estimated using the following equation (Fang et al. 2013; He et al. 2015; September 2010):

$$\mathrm{DEDair} = \mathrm{C\ IR\ fr/BW} \quad (1)$$

$$\mathrm{HQi} = \mathrm{DEDair/RfDi} \quad (2)$$

$$\mathrm{HQ} = \Sigma\,\mathrm{HQi} \quad (3)$$

$$\mathrm{ILCR} = \mathrm{DEDair} \times \mathrm{SF} \times \mathrm{EF} \times \mathrm{ED/AT} \quad (4)$$

where C is the average POP concentration in air (ng m^{-3}); IR is inhalation rate (16 m^3 day^{-1} for adults, 10.1 m^3 day^{-1} for children, and 4.1 m^3 day^{-1} for infants) (US-EPA 2011); fr is the alveolar fraction retained in the lungs (a value of 0.75 was used for both adults, children, and infants); BW is the body weight (70 kg for adults, 12 kg for children, and 5 kg for infants and were used in this study); HQi is hazard quotient, used to evaluate inhaled health risks for individual congeners of non-carcinogens and usually be a sign of health risk of chronic diseases. When multiple homologs coexist, the HQi of each congener should be added to the HQ; RfDi is a reference dose for a single congener of non-carcinogens (ng kg^{-1} -day^{-1}); ILCR means incremental lifetime cancer risk; SF means slope factor of carcinogens (kg d mg^{-1}); EF denotes the frequency of exposure of the human body to the contaminant each year (365 d a^{-1}); ED denotes exposure duration (70 a); AT denotes human life expectancy (25,550 d).

Chen et al. (2011b) discovered the estimated daily PBDE exposure dose via air inhalation (gas + particles) for Guiyu children and adults, respectively, varied between 3.25–13.56 and 2.48–10.37 ng kg^{-1} bw day^{-1}, which is significantly lower than the PBDE RfD given by integrated risk information system (IRIS) of the USA (the RfD of BDE-47, 99, 100, 153, 154, 183, and 209 is 100, 100, 2000, 200, 3000, 3000, and 7000 ng kg^{-1} day^{-1}, respectively) (US-EPA 2017). The RfD value proposed by IRIS is set to take into account soil/dust intake, dermal contact, and respiratory intake exposure. In this case, only the exposure dose through atmospheric inhalation was assessed, but not integrated the soil/dust intake and dermal contact dose, which explains why it is significantly lower than the RfD. Moreover, the DEDair of Guiyu residents was still higher than that of Guangzhou and Hong Kong (1.2 and 2.2 ng kg^{-1} bw day^{-1}, respectively) (Wang et al. 2014), was 14- to 74-fold higher than those observed in the USA (Johnson-Restrepo and Kannan 2009), and even was hundreds of times the amount of human exposure to PBDEs through inhalation air from people in the vicinity of a large recycling facility in Brisbane, Australia (0.027 ng kg^{-1} bw day^{-1}) (Hearn et al. 2013). In addition, it is worth noting that the DEDair of BDE-99 was 0.41–1.61 ng kg^{-1} bw day^{-1}, which was higher than the RfD (0.26 ng kg^{-1} bw day^{-1}) recommended by a research detailing sensitive toxicological endpoints relating to endocrine disruptions (Chen et al. 2011b; De Winter Sorkina et al. 2007). Then, based on the formula (1) (4) and atmospheric concentration provided by Chen et al. (2011b), the ILCR value of the suspected carcinogen BDE-209 was calculated to be 2.31×10^{-10}–1.48×10^{-9} for adults and 8.61×10^{-10}–5.46×10^{-9} for children (SF = 7×10^{-4} kg d mg^{-1}) (US-EPA 2017), which is all less than 10^{-6}, negligible health risk of carcinogenesis.

Xiao et al. (2012) measured the daily PCDD/F exposure dose via air inhalation for Guiyu adults and children and showed dose of 2.31–7.6 pg WHO-TEQ kg^{-1} day^{-1} (2.01–6.69 pg I-TEQ kg^{-1} day^{-1}) and 4.09–13.58 pg WHO-TEQ kg^{-1} day^{-1} (3.56–11.86 pg I-TEQ kg^{-1} day^{-1}), respectively, slightly higher than a previous study (adults: 2.54 pg WHO-TEQ kg^{-1} bw day^{-1}; children: 4.5 pg WHO-TEQ kg^{-1} bw day^{-1}) (Li et al. 2007a). Whether adult or child of Guiyu, their DEDair values were far higher than that of general population from non-e-waste site in China (6.93×10^{-2} pg WHO-TEQ kg^{-1} bw day^{-1}) (Li et al. 2007b; Zhang et al. 2007b), even slightly higher than the tolerable daily human intake (1–4 pg WHO-TEQ kg^{-1} day^{-1}) and the average DEDair of special population from e-waste site in China (2.54 pg WHO-TEQ kg^{-1} bw day^{-1}) (van Leeuwen et al. 2000). The results of both studies indicate that the influence on children was almost twofold that of adults (Li et al. 2007a; Xiao et al. 2012). This is a factor in the prevalence of respiratory disease in Guiyu children as high as 80% (Xiao et al. 2012). In addition, the ILCR value of PCDD/Fs was calculated to be 3.47×10^{-5}–1.14×10^{-4} and 6.14×10^{-5}–2.04×10^{-4} for adults and children (SF = 1.5×10^{-5} kg d mg^{-1}), respectively. The value is between 10^{-5} and 10^{-4}; it means adults and children of Guiyu are at risk of cancer when exposed to atmospheric PCDD/F pollution. These data indicate the importance of respiratory exposure to PCDD/Fs of Guiyu residents, and children are more vulnerable than adults. Air inhalation accounted for 12–30% of the total exposure dose of Guiyu children and adults (Li et al. 2007a). However, this proportion does not yet include dermal exposure and indoor dust ingestion does, so it may underestimate the risk of air pollution.

Xing et al. (2009) estimated the daily intake of PCBs via inhalation for e-waste workers engaging in open burning activities and the local residents in Guiyu. The mean exposure dose of total PCBs via air inhalation was 1900 ng day^{-1} and 390 ng day^{-1} for e-waste workers and residents, accounting for 87.8 and 59.6% of the total exposure (including dietary and inhalation exposure, 2163 and 654 ng day^{-1}, respectively), and the carcinogenic risk was 8.7×10^{-5} and 2.6×10^{-5}, respectively. The carcinogenic risk value is an order of magnitude higher than the reference value for cancer risk (1×10^{-6}) (US-EPA 1994); it means inhalation of atmospheric PCBs among workers and even residents of Guiyu may lead to cancer. In addition, the DEDair of PCBs was approximately 5.57 ng kg^{-1} bw day^{-1} for adults, 20.52 ng kg^{-1} bw day^{-1} for children, and 19.99 ng kg^{-1} bw day^{-1} for infants, none of whom have contact with e-waste recycling activities (calculated by the mean exposure dose of total PCBs via air inhalation of residents (390 ng day^{-1}) divided by the body weight of adults (70 kg), children (12 kg), and infants (5 kg), respectively). The DEDair of children is slightly higher than the RfD (2×10^{-5} mg kg^{-1} day^{-1}) (US-EPA 1994), the HQ is greater than 1, and it means Guiyu children are more likely to suffer from chronic diseases exposure to atmospheric PCBs than adults. These data indicate the importance of respiratory exposure to PCBs of Guiyu residents, and children are more affected by atmospheric PCB pollution than adults.

Based on the formula (1) and the atmospheric data published by Zhang et al. (2011), the DEDair of Σ16-PAHs was estimated to be 8.59–50.01 ng kg^{-1} bw day^{-1} for adults, 31.64–184.14 ng kg^{-1} bw day^{-1} for children, and 30.83–179.40 ng kg^{-1} bw day^{-1} for infants. Similarly, the DEDair of Σ7 carcinogenic PAHs was 1.50–18.34 ng kg^{-1} bw day^{-1}, 5.52–67.54 ng kg^{-1} bw day^{-1}, and 5.38–65.8 ng kg^{-1} bw day^{-1}, respectively. The RfD values of non-carcinogenic congeners of PAHs are between 1.5×10^{-2} and 1.5×10^{-1} mg kg^{-1} day^{-1} (Zhang et al. 2014). Therefore, the HQ of PAHs must be less than 1, negligible health risk of chronic diseases. The BaPeq value is generally used to evaluate the carcinogenic risk of PAHs. We estimated the ILCR of BaPeq to be 1.55×10^{-6}–2.58×10^{-5} for adults, 5.67×10^{-6}–9.51×10^{-5} for children, and 5.52×10^{-6}–9.27×10^{-5} for infants, all in the range of 10^{-6}–10^{-4}. It means Guiyu residents may be at risk of cancer due to inhalation of atmospheric PAHs, and children are at greater risk than adults. All of the above data confirm that air inhalation exposure from the high levels of local air pollution is a very important route of POP exposure to Guiyu residents, especially children.

Conclusions

This review of data on the atmospheric environment, body burden, respiratory exposure, and health risk assessment of four typical POPs in an e-waste recycling area of China suggests that the POP content in the atmosphere and human body of the e-waste recycling area, especially Guiyu, is obviously higher than that of other types of areas (industrial mixed areas, urban, suburban, or rural), due to the informal e-waste processing operations. Comparison and analysis of published data shows that air inhalation is the main exposure pathway of POP exposure of Guiyu residents, especially vulnerable groups such as children, infants, and e-waste workers. These findings provide clear evidence that there is an urgent need for reducing the negative impact due to e-waste recycling activities, especially air pollution caused by e-waste dismantling process. It is necessary for the government to control and monitor the e-waste dismantling activities, focus on those dismantling processes that cause severe air pollution, improve people's awareness to air pollution, and advocate the implementation of formal e-waste dismantling methods. Research gaps, such as atmospheric concentrations of PCBs in recent years, accumulation of PCDD/Fs and PAHs in different human tissues of Guiyu residents, in particular, the direct relationship between air pollution and body burden, and epidemiological and clinical studies, should be addressed.

Acknowledgements This work was supported by the National Natural Science Foundation of China (21876065). We would like to thank Dr. Stanley Lin for his constructive comments and English language editing.

References

Abad, E., Caixach, J., Rivera, J., Gustems, L., Massagué, G., & Puig, O. (2004). Temporal trends of PCDDs/PCDFs in ambient air in Catalonia (Spain). *Science of the Total Environment, 334*(334–335), 279–285.

Akutsu, K., Takatori, S., Nozawa, S., Yoshiike, M., Nakazawa, H., Hayakawa, K., et al. (2008). Polybrominated diphenyl ethers in human serum and sperm quality. *Bulletin of Environmental Contamination and Toxicology, 80*(4), 345–350. https://doi.org/10.1007/s00128-008-9370-4.

Altshul, L., Covaci, A., & Hauser, R. (2004). The relationship between levels of PCBs and pesticides in human hair and blood: Preliminary results. *Environmental Health Perspectives, 112*(11), 1193.

An, T., Huang, Y., Li, G., He, Z., Chen, J., & Zhang, C. (2014). Pollution profiles and health risk assessment of VOCs emitted during e-waste dismantling processes associated with different dismantling methods. *Environment International, 73*(4), 186. https://doi.org/10.1016/j.envint.2014.07.019.

An, T., Zhang, D., Li, G., Mai, B., & Fu, J. (2011). On-site and off-site atmospheric PBDEs in an electronic dismantling workshop in south China: Gas-particle partitioning and human exposure assessment. *Environmental Pollution, 159*(12), 3529–3535. https://doi.org/10.1016/j.envpol.2011.08.014.

And, S. H., & Harrad, S. (2006). Causes of variability in concentrations of polychlorinated biphenyls and polybrominated diphenyl ethers in indoor air. *Environmental Science and Technology, 40*(24), 7584–7589.

Andreas, S., H̊Akan, C., Kaj, T., Sverker, S., Åke, B., & Östman, C. (2001). Flame retardants in indoor air at an electronics recycling plant and at other work environments. *Environmental Science and Technology, 35*(3), 448–454.

Antignac, J. P., Cariou, R., Zalko, D., Berrebi, A., Cravedi, J. P., Maume, D., et al. (2009). Exposure assessment of French women and their newborn to brominated flame retardants: Determination of tri- to deca- polybromodiphenylethers (PBDE) in maternal adipose tissue, serum, breast milk and cord serum. *Environmental Pollution, 157*(1), 164–173.

Antkiewicz, D. S., Burns, C. G., Carney, S. A., Peterson, R. E., & Heideman, W. (2005). Heart malformation is an early response to TCDD in embryonic zebrafish. *Toxicological Sciences, 84*(2), 368–377. https://doi.org/10.1093/toxsci/kfi073.

Archibong, A. E., Inyang, F., Ramesh, A., Greenwood, M., Nayyar, T., Kopsombut, P., et al. (2002). Alteration of pregnancy related hormones and fetal survival in F-344 rats exposed by inhalation to benzo(a)pyrene. *Reproductive Toxicology, 16*(6), 801.

Asante, K. A., Adu-Kumi, S., Nakahiro, K., Takahashi, S., Isobe, T., Sudaryanto, A., et al. (2011). Human exposure to PCBs, PBDEs and HBCDs in Ghana: Temporal variation, sources of exposure and estimation of daily intakes by infants. *Environment International, 37*(5), 921–928.

Assunção, J. V. D., Pesquero, C. R., Bruns, R. E., & Carvalho, L. R. F. (2005). Dioxins and furans in the atmosphere of São Paulo City. *Brazil. Chemosphere, 58*(10), 1391–1398.

Balducci, C. (2008). Year time modulation of n-alkanes, PAH, nitro-PAH and organic acids at Montelibretti, Rome, Italy. *Polycyclic Aromatic Compounds, 28*(4–5), 500–517.

Behrooz, R. D., Barghi, M., Bahramifar, N., & Esmaili-Sari, A. (2012). Organochlorine contaminants in the hair of Iranian pregnant women. *Chemosphere, 86*(3), 235–241.

Belpomme, D., Irigaray, P., Hardell, L., Clapp, R., Montagnier, L., Epstein, S., et al. (2007). The multitude and diversity of environmental carcinogens. *Environmental Research, 105*(3), 414–429.

Berghuis, S. A., Soechitram, S. D., Hitzert, M. M., Sauer, P. J., & Bos, A. F. (2013). Prenatal exposure to polychlorinated biphenyls and their hydroxylated metabolites is associated with motor development of three-month-old infants. *Neurotoxicology, 38*(4), 124–130.

Bi, X., Qu, W., Sheng, G., Zhang, W., Mai, B., Chen, D., et al. (2006). Polybrominated diphenyl ethers in South China maternal and fetal blood and breast milk. *Environmental Pollution, 144*(3), 1024–1030.

Bi, X., Sheng, G., Peng, P. A., Chen, Y., Zhang, Z., & Fu, J. (2003). Distribution of particulate- and vapor-phase n-alkanes and polycyclic aromatic hydrocarbons in urban atmosphere of Guangzhou. *China Atmospheric Environment, 37*(2), 289–298.

Bi, X., Thomas, G. O., Jones, K. C., Qu, W., Sheng, G., Martin, F. L., et al. (2007). Exposure of electronics dismantling workers to polybrominated diphenyl ethers, polychlorinated biphenyls, and organochlorine pesticides in South China. *Environmental Science and Technology, 41*(16), 5647.

Binkova, R. J. S. B., Dejmek, J., & Solansky, I. (2001). The impact of polycyclic aromatic hydrocarbons and fine particles on pregnancy outcome. *Environmental Health Perspectives, 13*(4), 210. https://doi.org/10.1289/ehp.001081159.

Bocskay, K. A., Tang, D., Orjuela, M. A., Liu, X., Warburton, D. P., & Perera, F. P. (2005). Chromosomal aberrations in cord blood are associated with prenatal exposure to carcinogenic polycyclic aromatic hydrocarbons. *Cancer Epidemiology, Biomarkers & Prevention 14*(2), 506. https://doi.org/10.1158/1055-9965.EPI-04-0566.

Boucher, O., Muckle, G., & Bastien, C. H. (2009). Prenatal exposure to polychlorinated biphenyls: A neuropsychologic analysis. *Environmental Health Perspectives, 117*(1), 7–16.

Breivik, K., Armitage, J. M., Wania, F., & Jones, K. C. (2014). Tracking the global generation and exports of e-waste. Do existing estimates add up? *Environmental Science and Technology, 48*(15), 8735–8743. https://doi.org/10.1021/es5021313.

Bulay, O. M., & Wattenberg, L. W. (1971). Carcinogenic effects of polycyclic hydrocarbon carcinogen administration to mice during pregnancy on the progeny. *Journal of the National Cancer Institute, 46*(2), 397–402.

Cahill, T. M., Groskova, D., Charles, M. J., Sanborn, J. R., Denison, M. S., & Baker, L. (2007). Atmospheric concentrations of polybrominated diphenyl ethers at near-source sites. *Environmental Science and Technology, 41*(18), 6370–6377. https://doi.org/10.1021/es070844j.

Cao, J., Xu, X., Zhang, Y., Zeng, Z., Hylkema, M. N., & Huo, X. (2017). Increased memory T cell populations in Pb-exposed children from an e-waste-recycling area. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2017.10.220.

Carl-Elis, B., Per, G., Annika, H., Bengt, J., Christer, J., Titus, K., et al. (2002). Cancer risk assessment, indicators, and guidelines for polycyclic aromatic hydrocarbons in the ambient air. *Environmental Health Perspectives, 110*(Suppl 3), 451–488.

Cetin, B., Yatkin, S., Bayram, A., & Odabasi, M. (2007). Ambient concentrations and source apportionment of PCBs and trace elements around an industrial area in Izmir. *Turkey. Chemosphere, 69*(8), 1267–1277.

Chan, J. K., Man, Y. B., Wu, S. C., & Wong, M. H. (2013). Dietary intake of PBDEs of residents at two major electronic waste recycling sites in China. *Science of the Total Environment, 463–464*(5), 1138–1146.

Chan, J. K., Xing, G. H., Xu, Y., Liang, Y., Chen, L. X., Wu, S. C., et al. (2007). Body loadings and health risk assessment of polychlorinated dibenzo-p-dioxins and dibenzofurans at an intensive electronic waste recycling site in China. *Environmental Science and Technology, 41*(22), 7668–7674.

Chao, H. R., Wang, S. L., Lee, W. J., Wang, Y. F., & Päpke, O. (2007). Levels of polybrominated diphenyl ethers (PBDEs) in breast milk from central Taiwan and their relation to infant birth outcome and maternal menstruation effects. *Environment International, 33*(2), 239–245.

Chen, D., Bi, X., Liu, M., Huang, B., Sheng, G., & Fu, J. (2011a). Phase partitioning, concentration variation and risk assessment of polybrominated diphenyl ethers (PBDEs) in the atmosphere of an e-waste recycling site. *Chemosphere, 82*(9), 1246–1252.

Chen, D., Bi, X., Zhao, J., Chen, L., Tan, J., Mai, B., et al. (2009a). Pollution characterization and diurnal variation of PBDEs in the atmosphere of an e-waste dismantling region. *Environmental Pollution, 157*(3), 1051–1057.

Chen, A., Dietrich, K. N., Huo, X., & Ho, S. (2011b). Developmental neurotoxicants in e-waste: An emerging health concern. *Environmental Health Perspectives, 119*(4), 431–438.

Chen, S. J., Ma, Y. J., Wang, J., Chen, D., Luo, X. J., & Mai, B. X. (2009b). Brominated flame retardants in children's toys: Concentration, composition, and children's exposure and risk assessment. *Environmental Science and Technology, 43*(11), 4200–4206.

Chen, L. G., Mai, B. X., Bi, X. H., Chen, S. J., Wang, X. M., Ran, Y., et al. (2006). Concentration levels, compositional profiles, and gas-particle partitioning of polybrominated diphenyl ethers in the atmosphere of an urban city in South China. *Environmental Science and Technology, 40*(4), 1190–1196.

Chen, S. J., Tian, M., Zheng, J., Zhu, Z. C., Luo, Y., Luo, X. J., et al. (2014). Elevated levels of polychlorinated biphenyls in plants, air, and soils at an e-waste site in Southern China and enantioselective biotransformation of chiral PCBs in plants. *Environmental Science and Technology, 48*(7), 3847–3855.

Chevrier, J., Harley, K. G., Bradman, A., Gharbi, M., Sjödin, A., & Eskenazi, B. (2010). Polybrominated diphenyl ether (PBDE) flame retardants and thyroid hormone during pregnancy. *Environmental Health Perspectives, 118*(10), 1444–1449.

Chi, X., Streicher-Porte, M., Wang, M. Y., & Reuter, M. A. (2011). Informal electronic waste recycling: A sector review with special focus on China. *Waste Management, 31*(4), 731–742.

Cindoruk, S. S., & Tasdemir, Y. (2007). Characterization of gas/particle concentrations and partitioning of polychlorinated biphenyls (PCBs) measured in an urban site of Turkey. *Environmental Pollution, 148*(1), 325–333.

Colles, A., Koppen, G., Hanot, V., Nelen, V., Dewolf, M. C., Noël, E., et al. (2008). Fourth WHO-coordinated survey of human milk for persistent organic pollutants (POPs): Belgian results. *Chemosphere, 73*(6), 907–914.

Cong, X., Xu, X., Xu, L., Li, M., Xu, C., Qin, Q., et al. (2018). Elevated biomarkers of sympatho-adrenomedullary activity linked to e-waste air pollutant exposure in preschool children. *Environment International, 115,* 117–126. https://doi.org/10.1016/j.envint.2018.03.011.

Correa, O., Rifai, H., Raun, L., Suarez, M., & Koenig, L. (2004). Concentrations and vapor-particle partitioning of polychlorinated dibenzo-dioxins and dibenzofurans in ambient air of Houston. *TX. Atmospheric Environment, 38*(39), 6687–6699.

Costa, L. G., & Giordano, G. (2007). Developmental neurotoxicity of polybrominated diphenyl ether (PBDE) flame retardants. *Neurotoxicology, 28*(6), 1047–1067.

Curl, C. L. (2014). Characterizing dietary exposure to organophosphate pesticides, incorporating information on organic food consumption, for use in epidemiological research. doi:http://hdl.handle.net/1773/25395.

Darnerud, P. O. (2004). Toxic effects of brominated flame retardants in man and in wildlife. *Environment International, 29*(6), 841–853. https://doi.org/10.1016/S0160-4120(03)00107-7.

Darnerud, P. O., Aune, M., Lignell, S., Mutshatshi, N., Agyei, N., Botha, B., et al. (2006). Levels of POPs in human breast milk samples from Northern Province, South Africa; comparison to Swedish levels. *Organohalogen Compounds, 68,* 476–479.

De Winter Sorkina, R., Bakker, M. I., Wolterink, G., & Zeijlmaker, M. J. (2007). Brominated flame retardants: occurrence, dietary intake and risk assessment. https://www.researchgate.net/publication/27451633_Brominated_flame_retardants_occurrence_dietary_intake_and_risk_assessment.

Deng, W. J., Louie, P. K. K., Liu, W. K., Bi, X. H., Fu, J. M., & Wong, M. H. (2006). Atmospheric levels and cytotoxicity of PAHs and heavy metals in TSP and PM2.5 at an electronic waste recycling site in southeast China. *Atmospheric Environment, 40*(36), 6945–6955. https://doi.org/10.1016/j.atmosenv.2006.06.032.

Deng, B., Zhang, J., Zhang, L., Jiang, Y., Zhou, J., Fang, D., et al. (2012). Levels and profiles of PCDD/Fs, PCBs in mothers' milk in Shenzhen of China: Estimation of breast-fed infants' intakes. *Environment International, 42*(42), 47–52.

Deng, W. J., Zheng, J. S., Bi, X. H., Fu, J. M., & Wong, M. H. (2007). Distribution of PBDEs in air particles from an electronic waste recycling site compared with Guangzhou and Hong Kong. *South China. Environment International, 33*(8), 1063–1069.

Department, E. P. (2004). A report on the results from the Air Quality Monitoring Network http://www.aqhi.gov.hk/api_history/english/report/files/aqr04e.pdf.

Devanathan, G., Subramanian, A., Sudaryanto, A., Takahashi, S., Isobe, T., & Tanabe, S. (2012). Brominated flame retardants and polychlorinated biphenyls in human breast milk from several locations in India: potential contaminant sources in a municipal dumping site. *Environment International, 39*(1), 87.

Domingo, J. L., Schuhmacher, M., Agramunt, M. C., Llobet, J. M., Rivera, J., & Müller, L. (2002). PCDD/F levels in the neighbourhood of a municipal solid waste incinerator after introduction of technical improvements in the facility. *Environment International, 28*(1–2), 19–27.

Dong, S., Ding, C., Zhang, M., & Liu, Y. (2009). Relationship of PAHs levels in umbilical cord blood and the PAHs exposure between the mother and the paired newborns. *Journal of Hygiene Research, 38*(3), 339–342.

Dooley, E. E. (2010). UNEP offers e-waste predictions, guidance. (The Beat) (United Nations Environment Programme)(Brief article). doi:https://www.highbeam.com/doc/1G1-224912343.html.

Duan, J., Bi, X., Tan, J., Sheng, G., & Fu, J. (2007). Seasonal variation on size distribution and concentration of PAHs in Guangzhou city. *China. Chemosphere, 67*(3), 614–622.

Eiguren-Fernandez, A., Miguel, A. H., Froines, J. R., Thurairatnam, S., & Avol, E. L. (2004). Seasonal and spatial variation of polycyclic aromatic hydrocarbons in vapor-phase and PM2.5 in Southern California Urban and Rural Communities. *Aerosol Science and Technology, 38*(5), 447–455.

Ernst, M., Flesch-Janys, D., Morgenstern, I., & Manz, A. (1998). Immune cell functions in industrial workers after exposure to 2,3,7,8-tetrachlorodibenzo-p-dioxin: Dissociation of antigen-specific T-cell responses in cultures of diluted whole blood and of isolated peripheral blood mononuclear cells. *Environmental Health Perspectives, 106*(Suppl 2), 701–705. https://doi.org/10.2307/3433823.

Esteban, M., & Castaño, A. (2009). Non-invasive matrices in human biomonitoring: A review. *Environment International, 35*(2), 438–449.

Fang, G. C., Chang, C. N., Chu, C. C., Wu, Y. S., Fu, P. P., Yang, I. L., et al. (2003). Characterization of particulate, metallic elements of TSP, PM(2.5) and PM(2.5-10) aerosols at a farm sampling site in Taiwan, Taichung. *Science of the Total Environment, 308*(1–3), 157–166.

Fang, W., Yang, Y., & Xu, Z. (2013). PM10 and PM2.5 and health risk assessment for heavy metals in a typical factory for cathode ray tube television recycling. *Environmental Science and Technology, 47*(21), 12469–12476. https://doi.org/10.1021/es4026613.

Fängström, B., Hovander, L., Bignert, A., Athanassiadis, I., Linderholm, L., Grandjean, P., et al. (2005). Concentrations of polybrominated diphenyl ethers, polychlonnated biphenyls, and polychlorobiphenylols in serum from pregnant Faroese women and their children 7 years later. *Environmental Science and Technology, 39*(24), 9457–9463.

Frithsen, I. L. (2008). Association of polychlorinated biphenyls with hypertension in the 1999–2002 National Health and Nutrition Examination Survey. *Environmental Research, 108*(1), 94–97. https://doi.org/10.1016/j.envres.2008.05.006.

Gies, A., Neumeier, G., Rappolder, M., & Konietzka, R. (2007). Risk assessment of dioxins and dioxin-like PCBs in food–comments by the German Federal Environmental Agency. *Chemosphere, 67*(9), 344–349.

Govarts, E., Nieuwenhuijsen, M., Schoeters, G., Ballester, F., Bloemen, K., Boer, M. D., et al. (2012). Birth weight and prenatal exposure to polychlorinated biphenyls (PCBs) and dichlorodiphenyldichloroethylene (DDE): A meta-analysis within 12 European birth cohorts. *Environmental Health Perspectives, 120*(2), 162–170.

Gu, Z. P., Feng, J. L., Han, W. L., Li, L., Wu, M. H., Fu, J. M., et al. (2010a). Diurnal variations of polycyclic aromatic hydrocarbons associated with PM2.5 in Shanghai, China. *Journal of Environmental Sciences, 22*(3), 389–396.

Gu, Z., Feng, J., Han, W., Wu, M., Fu, J., & Sheng, G. (2010a). Characteristics of organic matter in PM 2.5 from an e-waste dismantling area in Taizhou, China. *Chemosphere, 80*(7), 800-806, https://doi.org/10.1016/j.chemosphere.2010.04.078

Gullett, B. K., Linak, W. P., Touati, A., Wasson, S. J., Gatica, S., & King, C. J. (2007). Characterization of air emissions and residual ash from open burning of electronic wastes during simulated rudimentary recycling operations. *Journal of Material Cycles and Waste Management, 9*(1), 69–79.

Guo, Y., Huo, X., Wu, K., Liu, J., Zhang, Y., & Xu, X. (2012). Carcinogenic polycyclic aromatic hydrocarbons in umbilical cord blood of human neonates from Guiyu. *China. Science of the Total Environment, 427–428*(12), 35–40.

Gupta, C. (2010). Reproductive malformation of the male offspring following maternal exposure to estrogenic chemicals. *Proceedings of the Society for Experimental Biology and Medicine, 224*(2), 61–68. https://doi.org/10.1046/j.1525-1373.2000.22402.x.

Gupta, A., Ketchum, N., Roehrborn, C. G., Schecter, A., Aragaki, C. C., & Michalek, J. E. (2006). Serum dioxin, testosterone, and subsequent risk of benign prostatic hyperplasia: A prospective cohort study of Air Force veterans. *Environmental Health Perspectives, 114*(11), 1649–1654.

Gurbani, D., Bharti, S. K., Kumar, A., Pandey, A. K., Ana, G. R. E. E., Verma, A., et al. (2013). Polycyclic aromatic hydrocarbons and their quinones modulate the metabolic profile and induce DNA damage in human alveolar and bronchiolar cells. *International Journal of Hygiene and Environmental Health, 216*(5), 553–565.

Hamers, T., Kamstra, J. H., Sonneveld, E., Murk, A. J., Kester, M. H., Andersson, P. L., et al. (2006). In vitro profiling of the endocrine-disrupting potency of brominated flame retardants. *Toxicological Sciences, 92*(1), 157–173.

Han, W., Feng, J., Gu, Z., Wu, M., Sheng, G., & Fu, J. (2010). Polychlorinated biphenyls in the atmosphere of Taizhou, a major e-waste dismantling area in China. *Journal of Environmental Sciences, 22*(4), 589–597.

Haraguchi, K., Koizumi, A., Inoue, K., Harada, K. H., Hitomi, T., Minata, M., et al. (2009). Levels and regional trends of persistent organochlorines and polybrominated diphenyl ethers in Asian breast milk demonstrate POPs signatures unique to individual countries. *Environment International, 35*(7), 1072–1079.

Hashmi, M. Z., Hasnain, A., Syed, J. H., Tariq, M., Su, X., Mubarak, H., et al. (2018). PCB118-induced cell proliferation mediated by oxidative stress and MAPK signaling pathway in HELF cells. *Dose Response*. https://doi.org/10.1177/1559325817751525.

Hayakawa, K., Takatsuki, H., Watanabe, I., & Sakai, S. (2004). Polybrominated diphenyl ethers (PBDEs), polybrominated dibenzo-p-dioxins/dibenzofurans (PBDD/Fs) and monobromo-polychlorinated dibenzo-p-dioxins/dibenzofurans (MoBPXDD/Fs) in the atmosphere and bulk deposition in Kyoto. *Japan. Chemosphere, 57*(5), 343–356.

He, Z., Li, G., Chen, J., Huang, Y., An, T., & Zhang, C. (2015). Pollution characteristics and health risk assessment of volatile organic compounds emitted from different plastic solid waste recycling workshops. *Environment International, 77,* 85–94. https://doi.org/10.1016/j.envint.2015.01.004.

Health, Occupational Environmental (2000). Guidelines for air quality. *Geneva World Health Organization*. http://www.who.int/iris/handle/10665/66537.

Hearn, L. K., Hawker, D. W., Toms, L. M., & Mueller, J. F. (2013). Assessing exposure to polybrominated diphenyl ethers (PBDEs) for workers in the vicinity of a large recycling facility. *Ecotoxicology and Environmental Safety, 92*(3), 222–228. https://doi.org/10.1016/j.ecoenv.2013.02.013.

Hsu, P. C., Pan, M. H., Li, L. A., Chen, C. J., Tsai, S. S., & Guo, Y. L. (2007). Exposure in utero to 2,2′,3,3′,4,6′-hexachlorobiphenyl (PCB 132) impairs sperm function and alters testicular apoptosis-related gene expression in rat offspring. *Toxicology and Applied Pharmacology, 221*(1), 68–75. https://doi.org/10.1016/j.taap.2007.01.027.

Huo, X., Peng, L., Xu, X., Zheng, L., Qiu, B., Qi, Z., et al. (2007). Elevated blood lead levels of children in guiyu, an electronic waste recycling town in China. *Environmental Health Perspectives, 115*(7), 1113–1117. https://doi.org/10.1289/ehp.9697.

Ingelido, A. M., Ballard, T., Dellatte, E., Domenico, A. D., Ferri, F., Fulgenzi, A. R., et al. (2007). Polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) in milk from Italian women living in Rome and Venice. *Chemosphere, 67*(9), 301–306.

Inoue, K., Harada, K., Takenaka, K., Uehara, S., Kono, M., Shimizu, T., et al. (2006). Levels and concentration ratios of polychlorinated biphenyls and polybrominated diphenyl ethers in serum and breast milk in Japanese mothers. *Environmental Health Perspectives, 114*(8), 1179–1185.

Ivnitski-Steele, I. D., Friggens, M., Chavez, M., & Walker, M. K. (2005). 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) inhibition of coronary vasculogenesis is mediated, in part, by reduced responsiveness to endogenous angiogenic stimuli, including vascular endothelial growth factor A (VEGF-A). *Birth Defects Res A Clin Mol Teratol, 73*(6), 440–446. https://doi.org/10.1002/bdra.20137.

Jaraczewska, K., Lulek, J., Covaci, A., Voorspoels, S., Kaluba-Skotarczak, A., Drews, K., et al. (2006). Distribution of polychlorinated biphenyls, organochlorine pesticides and polybrominated diphenyl ethers in human umbilical cord serum, maternal serum and milk from Wielkopolska region. *Poland. Science of the Total Environment, 372*(1), 20–31.

Jin, J., Ying, W., Yang, C., Hu, J., Liu, W., & Jian, C. (2010). Human exposure to polybrominated diphenyl ethers at production area. *China. Environmental Toxicology & Chemistry, 29*(5), 1031–1035.

Jing, M., Cheng, J., Wang, W., Kunisue, T., Wu, M., & Kannan, K. (2011). Elevated concentrations of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans and polybrominated diphenyl ethers in hair from workers at an electronic waste recycling facility in Eastern China. *Journal of Hazardous Materials, 186*(2–3), 1966–1971.

Johnson-Restrepo, B., & Kannan, K. (2009). An assessment of sources and pathways of human exposure to polybrominated diphenyl ethers in the United States. *Chemosphere, 76*(4), 542.

Julander, A., Westberg, H., Engwall, M., & Van, B. B. (2005). Distribution of brominated flame retardants in different dust fractions in air from an electronics recycling facility. *Science of the Total Environment, 350*(1–3), 151–160.

Jung, K. H., Torrone, D., Lovinskydesir, S., Perzanowski, M., Bautista, J., Jezioro, J. R., et al. (2017). Short-term exposure to PM 2.5 and vanadium and changes in asthma gene DNA methylation and lung function decrements among urban children. *Respiratory Research, 18*(1), 63.

Kim, K. S., Lee, Y. M., Kim, S. G., Lee, I. K., Lee, H. J., Kim, J. H., et al. (2014). Associations of organochlorine pesticides and polychlorinated biphenyls in visceral vs. subcutaneous adipose tissue with type 2 diabetes and insulin resistance. *Chemosphere, 94*(1), 151-157, https://doi.org/10.1016/j.chemosphere.2013.09.066.

Kizu, R., Ishii, K., Kobayashi, J., Hashimoto, T., Koh, E., Namiki, M., et al. (2000). Antiandrogenic effect of crude extract of C-heavy oil. *Materials Science and Engineering C, 12*(1), 97–102.

Kouimtzis, T., Samara, C., Voutsa, D., Ch, B., & Müller, L. (2002). PCDD/Fs and PCBs in airborne particulate matter of the greater Thessaloniki area. *N. Greece. Chemosphere, 47*(2), 193–205.

Król, S., Namieśnik, J., & Zabiegała, B. (2014). Occurrence and levels of polybrominated diphenyl ethers (PBDEs) in house dust and hair samples from Northern Poland; an assessment of human exposure. *Chemosphere, 110,* 91–96.

Kuang, D., Zhang, W., Deng, Q., Zhang, X., Huang, K., Guan, L., et al. (2013). Dose-response relationships of polycyclic aromatic hydrocarbons exposure and oxidative damage to DNA and lipid in coke oven workers. *Environmental Science and Technology, 47*(13), 7446–7456.

Kunisue, T., Someya, M., Kayama, F., Jin, Y., & Tanabe, S. (2004). Persistent organochlorines in human breast milk collected from primiparae in Dalian and Shenyang. *China. Environmental Pollution, 131*(3), 381–392.

Kuriyama, S. N., Talsness, C. E., Grote, K., & Chahoud, I. (2005). Developmental exposure to low-dose PBDE-99: Effects on male fertility and neurobehavior in rat offspring. *Environmental Health Perspectives, 113*(2), 149–154.

Kuriyama, S. N., Wanner, A., Fidalgo-Neto, A. A., Talsness, C. E., Koerner, W., & Chahoud, I. (2007). Developmental exposure to low-dose PBDE-99: Tissue distribution and thyroid hormone levels. *Toxicology, 242*(1), 80–90. https://doi.org/10.1016/j.tox.2007.09.011.

Landrigan, P. J., Sly, J. L., Ruchirawat, M., Silva, E. R., Huo, X., Diaz-Barriga, F., et al. (2016). Health consequences of environmental exposures: Changing global patterns of exposure and disease. *Annals of Global Health, 82*(1), 10–19.

Lapviboonsuk, J., & Loganathan, B. (2007). Polynuclear aromatic hydrocarbons in sediments and mussel tissue from the lower Tennessee river and Kentucky lake. *Journal of the Kentucky Academy of Science, 68*(2), 186–197. https://doi.org/10.3101/1098-7096(2007)68[186:pahisa]2.0.co;2.

Lee, W. S., Chang-Chien, G. P., Wang, L. C., Lee, W. J., Tsai, P. J., Wu, K. Y., et al. (2004). Source identification of PCDD/Fs for various atmospheric environments in a highly industrialized city. *Environmental Science and Technology, 38*(19), 4937–4944.

Leung, A., Cai, Z. W., & Ming, H. W. (2006). Environmental contamination from electronic waste recycling at Guiyu, Southeast China. *Journal of Material Cycles and Waste Management, 8*(2), 154.

Leung, A. O., Chan, J. K., Xing, G. H., Xu, Y., Wu, S. C., Wong, C. K., et al. (2010). Body burdens of polybrominated diphenyl ethers in childbearing-aged women at an intensive electronic-waste recycling site in China. *Environmental Science and Pollution Research, 17*(7), 1300–1313.

Li, C., Fu, J., Sheng, G., Bi, X., Hao, Y., Wang, X., et al. (2005). Vertical distribution of PAHs in the indoor and outdoor PM2.5 in Guangzhou, China. *Building and Environment, 40*(3), 329–341.

Li, M., Huo, X., Pan, Y., Cai, H., Dai, Y., & Xu, X. (2017). Proteomic evaluation of human umbilical cord tissue exposed to polybrominated diphenyl ethers in an e-waste recycling area. *Environment International*. https://doi.org/10.1016/j.envint.2017.09.016.

Li, Y. M., Jiang, G. B., Wang, Y. W., Pu, W., & Zhang, Q. H. (2008). Concentrations, profiles and gas-particle partitioning of PCDD/Fs, PCBs and PBDEs in the ambient air of an e-waste dismantling area. *Southeast China. Chinese Science Bulletin, 53*(4), 521–528.

Li, Z., Porter, E. N., Sjödin, A., Needham, L. L., Lee, S., Russell, A. G., et al. (2009). Characterization of PM2.5-bound polycyclic aromatic hydrocarbons in Atlanta—Seasonal variations at urban, suburban, and rural ambient air monitoring sites. *Atmospheric Environment, 43*(27), 4187–4193.

Li, J. G., Wu, Y. N., Zhang, L., & Zhao, Y. F. (2007a). Dietary intake of polychlorinated dioxins, furans and dioxin-like polychlorinated biphenyls from foods of animal origin in China. *Food Additives & Contaminants, 24*(2), 186–193. https://doi.org/10.1080/02652030600970366.

Li, H., Yu, L., Sheng, G., Fu, J., & Peng, P. (2007b). Severe PCDD/F and PBDD/F pollution in air around an electronic waste dismantling area in China. *Environmental Science and Technology, 41*(16), 5641–5646.

Ling, B., Han, G., & Xu, Y. (2008). PCB levels in humans in an area of PCB transformer recycling. *Annals of the New York Academy of Sciences, 1140*(1), 135–142.

Liu, Y., Huo, X., Xu, L., Wei, X., Wu, W., Wu, X., et al. (2017a). Hearing loss in children with e-waste lead and cadmium exposure. *Science of the Total Environment, 624,* 621. https://doi.org/10.1016/j.scitotenv.2017.12.091.

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. *Environmental Science and Technology, 50*(18), 9846–9854.

Liu, L., Zhang, B., Lin, K., Zhang, Y., Xu, X., & Huo, X. (2017b). Thyroid disruption and reduced mental development in children from an informal e-waste recycling area: A mediation analysis. *Chemosphere, 193,* 498–505. https://doi.org/10.1016/j.chemosphere.2017.11.059.

Lohmann, R., Brunciak, P. A., Dachs, J., Gigliotti, C. L., Nelson, E., Ry, D. V., et al. (2003). Processes controlling diurnal variations of PCDD/Fs in the New Jersey coastal atmosphere. *Atmospheric Environment, 37*(7), 959–969.

Lu, X., Xu, X., Zhang, Y., Zhang, Y., Wang, C., & Huo, X. (2018). Elevated inflammatory Lp-PLA2 and IL-6 link e-waste Pb toxicity to cardiovascular risk factors in preschool children. *Environmental Pollution, 234,* 601–609. https://doi.org/10.1016/j.envpol.2017.11.094.

Luksemburg, W. J. (2002). Polychlorinated dibenzodioxins and dibenzofurans (PCDDs/PCDFs) levels in environmental and human hair samples around an electronic waste processing site in Guiyu, Guangdong Province, China. *Organohalogen Compounds, 55,* 347–349.

Ma, J., Cheng, J., Xie, H., Hu, X., Li, W., Zhang, J., et al. (2007). Seasonal and spatial character of PCBs in a chemical industrial zone of Shanghai. *China. Environmental Geochemistry & Health, 29*(6), 503–511.

Ma, J., Kannan, K., Cheng, J., Horii, Y., Wu, Q., & Wang, W. (2008). Concentrations, profiles, and estimated human exposures for polychlorinated dibenzo-p-dioxins and dibenzofurans from electronic waste recycling facilities and a chemical industrial complex in Eastern China. *Environmental Science and Technology, 42*(22), 8252–8259.

Ma, S., Ren, G., Zeng, X., Yu, Z., Sheng, G., & Fu, J. (2017). Polychlorinated biphenyls and their hydroxylated metabolites in the serum of e-waste dismantling workers from eastern China. *Environmental Geochemistry and Health*(6), 1-10, https://doi.org/10.1007/s10653-017-9958-x.

Malarvannan, G., Isobe, T., Covaci, A., Prudente, M., & Tanabe, S. (2013). Accumulation of brominated flame retardants and polychlorinated biphenyls in human breast milk and scalp hair from the Philippines: levels, distribution and profiles. *Science of the Total Environment, 442*(1), 366–379.

Man, Y. B., Chow, K. L., Xing, G. H., Chan, J., Wu, S. C., & Wong, M. H. (2017). A pilot study on health risk assessment based on body loadings of PCBs of lactating mothers at Taizhou, China, the world's major site for recycling transformers. *Environmental Pollution, 227,* 364–371.

Mastrangelo, G., Fadda, E., & Marzia, V. (1996). Polycyclic aromatic hydrocarbons and cancer in man. *Environmental Health Perspectives, 104*(11), 1166.

Michelle, H., Bain, K. C., Ansong, A. K., Birnbaum, L. S., Lennart, B. Å., Marie-Noel, B., et al. (2016). E-waste and harm to vulnerable populations: A growing global problem. *Environmental Health Perspectives, 124*(5), 550–555. https://doi.org/10.1289/ehp.1509699.

Moon, H. B., Lee, S. J., Choi, H. G., & Ok, G. (2005). Atmospheric deposition of polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) in urban and suburban areas of Korea. *Chemosphere, 58*(11), 1525–1534.

Muto, M., Isobe, T., Ramu, K., Tue, N. M., Viet, P. H., Takahashi, S., et al. (2012). Contamination of Brominated Flame Retardants (BFRs) in human hair from e-waste recycling site in Vietnam. *Interdisciplinary Studies on Environmental Chemistry—Environmental Pollution and Ecotoxicology*, 229-237.

Nadal, M., Iacute, & Domingo, J. L. (2013). *Sources of Human Exposure*: John Wiley & Sons, Inc. 2013:8-25. ISBN: 9781118159262.

Nagayama, J., Kohno, H., Kunisue, T., Kataoka, K., Shimomura, H., Tanabe, S., et al. (2007). Concentrations of organochlorine pollutants in mothers who gave birth to neonates with congenital hypothyroidism. *Chemosphere, 68*(5), 972–976.

Nakao, T., Aozasa, O., Ohta, S., & Miyata, H. (2005). Survey of human exposure to PCDDs, PCDFs, and coplanar PCBs using hair as an indicator. *Archives of Environmental Contamination and Toxicology, 49*(1), 124–130.

Nouwen, J., Cornelis, C., De, F. R., Wevers, M., Viaene, P., Mensink, C., et al. (2001). Health risk assessment of dioxin emissions from municipal waste incinerators: The Neerlandquarter (Wilrijk, Belgium). *Chemosphere, 43*(4–7), 909–923.

Park, J. S., Wade, T. L., & Sweet, S. T. (2002). Atmospheric deposition of PAHs, PCBs, and organochlorine pesticides to Corpus Christi Bay. *Texas. Atmospheric Environment, 36*(10), 1707–1720.

Pellacani, C., Buschini, A., Galati, S., Mussi, F., Franzoni, S., & Costa, L. G. (2012). Evaluation of DNA damage induced by 2 polybrominated diphenyl ether flame retardants (BDE-47 and BDE-209) in SK-N-MC cells. *International Journal of Toxicology, 31*(4), 372–379.

Pérez-Maldonado, I. N., Ramírez-Jiménez, M. R., Martínez-Arévalo, L. P., López-Guzmán, O. D., Athanasiadou, M., Bergman, A., et al. (2009). Exposure assessment of polybrominated diphenyl ethers (PBDEs) in Mexican children. *Chemosphere, 75*(9), 1215–1220.

Qiu, B., Peng, L., Xu, X., Lin, X., Hong, J., & Huo, X. (2004). Medical investigation of e-waste demanufacturing industry in Guiyu town. In *Proceedings of the international conference on electronic waste and extended producer responsibility, 2004* (pp. 79–83): Greenpeace and Chinese Society for Environmental Sciences Beijing. https://www.researchgate.net/publication/284382940_Medical_investigation_of_e-waste_demanufacturing_industry_in_Guiyu_town

Qu, W., Bi, X., Sheng, G., Lu, S., Fu, J., Yuan, J., et al. (2007). Exposure to polybrominated diphenyl ethers among workers at an electronic waste dismantling region in

Guangdong. *China. Environment International, 33*(8), 1029–1034.

Raab, U., Preiss, U., Albrecht, M., Shahin, N., Parlar, H., & Fromme, H. (2008). Concentrations of polybrominated diphenyl ethers, organochlorine compounds and nitro musks in mother's milk from Germany (Bavaria). *Chemosphere, 72*(1), 87–94.

Rahman, F., Langford, K. H., Scrimshaw, M. D., & Lester, J. N. (2001). Polybrominated diphenyl ether (PBDE) flame retardants. *Science of the Total Environment, 275*(1), 1–17. https://doi.org/10.1016/S0048-9697(01)00852-X.

Ramesh, A., Archibong, A., Hood, D., Guo, Z., & Loganathan, B. (2011). Global Environmental Distribution and Human Health Effects of Polycyclic Aromatic Hydrocarbons. 97-126, https://doi.org/10.1201/b11098-7.

Raun, L. H., Correa, O., Rifai, H., Suarez, M., & Koenig, L. (2005). Statistical investigation of polychlorinated dibenzo-p-dioxins and dibenzofurans in the ambient air of Houston. *Texas. Chemosphere, 60*(7), 973–989.

Ren, M., Tang, Y. H., Peng, P. A., & Cai, Y. (2015). PCDD/Fs in air and soil around an e-waste dismantling area with open burning of insulated wires in South China. *Bulletin of Environmental Contamination and Toxicology, 94*(5), 647–652.

Rice, J. M., & Ward, J. M. (1982). Age dependence of susceptibility to carcinogenesis in the nervous system. *Annals of the New York Academy of Sciences, 381*(1), 274–289. https://doi.org/10.1111/j.1749-6632.1982.tb50392.x.

Roosens, L., D'Hollander, W., Bervoets, L., Reynders, H., Campenhout, K. V., Cornelis, C., et al. (2010). Brominated flame retardants and perfluorinated chemicals, two groups of persistent contaminants in Belgian human blood and milk. *Environmental Pollution, 158*(8), 2546–2552.

Roscales, J., Muñoz-Arnanz, J., Morales, L., Abad, E., & Jiménez, B. (2013). PCDD/Fs, dioxin-like PCBs and PBDEs in air. Preliminary results of the spanish monitoring program on POPs under the Stockholm Convention after four years monitoring. *Organohalogen Compounds, 75,* 137–140.

Ruby, S., Mendoza, L. T., Fournier, M., Brousseau, P., & Dégas, V. (2003). Reproductive system impairment of mice fed diets containing beluga whale blubber from the St Lawrence estuary and arctic populations. *Journal of Toxicology & Environmental Health, 66*(11), 1073–1085. https://doi.org/10.1080/15287390306393.

Rybicki, B. A., Rundle, A., Savera, A. T., Sankey, S. S., & Tang, D. (2004). Polycyclic aromatic hydrocarbon-DNA adducts in prostate cancer. *Cancer Research, 64*(24), 8854–8859.

Saldarriaga, H., Villalobos, R., Solano, G., Amador, O., Gaspariano, R., Palma, R., et al. (2008). Aliphatic, polycyclic aromatic hydrocarbons and nitrated-polycyclic aromatic hydrocarbons in PM 10 in Southwestern Mexico City. *Polycyclic Aromatic Compounds, 28*(4–5), 578–597.

Schantz, S. L., Widholm, J. J., & Rice, D. C. (2003). Effects of PCB exposure on neuropsychological function in children. *Environmental Health Perspectives, 111*(3), 357.

Schecter, A., Kassis, I., & Päpke, O. (1998). Partitioning of dioxins, dibenzofurans, and coplanar PCBS in blood, milk, adipose tissue, placenta and cord blood from five American women. *Chemosphere, 37*(9–12), 1817–1823.

Schwarzer, S., De Bono, A., Giuliani, G., Kluser, S., & Peduzzi, P. (2005). E-waste, the hidden side of IT equipment's manufacturing and use. *Environment Alert Bulletin*, *1*, 20–25. Retrieved from http://archive-ouverte.unige.ch/unige:23132.

September (2010). Federal contaminated site risk assessment in Canada. *British Medical Journal, 1*(5583), 35-37.

Shen, H., Ding, G., Han, G., Wang, X., Xu, X., Han, J., et al. (2010). Distribution of PCDD/Fs, PCBs, PBDEs and organochlorine residues in children's blood from Zhejiang. *China. Chemosphere, 80*(2), 170–175.

Siddiqi, M. A., Laessig, R. H., & Reed, K. D. (2003). Polybrominated diphenyl ethers (PBDEs): New pollutants-old diseases. *Clinical Medicine & Research, 1*(4), 281–290.

Sin, D. W., Wong, Y. C., Choi, Y. Y., Lam, C. H., & Louie, P. K. (2003). Distribution of polycyclic aromatic hydrocarbons in the atmosphere of Hong Kong. *Journal of Environmental Monitoring Jem, 5*(6), 989–996.

Song, Q., & Li, J. (2014). A systematic review of the human body burden of e-waste exposure in China. *Environment International, 68*(4), 82–93.

Stowers, S. J., & Anderson, M. W. (1985). Formation and persistence of benzo(a)pyrene metabolite-DNA adducts. *Environmental Health Perspectives, 62,* 31–39.

Sudaryanto, A., Kunisue, T., Kajiwara, N., Iwata, H., Adibroto, T. A., Hartono, P., et al. (2006). Specific accumulation of organochlorines in human breast milk from Indonesia: Levels, distribution, accumulation kinetics and infant health risk. *Environmental Pollution, 139*(1), 107–117.

Tadeo, J. L., Sánchez-Brunete, C., & Miguel, E. (2009). Determination of polybrominated diphenyl ethers in human hair by gas chromatography-mass spectrometry. *Talanta, 78*(1), 138–143.

Talsness, C. E., Kuriyama, S. N., Sternerkock, A., Schnitker, P., Grande, S. W., Shakibaei, M., et al. (2008). In utero and lactational exposures to low doses of polybrominated diphenyl ether-47 alter the reproductive system and thyroid gland of female rat offspring. *Environmental Health Perspectives, 116*(3), 308–314. https://doi.org/10.1289/ehp.10536.

Talsness, C. E., Shakibaei, M., Kuriyama, S. N., Grande, S. W., Sterner-Kock, A., Schnitker, P., et al. (2005). Ultrastructural changes observed in rat ovaries following in utero and lactational exposure to low doses of a polybrominated flame retardant. *Toxicology Letters, 157*(3), 189–202.

Tang, Z., Huang, Q., Cheng, J., Yang, Y., Yang, J., Guo, W., et al. (2014). Polybrominated diphenyl ethers in soils, sediments, and human hair in a plastic waste recycling area: A neglected heavily polluted area. *Environmental Science and Technology, 48*(3), 1508–1516.

Tang, D., Santella, R. M., Blackwood, A. M., Young, T. L., Mayer, J., Jaretzki, A., et al. (1995). A molecular epidemiological case-control study of lung cancer. *Cancer Epidemiology, Biomarkers & Prevention, 4*(4), 341–346.

Thomas, G. O., Wilkinson, M., Hodson, S., & Jones, K. C. (2006). Organohalogen chemicals in human blood from the United Kingdom. *Environmental Pollution, 141*(1), 30–41.

Tsapakis, M., & Stephanou, E. G. (2007). Diurnal cycle of PAHs, nitro-PAHs, and oxy-PAHs in a high oxidation capacity marine background atmosphere. *Environmental Science and Technology, 41*(23), 8011–8017.

Tseng, L. H., Li, M. H., Tsai, S. S., Lee, C. W., Pan, M. H., Yao, W. J., et al. (2008). Developmental exposure to decabromodiphenyl ether (PBDE 209): Effects on thyroid hormone and hepatic enzyme activity in male mouse offspring. *Chemosphere, 70*(4), 640–647. https://doi.org/10.1016/j.chemosphere.2007.06.078.

Tue, N. M., Sudaryanto, A., Tu, B. M., Isobe, T., Takahashi, S., Viet, P. H., et al. (2010). Accumulation of polychlorinated biphenyls and brominated flame retardants in breast milk from women living in Vietnamese e-waste recycling sites. *Science of the Total Environment, 408*(9), 2155–2162.

US-EPA (1994). Polychlorinated biphenyls (PCBs) CASRN 1336-36-3. https://cfpub.epa.gov/ncea/iris2/chemicalLanding.cfm?substance_nmbr=294&forceAssessmentTab=true.

US-EPA (2011). Exposure Factors Handbook. 2011 Edition(Final). https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252.

US-EPA, O., Oaa, Ffrro (2017). Technical Fact Sheet - Polybrominated Diphenyl Ethers (PBDEs) and Polybrominated Biphenyls (PBBs). https://www.epa.gov/sites/production/files/2014-03/documents/ffrrofactsheet_contaminant_perchlorate_january2014_final_0.pdf.

Van Den Heuvel, R. L., Koppen, G., Staessen, J. A., Den Hond, E., Verheyen, G., Nawrot, T. S., et al. (2002). Immunologic biomarkers in relation to exposure markers of PCBs and dioxins in flemish adolescents (Belgium). *Environmental Health Perspectives, 110*(6), 595–600. https://doi.org/10.1289/ehp.02110595.

van Leeuwen, F. X., Feeley, M., Schrenk, D., Larsen, J. C., Farland, W., & Younes, M. (2000). Dioxins: WHO's tolerable daily intake (TDI) revisited. *Chemosphere, 40*(9–11), 1095–1101.

Vasconcellos, P. C., Zacarias, D., Pires, M. A. F., Pool, C. S., & Carvalho, L. R. F. (2003). Measurements of polycyclic aromatic hydrocarbons in airborne particles from the metropolitan area of São Paulo City. *Brazil. Atmospheric Environment, 37*(21), 3009–3018.

Vesselinovitch, S. D., Rao, K. V., & Mihailovich, N. (1979). Neoplastic response of mouse tissues during perinatal age periods and its significance in chemical carcinogenesis. *National Cancer Institute Monograph, 51*(51), 239.

Vuong, A. M., Yolton, K., Xie, C., Webster, G. M., Sjödin, A., Braun, J. M., et al. (2017). Childhood polybrominated diphenyl ether (PBDE) exposure and neurobehavior in children at 8 years. *Environmental Research, 158,* 677–684.

Wang, Y., Hu, J., Wei, L., Ning, W., Cheng, L., Peng, L., et al. (2016). Health risk assessment of migrant workers' exposure to polychlorinated biphenyls in air and dust in an e-waste recycling area in China: Indication for a new wealth gap in environmental rights. *Environment International, 87,* 33–41.

Wang, Y., Sun, X., Fang, L., Li, K., Yang, P., Du, L., et al. (2018). Genomic instability in adult men involved in processing electronic waste in Northern China. *Environment International, 117,* 69–81. https://doi.org/10.1016/j.envint.2018.04.027.

Wang, Y., Wu, X., Hou, M., Zhao, H., Chen, R., Luo, C., et al. (2017). Factors influencing the atmospheric concentrations of PCBs at an abandoned e-waste recycling site in South China. *Science of the Total Environment, 578,* 34–39.

Wang, W., Zheng, J., Chan, C. Y., Huang, M. J., Cheung, K. C., & Ming, H. W. (2014). Health risk assessment of exposure to polybrominated diphenyl ethers (PBDEs) contained in residential air particulate and dust in Guangzhou and Hong Kong. *Atmospheric Environment, 89*(2), 786–796. https://doi.org/10.1016/j.atmosenv.2014.01.030.

Wei, Y., Han, I. K., Hu, M., Shao, M., Zhang, J. J., & Tang, X. (2010). Personal exposure to particulate PAHs and anthraquinone and oxidative DNA damages in humans. *Chemosphere, 81*(10), 1280–1285.

Wei, S., Huang, B., Liu, M., Bi, X., Ren, Z., Sheng, G., et al. (2012). Characterization of PM2.5-bound nitrated and oxygenated PAHs in two industrial sites of South China. *Atmospheric Research, 109–110*(7), 76–83.

Weisglas-Kuperus, N., Patandin, S., Berbers, G. A., Sas, T. C., Mulder, P. G., Sauer, P. J., et al. (2000). Immunologic effects of background exposure to polychlorinated biphenyls and dioxins in Dutch preschool children. *Environmental Health Perspectives, 108*(12), 1203–1207.

Wen, S., Yan, G., Jingguang, L. I., Shi, T. M., Zhao, Y. F., & Yongning, W. U. (2011). Particle-bound PCDD/Fs in the atmosphere of an electronic waste dismantling area in China. *Biomedical and Environmental Sciences, 24*(2), 102. https://doi.org/10.3967/0895-3988.2011.02.003.

Wen, S., Yang, F. X., Gong, Y., Zhang, X. L., Hui, Y., Li, J. G., et al. (2008). Elevated levels of urinary 8-hydroxy-2′-deoxyguanosine in male electrical and electronic equipment dismantling workers exposed to high concentrations of polychlorinated dibenzo-p-dioxins and dibenzofurans, polybrominated diphenyl ethers, and polychlorinate. *Environmental Science and Technology, 42*(11), 4202–4207.

Wilford, B. H., Thomas, G. O., Jones, K. C., Davison, B., & Hurst, D. K. (2008). Decabromodiphenyl ether (decaBDE) commercial mixture components, and other PBDEs, in airborne particles at a UK site. *Environment International, 34*(3), 412–419.

Wong, M. H., Wu, S. C., Deng, W. J., Yu, X. Z., Luo, Q., Leung, A. O., et al. (2007). Export of toxic chemicals—A review of the case of uncontrolled electronic-waste recycling. *Environmental Pollution, 149*(2), 131–140.

Wu, K. S., Xu, X., Liu, J. X., Guo, Y., & Huo, X. (2011). In utero exposure to polychlorinated biphenyls and reduced neonatal physiological development from Guiyu, China. *Ecotoxicology and Environmental Safety, 74*(8), 2141–2147.

Wu, K. S., Xu, X. J., Liu, J. X., Guo, Y. Y., Yan, L., & Xia, H. (2010). Polybrominated diphenyl ethers in umbilical cord blood and relevant factors in neonates from Guiyu. *China. Environmental Science & Technology, 44*(2), 813–819.

Xiao, X., Chen, D., Mei, J., & Jianfang, H. U. (2012). Particle-bound PCDD/Fs, PBDD/Fs and TBBPA in the atmosphere around an electronic waste dismantling site in Guiyu. *China. Acta Scientiae Circumstantiae, 32*(5), 1142–1148. https://doi.org/10.13671/j.hjkxxb.2012.05.021.

Xing, G. H., Kityan, J., Leung, O., Wu, S. C., & Wong, M. H. (2009). Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China. *Environment International, 35*(1), 76–82.

Xing, G. H., Liang, Y., Chen, L. X., Wu, S. C., & Wong, M. H. (2011). Exposure to PCBs, through inhalation, dermal contact and dust ingestion at Taizhou, China-a major site for recycling transformers. *Chemosphere, 83*(4), 605–611.

Xu, X., Liu, J., Huang, C., Lu, F., Chiung, Y. M., & Huo, X. (2015a). Association of polycyclic aromatic hydrocarbons (PAHs) and lead co-exposure with child physical growth and development in an e-waste recycling town. *Chemosphere, 139,* 295–302.

Xu, L., Xia, H., Zhang, Y., Li, W., Zhang, J., & Xu, X. (2015b). Polybrominated diphenyl ethers in human placenta associated with neonatal physiological development at a typical e-waste recycling area in China. *Environmental Pollution, 196,* 414–422.

Xu, X., Yekeen, T. A., Xiao, Q., Wang, Y., Lu, F., & Huo, X. (2013). Placental IGF-1 and IGFBP-3 expression correlate with umbilical cord blood PAH and PBDE levels from prenatal exposure to electronic waste. *Environmental Pollution, 182*(6), 63–69.

Yu, L., Meng, M. X., Bi, X., Sheng, G., Fu, J., & Peng, P. A. (2006). Particle-bound polychlorinated dibenzo-p-dioxins and dibenzofurans in the atmosphere of Guangzhou. *China Atmospheric Environment, 40*(1), 96–108.

Yu, Y., Wang, X., Wang, B., Tao, S., Liu, W., Wang, X., et al. (2011). Polycyclic aromatic hydrocarbon residues in human milk, placenta, and umbilical cord blood in Beijing. *China. Environmental Science & Technology, 45*(23), 10235–10242. https://doi.org/10.1021/es202827g.

Yuan, J., Chen, L., Chen, D., Guo, H., Bi, X., Ju, Y., et al. (2008). Elevated serum polybrominated diphenyl ethers and thyroid-stimulating hormone associated with lymphocytic micronuclei in Chinese workers from an e-waste dismantling site. *Environmental Science and Technology, 42*(6), 2195–2200.

Yuan, H., Jin, J., Bai, Y., Li, Q., Wang, Y., & Hu, J. (2016). Concentrations and distributions of polybrominated diphenyl ethers and novel brominated flame retardants in tree bark and human hair from Yunnan Province, China. *Chemosphere, 154,* 319–325.

Zeng, Z., Huo, X., Zhang, Y., Xiao, Z., Zhang, Y., & Xu, X. (2018a). Lead exposure is associated with risk of impaired coagulation in preschool children from an e-waste recycling area. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-018-2206-9.

Zeng, X., Xu, X., Qin, Q., Ye, K., Wu, W., & Huo, X. (2018b). Heavy metal exposure has adverse effects on the growth and development of preschool children. *Environmental Geochemistry and Health*. https://doi.org/10.1007/s10653-018-0114-z.

Zhang, D., An, T., Qiao, M., Loganathan, B. G., & Zeng, X. (2011). Source identification and health risk of polycyclic aromatic hydrocarbons associated with electronic dismantling in Guiyu town, South China. *Journal of Hazardous Materials, 192*(1), 1–7.

Zhang, H., Chai, Z., & Sun, H. (2007a). Human hair as a potential biomonitor for assessing persistent organic pollutants. *Environment International, 33*(5), 685–693.

Zhang, M., Feng, G., Yin, W., Xie, B., Ren, M., Xu, Z., et al. (2017). Airborne PCDD/Fs in two e-waste recycling regions after stricter environmental regulations. *Journal of Environmental Sciences, 62*(12), 3–10. https://doi.org/10.1016/j.jes.2017.07.009.

Zhang, C. H., Guo, J. Y., Shi, S. Q., Zhang, L., Wu, Y. G., Li, J., et al. (2014). Polycyclic aromatic hydrocarbons and their health risk assessment in urban surface dust from main roads of Guiyang. *Southwest China. Chinese Journal of Ecology, 33*(10), 2810–2816. https://doi.org/10.13292/j.1000-4890.2014.0249.

Zhang, J., Jiang, Y., Zhou, J., Wu, B., Liang, Y., Peng, Z., et al. (2010a). Elevated body burdens of PBDEs, Dioxins, and PCBs on thyroid hormone homeostasis at an electronic waste recycling site in China. *Environmental Science and Technology, 44*(10), 3956–3962.

Zhang, T., Sun, H. W., Wu, Q., Zhang, X. Z., Yun, S. H., & Kannan, K. (2010b). Perfluorochemicals in meat, eggs and indoor dust in China: Assessment of sources and pathways of human exposure to perfluorochemicals. *Environmental Science and Technology, 44*(9), 3572–3579.

Zhang, Y., Xu, X., Chen, A., Davuljigari, C. B., Zheng, X., Kim, S. S., et al. (2018). Maternal urinary cadmium levels during pregnancy associated with risk of sex-dependent birth outcomes from an e-waste pollution site in China. *Reproductive Toxicology, 75,* 49–55. https://doi.org/10.1016/j.reprotox.2017.11.003.

Zhang, J., Zhou, J., Jiang, Y., Jiang, J., Zhuang, Z., Liu, X., et al. (2007b). Polychlorinated dibenzo-p-dioxin and dibenzofuran concentrations in common fish species in the Pearl River Delta area. *China. Chemosphere, 66*(2), 199–202. https://doi.org/10.1016/j.chemosphere.2006.07.100.

Zhao, X. R., Qin, Z. F., Yang, Z. Z., Zhao, Q., Zhao, Y. X., Qin, X. F., et al. (2010). Dual body burdens of polychlorinated biphenyls and polybrominated diphenyl ethers among local residents in an e-waste recycling region in Southeast China. *Chemosphere, 78*(6), 659–666.

Zhao, Y., Ruan, X., Li, Y., Yan, M., & Qin, Z. (2013). Polybrominated diphenyl ethers (PBDEs) in aborted human fetuses and placental transfer during the first trimester of pregnancy. *Environmental Science and Technology, 47*(11), 5939–5946.

Zhao, G., Wang, Z., Dong, M. H., Rao, K., Luo, J., Wang, D., et al. (2008). PBBs, PBDEs, and PCBs levels in hair of residents around e-waste disassembly sites in Zhejiang Province, China, and their potential sources. *Science of the Total Environment, 397*(1–3), 46–57.

Zhao, G., Xu, Y., Li, W., Han, G., & Ling, B. (2007). Prenatal exposures to persistent organic pollutants as measured in cord blood and meconium from three localities of Zhejiang. *China. Science of the Total Environment, 377*(2–3), 179–191.

Zheng, J., Luo, X. J., Yuan, J. G., Wang, J., Wang, Y. T., Chen, S. J., et al. (2011). Levels and sources of brominated flame retardants in human hair from urban, e-waste, and rural areas in South China. *Environmental Pollution, 159*(12), 3706–3713.

Zheng, J., Yu, L. H., Chen, S. J., Hu, G. C., Chen, K. H., Yan, X., et al. (2016). Polychlorinated biphenyls (PCBs) in human hair and serum from e-waste recycling workers in Southern China: Concentrations, chiral signatures, correlations, and source identification. *Environmental Science and Technology, 50*(3), 1579–1586.

Zhu, L., Ma, B., Li, J., Wu, Y., & Gong, J. (2009). Distribution of polybrominated diphenyl ethers in breast milk from North China: Implication of exposure pathways. *Chemosphere, 74*(11), 1429–1434.

Zickus, M., Kvietkus, K., & Marsalka, A. (1997). Real time relations between local meteorological conditions and pollutant concentrations in the urban atmosphere. *Journal of Aerosol Science, 28*(6), 1117.