



Source Apportionment of Personal Exposure to Carbonyl Compounds and BTEX at Homes in Beijing, China

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ABSTRACT

Concentrations of carbonyl compounds (formaldehyde, acetaldehyde, acrolein and acetone) and BTEX (benzene, toluene and xylenes) were monitored at 128 residential homes (255) in Xicheng district, Beijing, during the period of November–December 2009. The indoor concentrations of formaldehyde, acetaldehyde, acrolein, acetone, benzene, toluene and xylenes were in the ranges of 1.3–85.6 $\mu\text{g}/\text{m}^3$, 0.7–102.0 $\mu\text{g}/\text{m}^3$, 0.3–102.1 $\mu\text{g}/\text{m}^3$, 0.1–25.1 $\mu\text{g}/\text{m}^3$, 1.0–47.5 $\mu\text{g}/\text{m}^3$, 1.3–86.0 $\mu\text{g}/\text{m}^3$ and 0.2–78.7 $\mu\text{g}/\text{m}^3$, respectively. The concentrations of all species during the investigation period were below the Chinese guideline values. Based on the measured concentrations, a receptor model (PMF; positive matrix factorization) coupled with the source information was applied to identify the major emission sources. The results showed that four major sources were identified by the PMF method, including (1) outdoor incursion factors, (2) emissions from building materials and paint solvent, (3) emissions from particle board and plywood flooring and (4) emissions from household cleaning chemicals. Our results also reveal that the health risks due to exposure to formaldehyde and benzene for Beijing residents were greater during this period than those for people living in Guangzhou and Hangzhou, China.

Keywords: Indoor air pollution; Carbonyl compounds; BTEX; PMF; Source.

INTRODUCTION

Among indoor volatile organic compounds (VOCs), the chemical families of carbonyls and BTEX are of interests (Dassonville *et al.*, 2009; Zhang *et al.*, 2012). The Environmental Protection Agency of USA has listed carbonyls and BTEX as hazardous air pollutants to human (George *et al.*, 2011). BTEX have been found to affect the immune, and central nervous system (brain), liver and kidneys (Karakitsios *et al.*, 2007; Sarigiannis *et al.*, 2009; George *et al.*, 2011). Some studies have suggested associations between ambient carbonyls and adverse health outcomes (Sarigiannis *et al.*, 2011). Numerous indoor sources of BTEX and carbonyls have been well documented, including off-gassing from furniture made of wood-pressed products, paints, floor varnishes glues, smoking, cooking and consumer products for cleaning, pest management, deodorizing, and personal care, etc. (Logue *et al.*, 2011; Sarigiannis *et al.*, 2011;

Vlachokostas *et al.*, 2011). Many studies have revealed that new decoration made remarkable contribution to indoor BTEX and carbonyls (Dassonville *et al.*, 2009; Guo *et al.*, 2009). Marchand *et al.* (2006) investigated the concentrations of carbonyls in 162 France homes related to the concentration of aldehyde, and found significant positive correlation between the presences of new coatings and formaldehyde concentrations. Clarisse *et al.* (2003) also mentioned the influence of new coverings of walls and ground on the aldehydes concentrations at homes in France.

Receptor-oriented models are expected to distinguish individual source contribution to VOCs based only on the concentrations of various pollutants and the chemical composition of emissions, or source profiles (Cai *et al.*, 2010; Choi *et al.*, 2011). The models have been widely used to identify the origins of outdoor air pollutants (Song *et al.*, 2006; Song *et al.*, 2007). Miller *et al.* (2002) have used four receptor-oriented source apportionment models (chemical mass balance, principal component analysis/absolute principal component scores, positive matrix factorization and graphical ratio analysis) to estimate sources' contribution to VOCs pollution based on Monte Carlo sampling. They found that most factor profiles extracted from the positive matrix factorization (PMF) closely represented the major sources.

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Based on the data collected from the 1980 to 1984 in New Jersey and California and the 1987–1990 CA Indoor Exposure study, Anderson *et al.* (2002) also used receptor-oriented models to identify sources contributing to personal exposure concentrations of toxic VOCs, and to estimate the relative contribution of each source.

Nowadays, human activities have greatly enhanced the concentrations of indoor and outdoor air pollutants, especially in China (Kim *et al.*, 2007; Santarsiero and Fuselli, 2008; Lu *et al.*, 2010; Han *et al.*, 2011). Serious outdoor air pollution in most of Chinese cities has aroused great attention to public and government in recent years. This, has pushed stricter air quality standard to be legislated (Zhang *et al.*, 2012). However, the guideline values for indoor air pollutants such as formaldehyde, acetaldehyde and benzene are quite differently recommended by some EU member states, USA and Chinese governments (Sarigiannis *et al.*, 2011). Taking benzene for example, the 24-h average value proposed in Flanders is $2 \mu\text{g}/\text{m}^3$, but $110 \mu\text{g}/\text{m}^3$ in China. In view of public health, the existence of concentrations under Chinese guideline would also imply carcinogenic risks of 2 to 3 magnitude higher than the acceptable risk of 10^{-6} . It is thus emergent to consider personal exposure limit levels of air pollutants at a public concern in China (Sarigiannis *et al.*, 2011). Study on source contribution of personal exposure to indoor pollutants of BTEX and carbonyl compounds can provide useful information to reflect the source burden on human health.

In this study, indoor concentrations of BTEX and carbonyl compounds were measured at 128 residential homes (255) with decoration age longer than > 5 years in Beijing. Based on the data measured, PMF model was applied to identify the contribution sources and estimate individual source contribution.

METHODOLOGY

Study Design

Based on house type and locations with relatively high population density, total 128 homes were selected to be investigated from 15 November and 20 December 2009. Without industry sources nearby, the sampling homes distribute on seven locations in Xicheng district (Fig. 1), about 10km southwest of downtown. The concentrations of BTEX and carbonyls were only measured at living room and cooking room. Samplers were placed in the center of the rooms with an inlet height of 1.5 m above the floor. In addition, to simulate the real situation of each home, all doors and windows were closed, and no mechanical ventilation systems were turned on during sampling period. The room temperature in winter was maintained by the district heating network at about $18\text{--}20^\circ\text{C}$. In the kitchen, natural gas was used as energy for cooking. Outdoor and indoor air samples were collected simultaneously for some homes for comparison. The questionnaire containing 30 questions about building conditions, residential life-style, residence time and indoor situations was completed by the participants.

Sample Collection and Analytical Methods

Concentrations of gaseous carbonyls were measured with the widely used derivative technique (Pang and Mu, 2006; Wang *et al.*, 2010). Air sample was pumped through a cartridge filled with silica, which was coated with an acidified solution of 2,4-dinitrophenylhydrazine (2,4-DNPH). Hydrazones, the reaction product of 2,4-DNPH and carbonyls, were quantified using high performance liquid chromatography (HPLC). Based on the HPLC program used in our previous study (Liu *et al.*, 2010), four kinds of lower carbonyl compounds (formaldehyde, acetaldehyde,

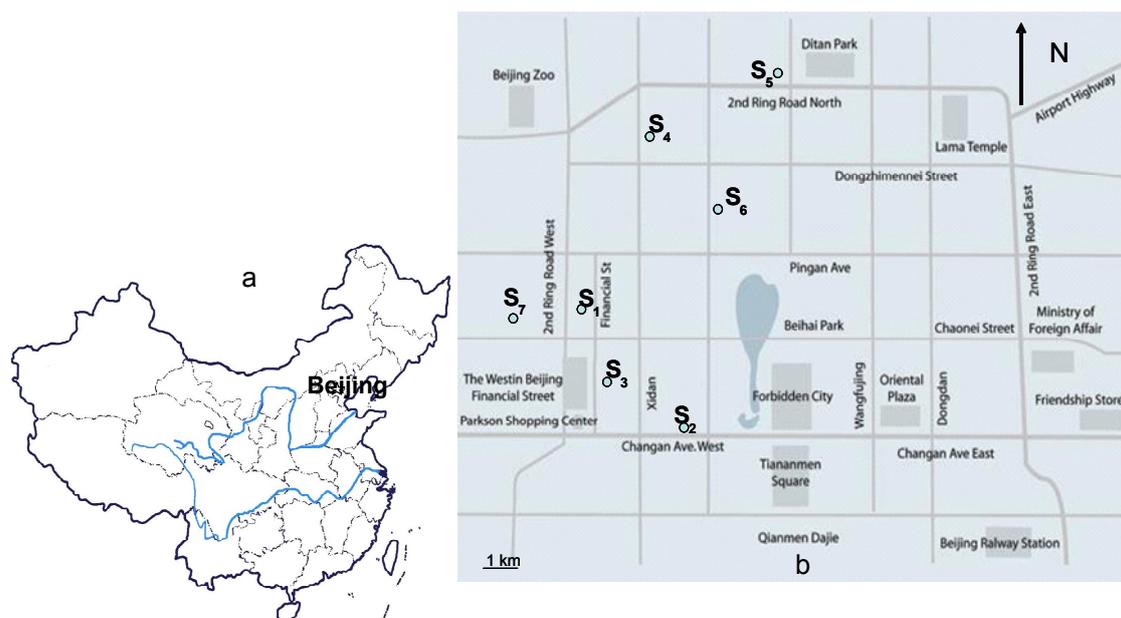


Fig. 1. Sketch map of sampling sites. (a) Location of Beijing in China. (b) Locations of sampling sites in Beijing. S1 Yutan Beijie residence area, S2 Xirongxian Hutong residence area, S3 Jingrongjie residence area, S4 Xinjiekou residence area, S5 Anbei residence area, S6 Huangchenggen residence area, S7 Sanlihe residence area.

acrolein and acetone) were determined here. To prevent any consumption of hydrazones by reaction with ozone which may lead to an underestimation of carbonyls concentrations, a pyrex cartridge filled with pure KI was placed before the entrance of the DNPH cartridge, to trap ozone. Air sampling was carried out for 60 min from 9:00 am to 10:00 am at a flow rate of 5 L/min which was calibrated at a flow calibrated meter (Agilent, 5850S, USA). Identification of carbonyl compounds was conducted by comparing the retention times between the samples and a standard solution (Accustandard Inc, USA). Quantification was performed by the ratios of the peak areas for the air samples to those of the standards. Cartridge collection efficiency was determined with two cartridges in a series, and over 99% of carbonyl compounds were found in the first cartridge, indicating almost no breakthrough of the first cartridge. Relative percent differences for duplicate analysis were less than 5%. Based on three times signal to noise, detection limits for formaldehyde, acetaldehyde, acrolein and acetone were calculated to be 0.01, 0.02, 0.05 and 0.04 $\mu\text{g}/\text{m}^3$, respectively. For BTEX (benzene, toluene and xylenes), samples were collected by the commercial active carbon adsorption tube (Kechuang Chromatograph Instrument Co., Ltd., Shanghai, China). Air sampling was carried out at 3 L/min for 30 min. BTEX in the adsorption tube were extracted by CS_2 and injected into an Agilent 6890 gas chromatography coupled with an Agilent 6890 mass-selective detector. A DB-5 capillary column, 60 m \times 320 μm \times 1.0 μm , was used for separation. The initial temperatures was held at 40°C for 2 min, and then increased at a rate of 8 °C/min to 210°C and held for 5 min. The compounds of interest were identified using their retention times and mass spectra (Lu *et al.*, 2010). The method detection limits (with a signal to noise ratio of 3) for the benzene, toluene and xylenes were 0.03, 0.06 and 0.12 $\mu\text{g}/\text{m}^3$, respectively. For BTEX determination at concentration of 3 $\mu\text{g}/\text{m}^3$, the relative standard deviations of seven repeated measurements were 3.2% (one day) and 5.6% (inter-day).

PMF Model

PMF assumes that concentrations at receptor sites are impacted by the linear combinations of source emissions, which are derived as factors in the model. In this study, PMF was applied to carbonyls and BTEX that were collected at sampling sites to identify emission sources and quantify the contributions of these sources. We used a PMF 3.0 for the current analysis, as shown in Eq. (1):

$$X_{ij} = \sum_{k=1}^p g_{ik} \cdot f_{kj} + e_{ij} \quad (1)$$

The data set can be expressed as a matrix X of i by j dimensions, where i is the number of samples and j is the species measured. Additionally, g_{ik} is the concentration of BTEX and carbonyls, f_{kj} is the mass fraction, e_{ij} is the residual of the j_{th} species concentration measured in the i_{th} sample, and p is the total number of the independent factors. The objective of a PMF analysis is to determine the number of factors, p , the chemical composition profile, f_k ,

the factor contributions, and g_{ik} , residuals. Concentrations (X_{ij}) and their associated uncertainties were prepared according to the method suggested by Reff *et al.* (2007). The PMF 3.0 determines signal-to-noise ratio (S/N) statistics for every input species and allows the user to downgrade the importance or remove species with small S/N values. All seven measured species in this study were found to have S/N levels more than 2 and considered as “strong”. Detailed discussions about the PMF model have been previously reported in the literature (Song *et al.*, 2007; Sarnat *et al.*, 2008; Zhang *et al.*, 2009).

RESULTS AND DISCUSSION

Concentrations of Carbonyl Compounds and BTEX

One hundred and twenty eight homes (255 indoor air samples) with decoration age longer than > 5 years, were selected in this study, and all buildings were built before 1990. The carbonyls and BTEX were detected in almost all samples. Arithmetic mean concentrations of the carbonyl compounds and BTEX were listed in Table 1. Formaldehyde was the most abundant carbonyl in most of samples and accounted for 34%–56% of the total indoor carbonyl concentrations. Its concentration varied from 1.3 to 85.6 $\mu\text{g}/\text{m}^3$, keeping within the guideline values of 100 $\mu\text{g}/\text{m}^3$ in China (Lu *et al.*, 2006) No statistic difference of the carbonyls between the living rooms and cooking rooms was found. This might be due to no cooking, occurred during the sampling. The three principal carbonyls, formaldehyde, acetaldehyde and acetone, accounted for 78–82% of the total indoor carbonyl concentrations. According to previous studies, typical indoor concentrations ranged from 1.03 to 7.55 $\mu\text{g}/\text{m}^3$ for formaldehyde and 4.5 to 66.8 $\mu\text{g}/\text{m}^3$ for acetaldehyde in Guangzhou, China (Lu *et al.*, 2010). The maximum formaldehyde concentration (468.9 $\mu\text{g}/\text{m}^3$) was recorded in Hong Kong Homes (Guo *et al.*, 2009). Formaldehyde concentrations in this study were lower than that in Hong Kong (Guo *et al.*, 2009), in Japan (Ohura *et al.*, 2006) and in Taiwan (Jia and Yao, 1993).

The most important indoor sources of carbonyls are cigarette smoke, insulating materials, particle board, adhesives containing carbonyls, cooking and outdoor invasion (Sarigiannis *et al.*, 2011). Carbonyl compounds may also be emitted by gas cookers and open fireplaces. In this study, cigarette smoking excluded as smoking was not permitted indoors during air sampling. As shown in Table 1, the outdoor concentrations of acetone and acrolein were higher than those in indoor air, but outdoor formaldehyde was occasionally higher than those in the indoor. It should be underlined that the indoor concentrations of acetone and acrolein were strong correlated with outdoor sources. Nevertheless, indoor concentration/outdoor concentration of formaldehyde and acetaldehyde (I/O) ratios showed large variations. For example, I/O ratios for the median concentrations of formaldehyde was > 1.0 at homes, but < 1.0 for the median concentrations of acetaldehyde with or without ventilation system. This was expected that the main source of acetaldehyde was from outdoor emission in most samples.

Table 1. Concentrations of carbonyl compounds and BTEX ($\mu\text{g}/\text{m}^3$) with the corresponding compound concentrations per home.

Compounds	Sampling localization	N*	Concentration range	Arithmetic mean value	Standard deviation	p^a	Ventilation	n	Arithmetic mean value	Standard deviation	p^a	Outdoor value	I/O Ratio ^b
Formaldehyde	Living room	130	1.3–85.6	15.8	10.2	0.142	opened	167	17.2	15.2	$p^a = 0.189$	15.4	> 1.0
	Cooking room	125	1.3–85.1	16.6	11.2		closed	88	16.1	12.6		15.4	> 1.0
Acetaldehyde	Living room	130	0.7–102.0	13.2	8.1	0.231	opened	167	13.9	9.8	$p^a = 0.202$	12.4	> 1.0
	Cooking room	125	0.7–84.0	14.0	9.3		closed	88	13.2	8.5		12.4	> 1.0
Acetone	Living room	130	0.3–102.1	10.2	8.4	0.314	opened	167	10.1	7.8	$p^a = 0.225$	10.2	< 1.0
	Cooking room	125	0.3–92.1	9.7	5.6		closed	88	9.6	7.3		10.2	< 1.0
Acrolein	Living room	130	0.1–25.1	2.1	1.7	0.312	opened	167	2.4	1.9	$p^a = 0.236$	3.9	< 1.0
	Cooking room	125	0.1–15.2	2.3	3.4		closed	88	2.1	2.1		3.9	< 1.0
Benzene	Living room	130	1.0–47.5	10.2	8.1	0.214	opened	167	10.3	5.7	$p^a = 0.453$	7.6	> 1.0
	Cooking room	125	1.2–45.9	9.2	6.9		closed	88	9.6	6.1		7.6	> 1.0
Toluene	Living room	130	1.3–75.6	17.7	10.5	0.304	opened	167	17.5	12.9	$p^a = 0.265$	14.3	> 1.0
	Cooking room	125	1.4–86.0	16.9	9.7		closed	88	16.8	12.2		14.3	> 1.0
Xylenes	Living room	130	0.2–75.6	10.8	7.0	0.327	opened	167	11.8	3.7	$p^a = 0.363$	13.1	< 1.0
	Cooking room	125	0.2–78.7	11.2	6.3		closed	88	12.0	3.7		13.1	< 1.0

^a n , number of sampling sites, one sample was missing; p^a is derived from the Student test; I/O Ratio^b, mean indoor concentration/outdoor concentration.

The concentrations of toluene and xylenes (o,m,p-xylenes) varied from 1.3 to 75.6 $\mu\text{g}/\text{m}^3$, 0.2 to 75.6 $\mu\text{g}/\text{m}^3$ in living room and 1.4 to 86.0 $\mu\text{g}/\text{m}^3$, 0.2 to 78.7 $\mu\text{g}/\text{m}^3$ in cooking rooms, respectively. Toluene was the most abundant component among BTEX, followed by xylenes. Benzene exhibited lower concentration ranging from 1.0 to 37.5 $\mu\text{g}/\text{m}^3$ in living rooms and 1.0 to 45.9 $\mu\text{g}/\text{m}^3$ in cooking rooms. Benzene has been widely used as an industrial solvent in paints, varnishes, lacquer thinners and gasoline. Therefore, benzene could be easily detected in almost all indoor environments. The highest benzene concentration in Europe (109 $\mu\text{g}/\text{m}^3$) was reported by a comparative study on indoor air VOCs concentration between public offices in Europe and Singapore (Sarigiannis *et al.*, 2011). The mean concentration of benzene in all European buildings studied was 14.6 $\mu\text{g}/\text{m}^3$, while in Singapore the mean value was 87.1 $\mu\text{g}/\text{m}^3$. Toluene has been used as a solvent in a variety of household products such as paints, rubbers and adhesives. Toluene is almost always present in indoor air in detectable concentrations, which range from 0.3 $\mu\text{g}/\text{m}^3$ to 358 $\mu\text{g}/\text{m}^3$. The highest value was observed in a hospital room in Germany due to the extensive use of cleaning products. In residential houses, typical concentrations of toluene range from 4 $\mu\text{g}/\text{m}^3$ to 50 $\mu\text{g}/\text{m}^3$. Xylenes (o,m,p-xylenes) are widely used in the chemical industry as solvents for products such as paints, rubbers and adhesives. Xylenes are also emitted in the indoor environment as a result of cigarette smoking. In another study dealing with new apartments, xylenes were found to be the most abundant VOCs (mean concentration 160 $\mu\text{g}/\text{m}^3$). Currently, the guideline values in China for indoor concentration of BTEX are 110 $\mu\text{g}/\text{m}^3$ for benzene, 200 $\mu\text{g}/\text{m}^3$ for toluene and 200 $\mu\text{g}/\text{m}^3$ for xylenes (Sarigiannis *et al.*, 2011). Clearly, the concentrations of benzene found in Beijing houses are far lower than the guideline values. Moreover, there are no significant differences to be found between living and cooking rooms for BTEX. By comparison of the indoor and outdoor of BTEX concentrations (Table 1), it was found that, except xylenes, the ratios of indoor/outdoor for BTEX were all > 1.0, mainly owing to indoor source emissions for most compounds (e.g., emission of decoration materials, paint organic solvent and household cleaning chemicals).

PMF Results

This study considered 2 to 6 factors with rotational parameter values between -0.3 and 0.3 at 0.1 intervals. The PMF solutions were assessed according to the distributions of the scaled residuals, correlations between the source contributions and the temporal variations of each factor.

The 3-factor solutions produced a factor dominated with BTEX which also contained approximately 20% of ambient formaldehyde. Additionally, this factor contributed more than 70% of total concentrations. Consequently, this factor was associated with known solvents, cleaning chemicals and building material tracers, suggesting that the 3-factor solution merged these into a signal factor.

By increasing the number of allowed factors, the aforementioned factor was split into three factors: one dominated by benzene and the other two factors were the

dominant source of toluene and xylenes. Therefore, solutions having 5 or more factors probed BTEX better than 3-factor case. The 6-factor solutions further split the factor associated with toluene dominated factor, and generated an unknown factor. In this study, 5-factors were chosen as the optimal number for the PMF models (Fig. 2). Detailed results for PMF indicate that minimum R^2 value of 0.97 and minimum signal to noise ratio of 2.5 are both above the respective thresholds of 0.80 and 2.0 recommended for a good model. The factors contributing most to the total personal exposure concentrations at homes in Beijing and appearing across multiple models were interpreted as five different sources or combinations of sources based on a qualitative comparison to emissions or exposure profiles reported in the literature (Anderson *et al.*, 2002). Precise matches with profiles reported in the literature were not expected due to variability in the reported profiles and the fact that carbonyls and BTEX can undergo chemical degradation from the time they are emitted (Sarigiannis *et al.*, 2011). The five most significant sources appear to be concluded.

The factor 1 had high values of acetaldehyde, acetone and acrolein. Because I/O ratios of acetone and acrolein showed main determinants of indoor levels were from outdoor emissions. The factor 1 was considered as emission

from outdoor air. Considering acetaldehyde, unexpected high contribution (80.3%) was extracted by factor 1, proving the major existence source was from outdoor emissions in this study (Fig. 3 and Table 2). The factor 2 in Fig. 1 was characteristic by high xylene values. Since I/O ratios showed indoor levels of xylenes were mainly from outdoor emission. The factor 2 was mainly considered as outdoor emission factor II. This source extracts 85.5% of xylenes concentrations. In the factor 3, the value of benzene is high. Since benzene was a major constituent of building material and paint solvents (Vlachokostas *et al.*, 2011), the factor 3 was primarily resulted from building material and paint solvent source. It was noticed that high relative contributions with 82.4% was obtained from factor 3. Other compounds all contributed small percentages, ranging from 0.4% (xylenes) to 3.7% (acetaldehyde). The factor 4 was dominated by formaldehyde, this specie was closed related to particle board and plywood flooring usage (Kim *et al.*, 2007). Thus, the factor was primarily resulted from particle board and plywood flooring usage. High contribution of formaldehyde to this factor was calculated as 84.7%, whilst similar small relative contribution of other compounds were obtained for acetaldehyde (6.4%), actone (4.0%), acrolein (4.0%), benzene (4.5%), toluene (3.8%) and xylenes (1.2%), respectively. In

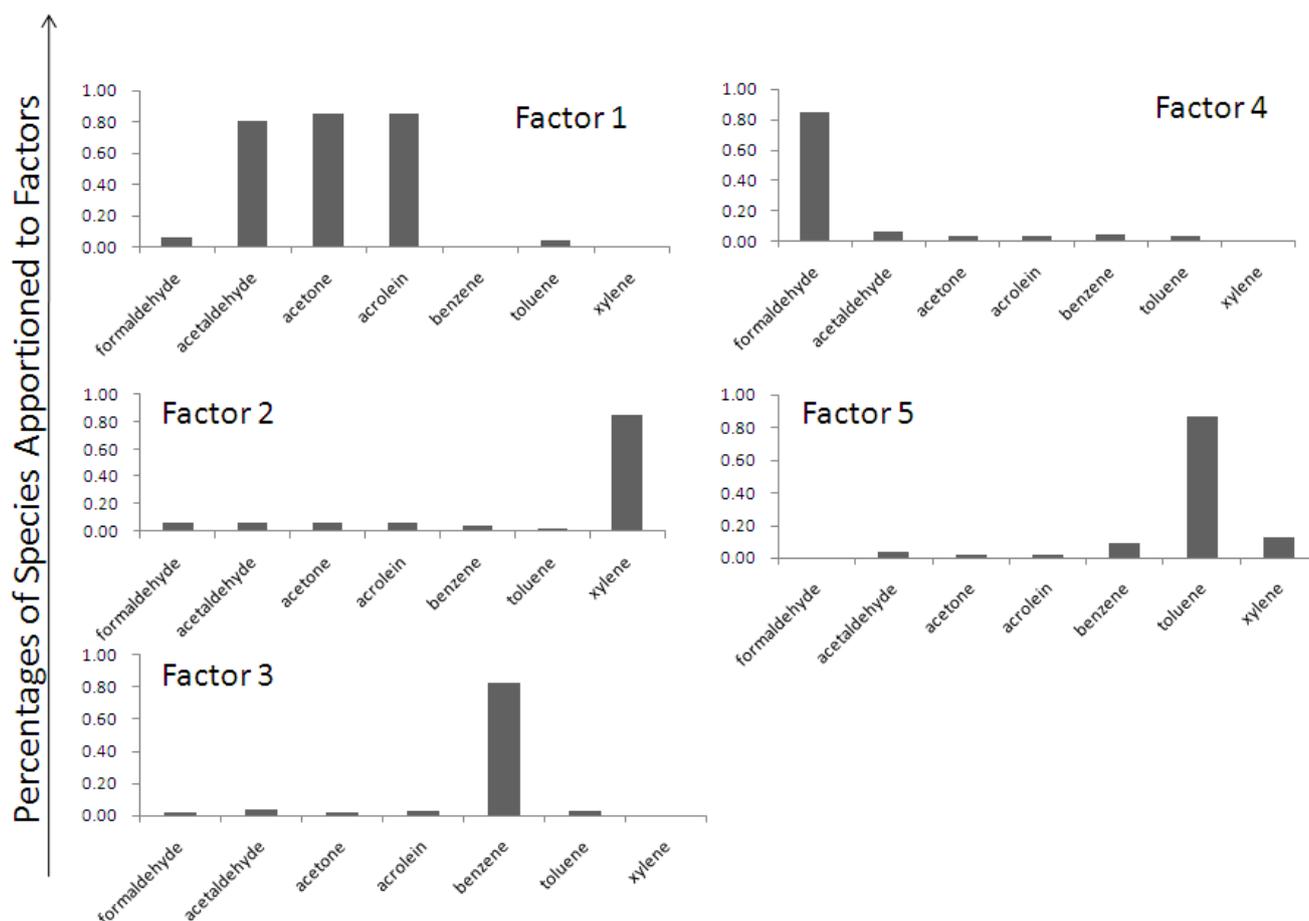


Fig. 2. PMF factorization results (mass fractions) for personal exposure to carbonyls and BTEX ($n = 255$). Performance statistics: $R^2 > 0.97$ and %mass $> 75\%$ for total carbonyl and BTEX concentrations; Q (robust) = 1551.6, Q (true) = 2253.1 for individual species concentrations.

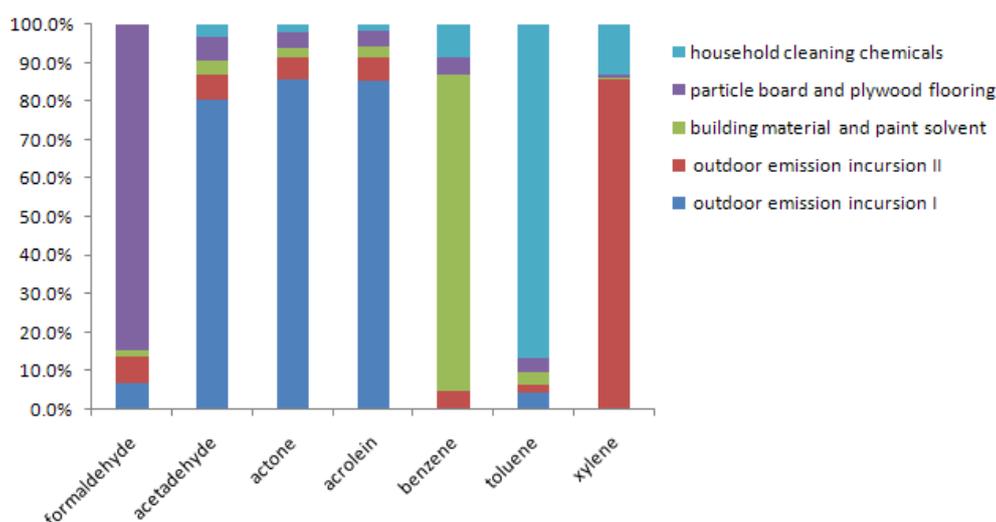


Fig. 3. Average source contributions (%) of personal exposure to carbonyls and BTEX.

Table 2. Average source contributions (%) of personal exposure to carbonyls and BTEX.

Source factor	Formaldehyde	Acetaldehyde	Acetone	Acrolein	Benzene	Toluene	Xylenes
Outdoor emission incursion I	6.6%	80.3%	85.6%	85.4%	0	4.2%	0
Outdoor emission incursion II	6.9%	6.4%	5.9%	6.0%	4.6%	2.1%	85.5%
building material and paint solvent	1.8%	3.7%	2.5%	2.9%	82.4%	3.1%	0.4%
particle board and plywood flooring	84.7%	6.4%	4.0%	4.0%	4.5%	3.8%	1.2%
household cleaning chemicals	0	3.3%	1.9%	1.7%	8.5%	86.8%	12.8%

Table 3. Average concentrations and estimated daily intakes (E) and health risks of formaldehyde, acetaldehyde and benzene in indoor air.

Parameter	Formaldehyde			Acetaldehyde			Benzene		
	C ^a ($\mu\text{g}/\text{m}^3$)	E ^b ($\mu\text{g}/\text{d}$)	Risk	C ($\mu\text{g}/\text{m}^3$)	E ($\mu\text{g}/\text{d}$)	Risk	C ($\mu\text{g}/\text{m}^3$)	E ($\mu\text{g}/\text{d}$)	Risk
This work	16.4	103	3.7×10^{-4}	13.6	85	5.1×10^{-5}	9.7	61	0.9×10^{-4}
Ballroom ^c	33.1	124	4.4×10^{-4}	100	378	2.3×10^{-4}	N/A ^g	N/A	N/A
Bus stations ^d	16.6	83.5	2.2×10^{-4}	12.3	62.1	2.7×10^{-5}	N/A	N/A	N/A
Living room ^e	37.0	N/A	N/A	15.0	N/A	N/A	N/A	N/A	N/A
Homes ^f	112.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

^a Arithmetic mean; ^b A mean residence time of 10 h was considered in this work; ^c Guangzhou, China; ^d Xalapa, Mexico; ^e Hangzhou, China; ^f Strasbourg area, France; ^f Hong Kong; ^g Not available.

the factor 5, toluene was dominated accounted for 86.8%. This compound was related to household cleaning chemicals (Sarigiannis *et al.*, 2011; Vlachokostas *et al.*, 2011). In the case of other compounds, similar small relative contributions were found, ranging from 0 (formaldehyde) to 12.8% (xylenes). Overall, factors corresponding to the first five of these sources appeared in both data sets. Detailed results showed PMF agreed well with data sheets.

There were only scarce literatures information available for carbonyls and BTEX measured at homes and monitoring was restricted to formaldehyde and acetaldehyde. Our measurements for formaldehyde and acetaldehyde at homes in Beijing were lower than those determined in Strasbourg area, France (Marchand *et al.*, 2006) and Hong Kong (Guo *et al.*, 2009) (Table 3). It was worth to emphasize that those results were obtained from the measurements in these cities using different same sampling and analytical method (Guo

et al., 2009) or in different seasons (Marchand *et al.*, 2006). Thus, the indoor levels of formaldehyde and acetaldehyde in different countries and regions were less comparative. Due to the largely differences, cancer risk of personal exposure to formaldehyde, acetaldehyde and benzene was selected in this study to compare with relevant health guidelines and existing literatures.

The relevant metric for assessing the risk of the carcinogenic compounds was the estimated lifetime cancer risk (R), derived by the methodology proposed by the US EPA. The given formula is $E = C_j IR_j t_{ij}$, where C is the exposure concentration in $\mu\text{g}/\text{m}^3$, IR is the inhalation rate (m^3/h), t is the exposure time (h/d), and j is the microenvironment room. Based on information collected via questionnaires, people usually spend 8–12 hours (length exposure) at their homes. Average personal indoor inhalation rates were estimated as $IR = 0.63 \text{ m}^3/\text{h}$. A mean residence time of 10 h was considered

as exposure time based on the questionnaires in this study.

The results of average concentrations, estimated daily intakes and health risks were shown in Table 3. The mean cancer risk at homes in this work was 3.7×10^{-4} for formaldehyde, 5.1×10^{-5} for acetaldehyde and 0.9×10^{-4} for benzene, respectively, which are all magnitude higher than the European commonly acceptable risk of 10^{-6} (Cavalcante et al., 2006; Sarigiannis et al., 2011). Average exposure for formaldehyde at homes in Beijing was 1.1 and 1.7 times higher than that in ballrooms in Guangzhou, China and bus station in Hangzhou, China (Feng et al., 2005; Weng et al., 2009). The average cancer risk for acetaldehyde observed at homes was 5.1×10^{-5} , which is lower than in ballrooms in Guangzhou, China, but slightly higher than that the bus station in Hangzhou, China (Feng et al., 2005; Weng et al., 2009). In this study, building material, paint solvents, particle board and plywood flooring sources were found to be important contributor to personal exposure to benzene and formaldehyde. Thus, green usage of building material was indeed widely used in Beijing.

CONCLUSIONS

In this study, the concentrations and source apportionment of carbonyl compounds and BTEX in indoor air at homes in Beijing were characterized. Indoor mean concentrations mean ranged from $2.8 \mu\text{g}/\text{m}^3$ for acrolein to $18.7 \mu\text{g}/\text{m}^3$ for toluene. On average, the measured concentrations of carbonyl compounds and BTEX were not significantly different between in both living and cooking rooms, indicating that the indoor air was generally homogeneous. Based on the measured concentrations, a receptor model (PMF; positive matrix factorization) coupled with the source information is applied to identify the major emission source contributions to personal exposure at homes in Beijing. The results showed that four major sources were identified by the PMF method, including (1) outdoor incursion factors, (2) emissions from building materials and paint solvent, (3) emissions from particle board and plywood flooring, (4) emissions from household cleaning chemicals.

Personal exposure risks of carcinogenic compounds (formaldehyde, acetaldehyde and benzene) were calculated using the equation of cancer risk proposed by US EPA. Our results showed that the cancer risks for these chemicals were 1–2 magnitude higher than the European commonly acceptable risk of 10^{-6} and 1–2 times higher than that in previous studies with some exceptions. Our results also observed that human exposures to formaldehyde and benzene, which was related with building material and paint solvents and particle board and plywood flooring sources, were found to pose a higher health risk than previous studies in Guangzhou and Hangzhou, China.

ACKNOWLEDGMENTS

We thank two anonymous for their constructive suggestions and comments. Financial supports for this work have been provided by Natural Science Foundation of China (No. 41175104, 41305110) and the Earmarked Fund

of State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, CAS (LAPC-KF-2013-01). We would like to thank Dr. Jianxin Yin for revising the manuscript.

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Received for review, January 6, 2013

Accepted, June 3, 2013