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Source contributions to total concentrations and carcinogenic potencies of polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDD/Fs) in ambient air: a case study in Suzhou City, China

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Abstract The potential source categories and source contributions of polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDD/Fs) in ambient air from Suzhou City, China, were performed by principal component analysis-multiple linear regression (PCA-MLR) and positive matrix factorization (PMF). The carcinogenic potencies of PCDD/Fs were quantitatively apportioned based on the positive matrix factorization-toxic equivalent concentration (PMF-TEQ) method. The results of the present study were summarized as follows. (1) The total concentrations and toxic equivalent concentrations of PCDD/Fs (∑PCDD/Fs and TEQ) in ambient air from Suzhou City were 1.34–42.80 pg N m^{-3} and 0.081–1.22 pg I-TEQ N m^{-3}, respectively. (2) PCA-MLR suggested that industrial combustion (IC), electric arc furnaces (EAFs) and secondary aluminum smelters (ALSs), unleaded gas-fueled vehicle sources (UGFVs), ALSs, and hazardous solid waste incinerators (HSWIs) could be the primary PCDD/F contributors, accounting for 13.2, 16.7, 35.5, 19.4, and 15.2% of ∑PCDD/Fs, respectively. (3) PMF and PMF-TEQ indicated that EAFs (carbon steel), UGFVs, IC, ALSs,

municipal solid waste incinerators (MSWIs) and hospital waste incinerators (HWIs), and HSWIs contributed 10.9, 10.9, 42.8, 11.3, 10.7, and 13.4% to ∑PCDD/Fs, but contributed 8.3, 12.3, 50.3, 12.7, 6.0, and 10.4% to carcinogenic potencies of PCDD/Fs. This study was the first attempt to quantitatively apportion the source-specific carcinogenic potencies of PCDD/Fs in ambient air.

Introduction

Polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDD/Fs) are one group of the most toxic compounds. Previous studies have confirmed that the exposure of humans to PCDD/Fs may cause severe reproductive and developmental problems (Kakuta et al. 2007). Due to their carcinogenic and mutagenic properties, PCDD/Fs have been widely researched in various environmental matrices in the world, including soils, water, ambient air, food, fly ash, and biota (Fernandez-Gonzalez et al. 2015; Roscales et al. 2016; González-Barreiro et al. 2015; Squadrone et al. 2015, 2016; Jeong et al. 2016; Perelló et al. 2015; Domingo and Nadal 2016; Wu et al. 2016).

Ambient air is one of the most important components of the environment. However, the health and safety of ambient air have attracted more attention due to the serious problem of atmospheric pollution in recent years in China. Suzhou City is a highly industrialized city in China. The total gross domestic product (GDP) and population of Suzhou City were 220.7 billion dollars and 10.6 million in 2015, respectively. However, the researches about persistent organic pollutants

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(POPs) in ambient air of Suzhou City was quite limited, especially PCDD/Fs.

The principal component analysis-multiple linear regression (PCA-MLR) method and the positive matrix factorization (PMF) method have been widely applied to apportion the sources of POPs in various environmental matrices, including stack gas, soil, sediment, water, and ambient air (Li et al. 2015, 2016a; Qureshi et al. 2015; Gao et al. 2009; Lee et al. 2007). The PMF method is particularly applicable to the environmental data because it incorporates the variable uncertainties and forces all the values to be positive, which is reasonable to real environmental problems. In addition, the positive matrix factorization-toxic equivalent concentration (PMF-TEQ) method has been used to quantitatively apportion the carcinogenicities of POPs such as polycyclic aromatic hydrocarbons (PAHs) in previous studies (Wang et al. 2015; Li et al. 2016a). However, no study about quantitatively apportioning the source-specific carcinogenic potencies of PCDD/Fs has been reported in China.

In the present study, 55 ambient air samples were collected and analyzed from Suzhou City, China. The sources and source contributions to the mass concentration of PCDD/Fs were qualitatively and quantitatively researched based on PCA-MLR and PMF methods. In addition, the PMF-TEQ method was used to quantitatively apportion the carcinogenic potency of PCDD/Fs.

Material and methods

Sample collection

Fifty-five ambient air samples were collected from 11 sampling sites in Suzhou City from August to October in 2015 (Fig. 1). And ambient air samples were collected in five consecutive days in each sampling site.

Ambient air samples were collected using high-volume air samplers operating at 1.05 m³ min⁻¹, which was equipped with a glass fiber filter (GFF, 220.3 cm × 25.4 cm, GB100R, 0.6 μm nominal rating) followed by a glass cartridge containing two polyurethane foam (PUF, 90 mm × 65 mm) plugs. Before sampling, the GFFs were baked at 450 °C for 12 h to remove potential organic compounds, and the PUFs were cleaned with acetone and dichloromethane.

Sample analysis

Seventeen PCDD/F congeners were analyzed according to the Chinese national standard method (HJ77.2-2008). The process has been reported in previous studies (Li et al. 2016b; Li et al. 2017), and the results suggested that the performance of the Chinese national standard method was comparable with USEPA method TO-9A and 8290A (USEPA 1999, 2007).

Briefly, the ambient air samples were transferred into a Soxhlet extractor with toluene. The extracts were subjected to the following cleanup procedures: H_2SO_4 treatment, multi-layer silica gel column, and alumina. The fractions which contained PCDD/Fs were collected and concentrated under N_2 purging. The injection standards were spiked, and the samples were re-dissolved in 1 mL of decane. PCDD/Fs analysis was performed on high-resolution gas chromatography (HRGC) and high-resolution mass spectrometry (HRMS).

Quality assurance (QA) and quality control (QC)

Procedural blanks and matrix-spiked samples were processed and analyzed along with field samples and were used to enforce the quality of data. Procedural blanks indicated that the analysis system and glassware did not have influence on the mass concentrations of PCDD/Fs. Eleven samples were randomly selected as parallel samples which were used to check the repeatability. And the results suggested that relative standard deviations were less than 10% ($n = 3$) for these parallel samples. The detection limits (DLs) of 17 PCDD/Fs were estimated from a signal-to-noise ratio of 3:1 in blank samples, and varied from 0.0019 to 0.0069 pg N m⁻³ for HRGC-HRMS. The sampling recoveries of five $^{13}C_{12}$-PCDD/F surrogate standards were measured relative to the $^{13}C_{12}$-PCDD/F internal standards to obtain a measure of the collection efficiency. The recoveries for the surrogate-labeled PCDD/Fs sampling standards were between 78 and 124%.

### Principal component analysis (PCA) and positive matrix factorization (PMF) method

PCA and PMF were performed using the SPSS 18.0 software package and the PMF 5.0 method, respectively.

PCA-MLR method

The PCA-MLR method was a traditional receptor method and has been widely used to apportion the sources of POPs in various environmental matrices. The essence of PCA was to find a common factor which was used to reduce dimensionality. Factor loading and score matrices can be calculated by Eq. (1).

$$X = T \times L \tag{1}$$

where X is the concentration matrix, T is the factor score matrix, and L is the factor loading matrix. The possible source categories can be determined by the factor loading matrix. Then the absolute principal component scores were calculated based on the factor score matrix (Zhang et al. 2012a). A more
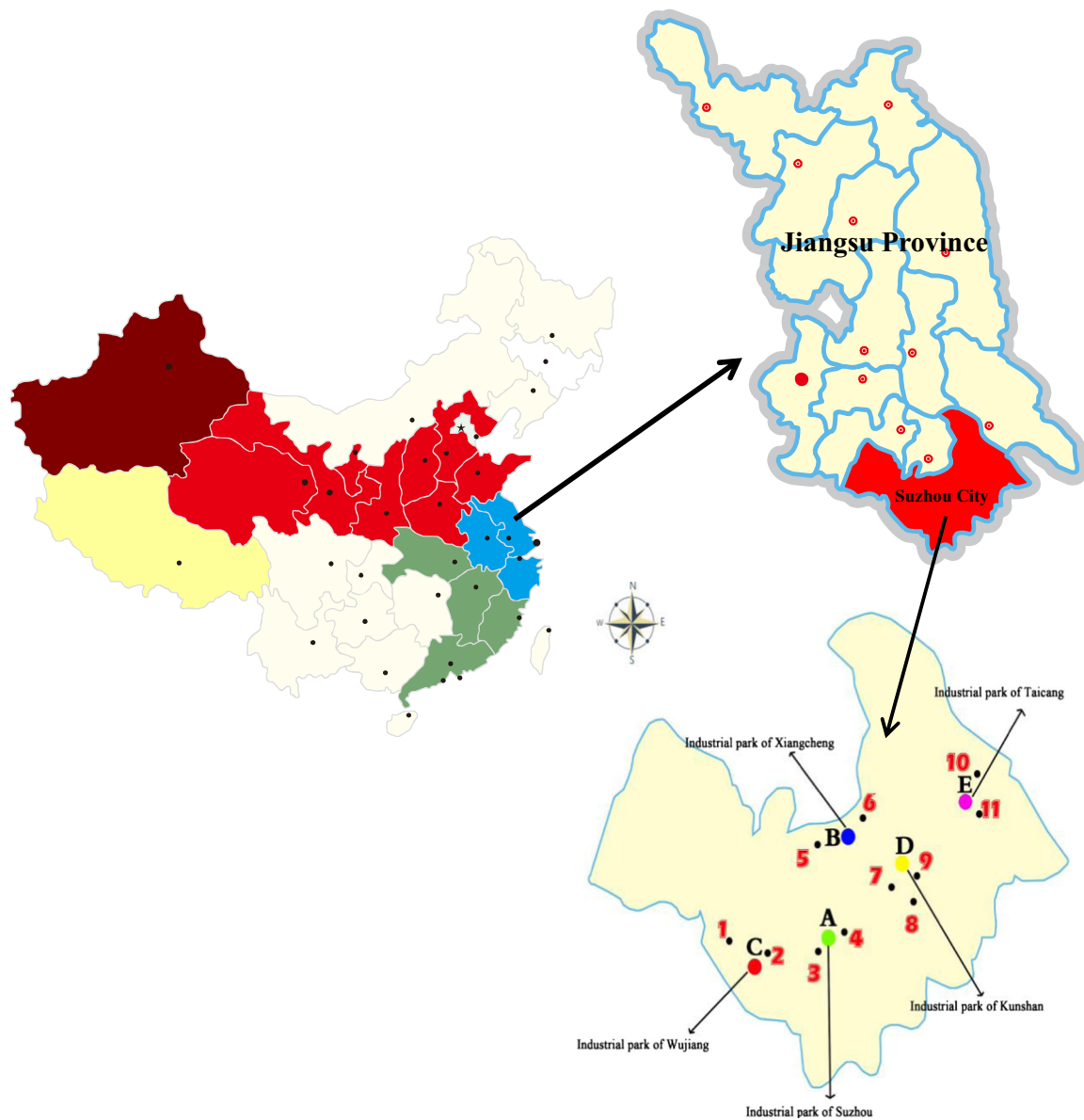
Fig. 1 Map of the sampling sites of the present study

detailed description of PCA-MLR can be found in previous studies (Yang et al. 2013; Zhang et al. 2012b).

PMF method

For the PMF method, a 17 × 55 dataset (17 PCDD/F conge-ners and 55 ambient air samples) was used to distinguish possible sources of PCDD/Fs in ambient air based on the PMF 5.0 method. Different to other methods, PMF considers the uncertainty (*Unc*) of each variable in the regression pro-cess. The *Unc* for PCDD/Fs concentrations was estimated based on the DL for the individual PCDD/Fs and the error fraction. The *Unc* is set to be five sixths of the DL if the

concentration is below the DL; otherwise, it is calculated by Eq. (2) (Cesari et al. 2016; Wang et al. 2015; Lang et al. 2015; Liao et al. 2015; Li et al. 2016b).

$$Unc = \sqrt{(Error\ Fraction \times Concentration)^2 + (DL)^2} \quad (2)$$

The value of error fraction was 20% according to previous studies (Li et al. 2016a; Pekey and Dogan 2013).

The S/N ratio and the Q values (the Q robust and the Q true values) were used to select variables and optimization of fac-tors. If the S/N ratio is greater than 0.2 but less than 2, the corresponding PCDD/F congeners will be considered as

"weak." If the S/N ratio is greater than 2, the corresponding PCDD/F congeners will be considered as "strong." In this way, 2,3,7,8-T4CDD and 2,3,7,8-T4CDF were considered as weak and the other 15 PCDD/F congeners were considered as strong.

The theoretical Q value was 935, which was calculated by the number of data entries ($n \times m$), where n was the number of PCDD/F congeners and m was the number of ambient air samples. The "optimal" solution was considered as a stable solution that did not depend on the initial seed and had a robust Q value near the theoretical value. Additionally, the number of factors was determined by considering whether the decrease in Q value is significantly greater than the value of $2 \times (m + n)$ while increasing the number of factor by 1. Consequently, the seven-factor solution was chosen. The PMF method was then run with seven factors. The robust Q value was 1139.4 and the true Q value was 1162.8. In addition, a higher correlation between the predicted and measured concentrations of PCDD/Fs in ambient air samples occurred in the present study, suggesting that PCDD/Fs were well apportioned by the PMF model.
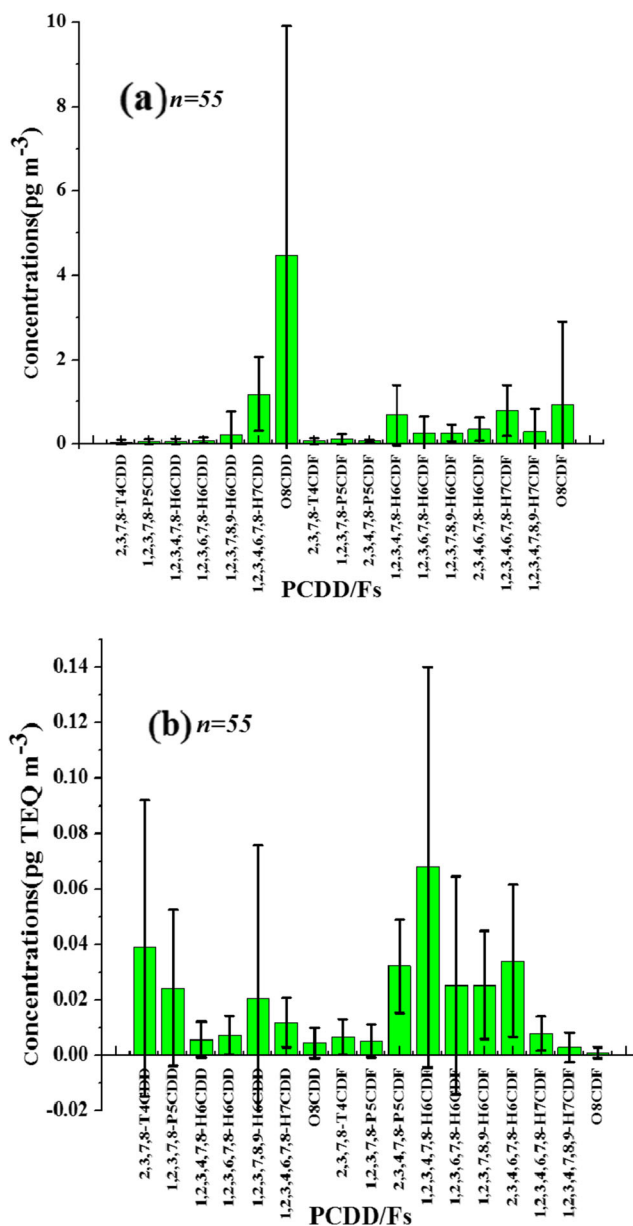
Results and discussion

Concentration and congener profiles of PCDD/Fs in ambient air

The mass concentrations and toxic equivalent concentrations (TEQ) of 17 PCDD/Fs in ambient air from Suzhou City are shown in Fig. 2a, b, respectively. The total concentrations of PCDD/Fs ($\sum$PCDD/Fs) ranged from 1.34 to 42.80 pg N m^{-3} with a mean of 9.86 pg N m^{-3}. The TEQ varied from 0.081 to 1.22 pg I-TEQ N m^{-3} with a mean of 0.32 pg I-TEQ N m^{-3}.

For individual PCDD/Fs, the concentration of O8CDD was much higher than other congeners and accounted for 45.4% of $\sum$PCDD/Fs. 1,2,3,4,6,7,8-H7CDD was also the dominant contributor of $\sum$PCDD/Fs, and the sum of these two dominant congeners accounted for 57.5% of $\sum$PCDD/Fs. For TEQ, 1,2,3,4,7,8-H6CDF was the largest contributor, and accounted for 21.1% of total TEQ, followed by 2,3,7,8-T4CDD (12.1%) and 2,3,4,6,7,8-H6CDF (10.6%). The sum of these three dominant contributors accounted for 43.8% of total TEQ.

Source apportionment of PCDD/Fs

PCA-MLR and PMF have been widely used to apportion the sources of POPs in various environmental matrices. In the present study, PCA-MLR and PMF were used to understand the potential source categories and source contributions of PCDD/Fs in ambient air of Suzhou City (Figs. 3 and 4), and


Fig. 2 Concentration and composition profiles of PCDD/Fs in ambient air from Suzhou City, China (**a** mass concentration; **b** toxic equivalent concentration)

PMF-TEQ was used to apportion the source-specific carcinogenic potencies of PCDD/Fs.

Source categories and source contributions of PCDD/Fs based on the PCA-MLR method

The rotated factors of 17 PCDD/Fs from ambient air of Suzhou City are shown in Fig. 3. Based on the loadings of the 17 PCDD/Fs, five principal components (PC1, PC2, PC3, PC4, and PC5) were identified and the variances of these five
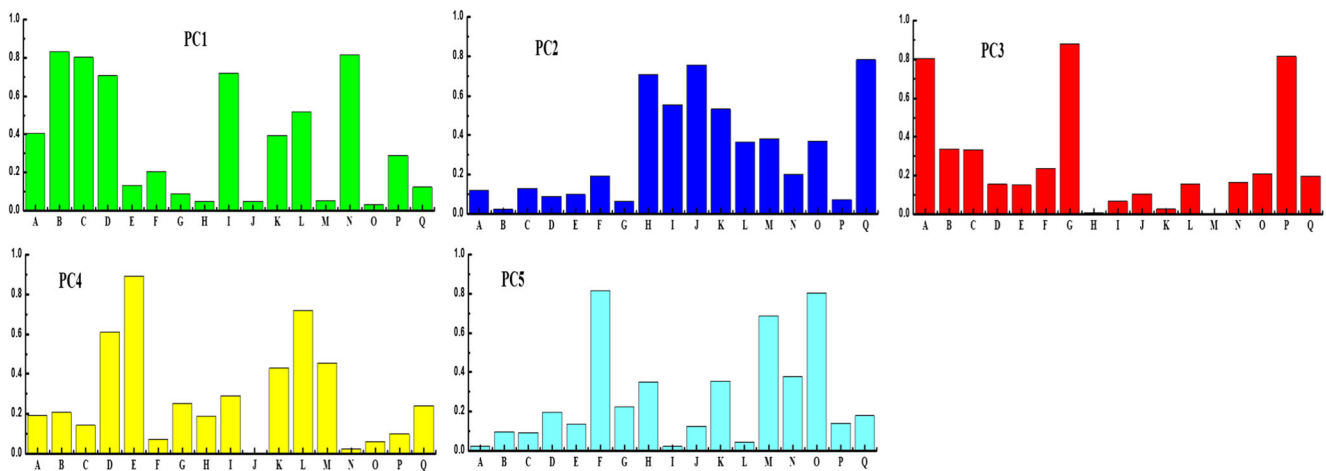
Fig. 3 Principal component analysis (PCA) after Varimax rotation for PCDD/Fs in ambient air (the loading of congeners in the figure was shown as absolute value; A−Q were represented by the 17 PCDD/Fs congeners)

principal components were 39.3, 18.1, 10.1, 8.1, and 6.7%, respectively.

PC1 has high positive loadings for 1,2,3,7,8-P5CDD, 1,2,3,4,7,8-H6CDD, 1,2,3,6,7,8-H6CDD, 1,2,3,7,8-P5CDF, and 2,3,4,6,7,8-H6CDF, and has moderate loadings for 1,2,3,4,7,8-H6CDF and 1,2,3,6,7,8-H6CDF. 1,2,3,7,8-P5CDF was suggested to be an indicator of sinter plant (Lee et al. 2004). 2,3,4,6,7,8-H6CDF, 1,2,3,4,7,8-H6CDF, and 1,2,3,6,7,8-H6CDF mainly originate from industrial

combustion (IC) (Qi et al. 2015; Du et al. 2010). Therefore, PC1 was selected to represent IC, such as small scale waste incinerator, sinter plant, and domestic heating.

PC2 was heavily loaded with six PCDFs (including 2,3,7,8-T4CDF, 1,2,3,7,8-P5CDF, 2,3,4,7,8-P5CDF, 1,2,3,4,7,8-H6CDF, 1,2,3,7,8,9-H6CDF, and O8CDF). 2,3,7,8-T4CDF, 1,2,3,7,8-P5CDF, 2,3,4,7,8-P5CDF, and 1,2,3,7,8,9-H6CDF were the important indicators of electric arc furnaces (EAFs) (carbon steel and steel) (Hofstadler et al.
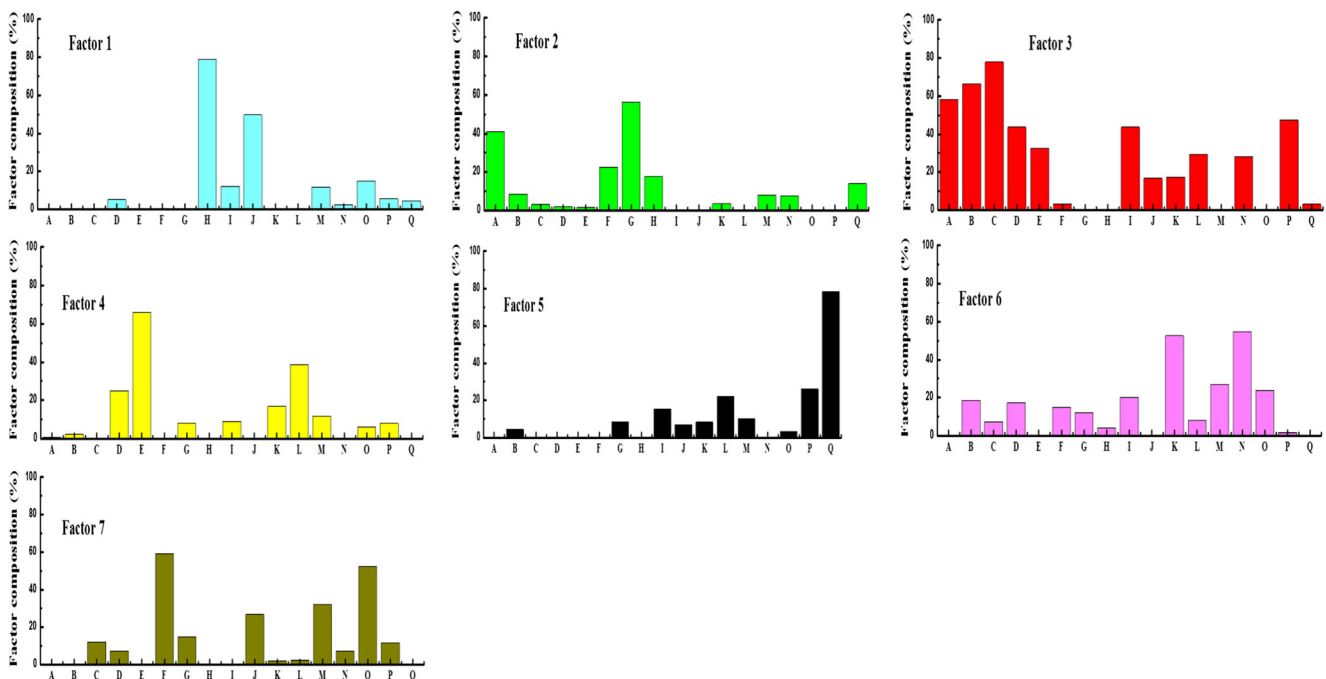
Fig. 4 Source profiles of PCDD/Fs as obtained from the PMF method

2000; Anderson and fisher 2002; Lee et al. 2004). 1,2,3,7,8-P5CDF, 2,3,4,7,8-P5CDF, and O8CDF were the important indicators of secondary aluminum smelters (ALSs) (Lee et al. 2004). Therefore, it was reasonable to assign PC2 1 to EAFs and ALSs.

PC3 was characterized by high loadings of 2,3,7,8-T4CDD, O8CDD, and 1,2,3,4,7,8,9-H7CDF. According to the congener profile of unleaded gas-fueled vehicle source (UGFVs), 2,3,7,8-T4CDD and O8CDD were the dominant PCDD/F congeners (USEPA 2001). Consequently, PC3 was selected to represent UGFVs.

PC4 has positive loadings for 1,2,3,6,7,8-H6CDD, 1,2,3,7,8,9-H6CDD, and 1,2,3,4,7,8-H6CDF, and has moderate loadings for 2,3,4,7,8-P5CDF and 1,2,3,6,7,8-H6CDF. Lee et al. (2004) indicated that 1,2,3,6,7,8-H6CDD, 1,2,3,7,8,9-H6CDD, and 2,3,4,7,8-P5CDF were also the indicators of one type of ALSs. Consequently, PC4 was selected to represent ALSs.

PC5 was characterized by high loadings of 1,2,3,4,6,7,8-H7CDD, 1,2,3,7,8,9-H6CDF, 1,2,3,4,6,7,8-H7CDF, and 2,3,4,6,7,8-H6CDF, which were important indicators of hazardous solid waste incinerators (HSWIs) (Chen et al. 2014). Therefore, PC5 was selected to represent HSWIs.

The contributions of each principal component to ∑PCDD/Fs were calculated by MLR, and corresponding equations were as follows:

$$Y = \sum a_i X_i + b \qquad (3)$$

$$C = \frac{a_i}{\sum a_i} \qquad (4)$$

where X_i is the factor score of each principal component, Y is the standardized score of ∑PCDD/Fs, and a_i and b are the regression coefficient and constant of the method, respectively. C is the contributions of each principal component to ∑PCDD/Fs.

The results suggested that IC, EAFs and ALSs, UGFVs, ALSs, and HSWIs were key sources of PCDD/Fs in ambient air of Suzhou City, accounting for 13.2, 16.7, 35.5, 19.4, and 15.2% of ∑PCDD/Fs, respectively.

Source categories and source contributions of PCDD/Fs based on the PMF method

The PMF method was also used to apportion the sources of PCDD/Fs in ambient air, and the results are listed in Fig. 4.

Factor 1 was characterized by high loadings of 2,3,7,8-T4CDF and 2,3,4,7,8-P5CDF, which were important indicators of EAFs (carbon steel) (Hofstadler et al. 2000).

Consequently, factor 1 was selected to represent EAFs (carbon steel).

Factor 2 has high positive loadings for 2,3,7,8-T4CDD, O8CDD, and 2,3,4,7,8-P5CDF. The composition profile of factor 2 was consistent with the result of PC3 of PCA. Consequently, factor 2 was selected to represent UGFVs.

Factor 3 was heavily loaded with 2,3,7,8-T4CDD, 1,2,3,7,8-P5CDD, and 1,2,3,4,7,8-H6CDD, and has moderate loadings of 1,2,3,6,7,8-H6CDD, 1,2,3,7,8,9-H6CDD, 1,2,3,7,8-P5CDF, and 1,2,3,4,7,8,9-H7CDF. The composition profile of factor 3 was consistent with the result of PC1 of PCA. Therefore, factor 3 was selected to represent IC. Factor 6 was characterized by high loadings of 1,2,3,4,7,8-H6CDF, 1,2,3,7,8,9-H6CDF, 2,3,4,6,7,8-H6CDF, and 1,2,3,4,6,7,8-H7CDF. PCDFs mainly originate from IC (Qi et al. 2015; Tian et al. 2008). Therefore, factor 6 was also selected to represent IC.

Factor 4 has positive loadings for 1,2,3,6,7,8-H6CDD, 1,2,3,7,8,9-H6CDD, and 1,2,3,6,7,8-H6CDF. The composition profile of factor 4 was consistent with the result of PC4 of PCA. Therefore, it was reasonable to assign factor 4 to ALSs.

Factor 5 was characterized by high loadings of 1,2,3,4,7,8,9-H7CDF, O8CDF, and 1,2,3,6,7,8-H6CDF. O8CDF was suggested to be indicator of municipal solid waste incinerators (MSWIs), and 1,2,3,4,7,8,9-H7CDF was the indicator of hospital waste incinerators (HWIs) (Lee et al. 2004). Therefore, factor 5 was selected to represent MSWIs and HWIs.

Factor 7 was heavily loaded with 1,2,3,4,6,7,8-H7CDD, 2,3,4,7,8-P5CDF, 1,2,3,7,8,9-H6CDF, and 1,2,3,4,6,7,8-H7CDF. The composition profile of factor 7 was consistent with the result of PC5 of PCA. Therefore, it was reasonable to assign factor 7 to HSWIs.

In addition, the contributions of each source to mass concentrations of PCDD/Fs were also calculated by the PMF method. The result showed that EAFs (carbon steel), UGFVs, IC, ALSs, MSWIs and HWIs, and HSWIs accounted for 10.9, 10.9, 42.8, 11.3, 10.7, and 13.4% of ∑PCDD/Fs, respectively.

Source contributions to carcinogenic potencies of PCDD/Fs based on the PMF-TEQ method

The carcinogenic potencies of PCDD/Fs from different sources were quantitatively calculated by the PMF-TEQ method. The TEQ$_{contribution}$ for the jth source was calculated by Eqs. (13) and (14) (Li et al. 2016b; Wang et al. 2015; Pekey and Dogan 2013).

$$(TEQ_{contribution})_{kj} = \sum_{i=1}^{17} \left[I{-}TEF_i \times (PCDD/F_i)_{kj} \right] \quad (5)$$

$$(PCDD/F_i)_{kj} = S_{kj} \times f_{ij} \quad (6)$$

where $(TEQ_{contribution})_{kj}$ is the contribution of the jth source to TEQ in the kth ambient air sample (pg I-TEQ N m^{-3}). $(PCDD/F_i)_{kj}$ is the estimated contribution of the jth source to the ith PCDD/F congeners in the kth ambient air sample (pg N m^{-3}); S_{kj} is the contribution of the jth source in the kth ambient air sample which was obtained in PMF, and f_{ij} is the fraction of the ith PCDD/F congeners in the jth source profile (%).

The source contributions to carcinogenic potencies of PCDD/Fs for 55 ambient samples are listed in Table 1. The contribution of each source to the carcinogenic potencies of PCDD/Fs in ambient air of Suzhou City varied according to the following order: IC (50.3%), ALSs (12.7%), UGFVs (12.3%), HSWIs (10.4%), EAFs (8.3%), and MSWIs and HWIs (6%).

Discussion

O8CDD and 1,2,3,4,6,7,8-H7CDD were the dominant contributors of ∑PCDD/Fs, and the sum of them accounted for 57.5% of ∑PCDD/Fs, but the contribution of them to TEQ was quite low (5.1%). It could be explained by the fact that although the mass concentrations of O8CDD and 1,2,3,4,6,7,8-H7CDD were higher than other congeners, the toxic equivalent factors (I-TEFs) of these two congeners were significantly lower than those of 1,2,3,4,7,8-H6CDF, 2,3,7,8-T4CDD, and 2,3,4,6,7,8-H6CDF, which leads to the result of that these two PCDD/F congeners have limited influence on TEQ.

In the present study, the TEQ of PCDD/Fs in ambient air of Suzhou City varied from 0.081 to 1.22 pg I-TEQ N m^{-3} with a mean of 0.32 pg I-TEQ N m^{-3}. Compared with the air quality limitation of PCDD/Fs in Japan (0.6 pg TEQ N m^{-3}), there were eight ambient air samples (14.5%) which exceeded the threshold value of 0.6 pg TEQ N m^{-3}, indicating that adverse effects might occur at this sample (Shih et al. 2006). In addition, most of ambient air samples were lower than the acceptable value (0.6 pg TEQ N m^{-3}), indicating no significant risk occurred.

A comparison of TEQ of PCDD/Fs in ambient air from different cities in the world is listed in Table 2. The results suggested that the TEQ of PCDD/Fs in ambient air in Suzhou City was comparable with that in some other Chinese cities, which were much higher than that in some cities of Europe and Latin America. In addition, the TEQ of PCDD/Fs in ambient air from Chinese cities was much higher than that of cities in Europe and Latin America. This could be explained by the fact that China has stepped into the latter half of the middle stage of industrialization and urbanization, so compared with other countries, China is facing with more serious environmental issues now.

In the present study, PCA-MLR suggested that IC, EAFs and ALSs, UGFVs, ALSs, and HSWIs were key sources of PCDD/Fs in ambient air from Suzhou City, accounting for 13.2, 16.7, 35.5, 19.4, and 15.2% of ∑PCDD/Fs, respectively. PMF indicated that EAFs (carbon steel), UGFVs, IC, ALSs, MSWIs and HWIs, and HSWIs accounted for 10.9, 10.9, 42.8, 11.3, 10.7, and 13.4% of ∑PCDD/Fs, respectively. According to the above discussion, it is obvious that the result of PMF has a good corresponding relation with that of PCA. And the source information from PMF was more detailed than that of PCA. PMF-TEQ suggested that IC was the largest contributor of the carcinogenic potencies of PCDD/Fs (TEQ) (50.3%).

The source apportionment based on PCA-MLR and PMF suggested that UGFVs and IC were the largest contributors to ∑PCDD/Fs in ambient air, respectively. In addition, PMF-TEQ suggested that IC was the largest contributor to the carcinogenic potencies of PCDD/Fs (TEQ). Due to the sources that are responsible for most of the environment impact (TEQ) which is much more important than the participation of ∑PCDD/Fs, the IC source of PCDD/Fs is more important than other sources of PCDD/Fs in terms of environment impact. It could be explained by the fact that the IC source of PCDD/Fs mainly comes from small-scale waste incinerator, sinter plant, and domestic heating, as most of small-scale factories did not have sufficient capital investment and technical support to control the emission of PCDD/Fs. Thus, although eliminating PCDD/Fs from IC might be the most significant way to relieve the burden of PCDD/Fs' toxicity in ambient air from Suzhou City, there are still many difficulties and challenges to achieve this objective.

In the present study, the PCDD/F exposures via inhalation of air from Suzhou City ranged from 0.044 to 0.666 pg I-TEQ kg^{-1} day^{-1} with a mean of 0.175 pg I-TEQ kg^{-1} day^{-1}, which was below the PCDD/F exposures via inhalation, dermal contact, and ingestion of soils. Han et al. (2016) indicated that PCDD/F exposures via inhalation, dermal contact, and ingestion of soils around industrial sites in China suggested that the daily PCDD/F exposure was about 0.4 pg I-TEQ kg^{-1}. In addition, the food chain was the dominant pathway for PCDD/F and DL-PCB exposure to humans (Shin et al. 2016; Li et al. 2016c). Among all potential food sources,

	Station	Electric arc furnaces	Unleaded gas-fueled vehicles	Industrial combustion	Secondary aluminum smelters	Municipal solid waste incineration and hospital waste incineration	Hazardous solid waste incineration
Table 1 Source contributions to carcinogenic potency of PCDD/Fs from different sources for 55 ambient air samples	1	0.029	0.006	0.041	0.011	0.011	0.022
	2	0.036	0.009	0.067	0.016	0.015	0.031
	3	0.052	0.019	0.139	0.031	0.024	0.059
	4	0.053	0.024	0.252	0.061	0.040	0.052
	5	0.059	0.045	0.385	0.135	0.086	0.068
	6	0.023	0.011	0.041	0.010	0.007	0.021
	7	0.028	0.014	0.056	0.013	0.009	0.031
	8	0.036	0.024	0.103	0.021	0.014	0.062
	9	0.035	0.031	0.165	0.039	0.021	0.051
	10	0.043	0.093	0.318	0.118	0.045	0.068
	11	0.016	0.016	0.048	0.008	0.005	0.015
	12	0.020	0.018	0.065	0.010	0.006	0.022
	13	0.032	0.030	0.119	0.016	0.010	0.048
	14	0.033	0.043	0.183	0.031	0.016	0.041
	15	0.035	0.121	0.386	0.092	0.035	0.055
	16	0.013	0.029	0.059	0.032	0.008	0.015
	17	0.017	0.032	0.080	0.037	0.011	0.025
	18	0.028	0.042	0.148	0.049	0.021	0.057
	19	0.026	0.070	0.276	0.097	0.033	0.046
	20	0.030	0.307	0.572	0.392	0.074	0.064
	21	0.013	0.008	0.039	0.005	0.005	0.012
	22	0.016	0.010	0.057	0.007	0.006	0.018
	23	0.021	0.019	0.111	0.012	0.009	0.035
	24	0.021	0.025	0.161	0.023	0.016	0.029
	25	0.027	0.063	0.324	0.059	0.035	0.044
	26	0.006	0.009	0.058	0.010	0.006	0.010
	27	0.009	0.011	0.085	0.015	0.009	0.017
	28	0.015	0.021	0.170	0.028	0.017	0.042
	29	0.014	0.030	0.303	0.058	0.031	0.037
	30	0.020	0.072	0.530	0.120	0.060	0.050
	31	0.015	0.013	0.043	0.007	0.005	0.015
	32	0.019	0.015	0.061	0.010	0.007	0.024
	33	0.025	0.027	0.116	0.017	0.012	0.050
	34	0.024	0.036	0.179	0.032	0.018	0.039
	35	0.031	0.098	0.354	0.085	0.038	0.057
	36	0.015	0.014	0.046	0.006	0.005	0.009
	37	0.018	0.014	0.052	0.007	0.005	0.012
	38	0.024	0.019	0.080	0.010	0.007	0.017
	39	0.025	0.036	0.144	0.021	0.012	0.016
	40	0.029	0.108	0.334	0.067	0.029	0.026
	41	0.009	0.023	0.060	0.007	0.005	0.008
	42	0.011	0.024	0.069	0.008	0.006	0.013
	43	0.018	0.033	0.108	0.013	0.009	0.028
	44	0.019	0.058	0.187	0.024	0.016	0.023
	45	0.021	0.171	0.450	0.071	0.037	0.038
	46	0.016	0.012	0.040	0.008	0.005	0.015
	47	0.020	0.014	0.054	0.010	0.006	0.022

Table 1 (continued)

Station	Electric arc furnaces	Unleaded gas-fueled vehicles	Industrial combustion	Secondary aluminum smelters	Municipal solid waste incineration and hospital waste incineration	Hazardous solid waste incineration
48	0.029	0.024	0.099	0.015	0.009	0.045
49	0.030	0.033	0.148	0.028	0.014	0.037
50	0.033	0.103	0.316	0.096	0.030	0.050
51	0.034	0.007	0.045	0.009	0.009	0.021
52	0.041	0.010	0.070	0.013	0.012	0.029
53	0.060	0.021	0.141	0.025	0.019	0.051
54	0.063	0.027	0.235	0.049	0.030	0.046
55	0.068	0.056	0.386	0.108	0.059	0.061
Mean	0.027 (8.3%)	0.041 (12.3%)	0.166 (50.3%)	0.042 (12.7%)	0.020 (6.0%)	0.035 (10.4%)

fish was suggested to be the major route of PCDD/F and DL-PCB exposures (Perelló et al. 2012). And the value of dietary exposure to PCDD/Fs via intake of fish was 0.25 pg WHO-TEQ kg^{-1} day^{-1}, which was slightly higher than that of the present study and accounted for 28.0% of dietary exposure in Spain (Perelló et al. 2012). Compared with the value of tolerable daily intake (TDI 4 pg WHO-TEQ kg^{-1} day^{-1}) in Korea, the PCDD/F exposure via inhalation of air was negligible (Shin et al. 2016).

Conclusions

In the present study, source contributions to total concentrations and carcinogenic potencies of PCDD/Fs in ambient air from Suzhou City, China, were studied. Source apportionment suggested that industrial combustion, electric arc furnaces and secondary aluminum smelters, unleaded gas-fueled vehicle sources, and hazardous solid waste incinerators were individuated as the primary PCDD/F contributors. The TEQ of PCDD/Fs in ambient air in Suzhou City was found to be

Table 2 Comparison of TEQ of PCDD/Fs in ambient air from different cities in the world

Areas	Period	TEQ (mean)	References
Shanghai City, China	2013	Summer 0.011–0.259 (0.063) pg WHO-TEQ N m^{-3} Winter 0.0241–0.154 (0.083) pg WHO-TEQ N m^{-3}	Tian et al. 2015
	2006	0.143–0.497 (0.268) pg I-TEQ N m^{-3}	Li et al. 2008a
Beijing City, China	2006	0.018–0.644 (0.268) pg I-TEQ N m^{-3}	Li et al. 2008b
Tianjin City, China	2008–2009	0.004–0.325 (0.091) pg I-TEQ N m^{-3}	Ding et al. 2013
Guangzhou City, China	2004–2005	0.058–1.280 (0.367) pg I-TEQ N m^{-3}	Yu et al. 2006
Chongqing City, China	2011	0.017–0.210 (0.094) pg I-TEQ N m^{-3}	Zhang et al. 2014
Shenzhen City, China	2009	0.014–0.290 (0.135) pg I-TEQ N m^{-3}	Wang et al. 2010
Taiwan Province, China	2003	0.006–0.150 pg I-TEQ N m^{-3}	Lee et al. 2004
Porto City, Portugal	2001–2014	0.008–0.904 (0.145) pg WHO-TEQ m^{-3}	Coutinho et al. 2015
Manizales City, Colombian	2012–2013	0.00444–0.0721 pg WHO-TEQ m^{-3}	Cortés et al. 2014
São Paulo City, Brazil	2010–2015	0.006–0.031 pg WHO-TEQ m^{-3}	Tominaga et al. 2016
Brescia City, Italy		0.04–0.05 pg WHO-TEQ m^{-3}	Colombo et al. 2013
Catalonia City, Spain	2005–2006	0.008–0.024 pg WHO-TEQ m^{-3}	Mari et al. 2008
Suzhou City, China	2016	0.081–1.22 (0.32) pg I-TEQ N m^{-3}	Present study

comparable with other Chinese cities, but higher than that in some cities of Europe and Latin America.

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