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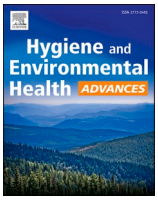

Volatile organic compounds (VOCs) in residential indoor air during interior finish period: Sources, variations, and health risks

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ABSTRACT

Building and furniture materials are significant sources of volatile organic compounds (VOCs) and determine their long-time indoor levels. However, the variations of indoor VOCs and associated health risks of interior finishers during the construction stages are poorly understood. In this study, VOCs in the indoor microenvironments were measured at different interior finishing stages at two renovated residences using thermal desorption and gas chromatography-mass spectrometry. The mean concentrations of the Σ15 VOCs were 118.2 μg/m^3 in Home A and 232.5 μg/m^3 in Home B. The simultaneous outdoor levels were approximately three times lower than indoors. The VOC concentrations were obviously lower than previous measurements in newly renovated residences, reflecting reduced use of these VOCs in interior materials. Temporal variations in the VOC concentrations during the interior finish period were compound- or room-dependent at each residence The remarkable rise in the VOC concentrations was largely affected by furniture installation at both residences. The non-cancer risks of VOC exposure were lower for both interior finishers and occupants. However, the cumulative cancer risks for interior finishers (1.2×10^{-4}) exceed the acceptable threshold limit. The occupational exposure at the wall painting stage was the highest, and formaldehyde is the most significant contributor to both cancer and noncancer risks. This study also highlights the importance of detecting novel VOCs that may be present in interior finish materials as indicated by the TVOC measurements.

Introduction

Indoor air quality plays a crucial role in human health because most people spend over 80 % of their time indoors (Gonzalez-Martin et al., 2021). Indoor pollutants can be emitted from a variety of sources, such as the interiors, fuel combustion, and cleaning supplies (Ayri et al., 2020; Bai et al., 2022; Pei et al., 2020). Recent estimates showed that 2.3–3.8 million premature deaths per year are attributable to indoor air pollution (Roser, 2021). VOCs represent a significant fraction of indoor pollutants, mainly composed of C_6–C_{16} aromatic hydrocarbons, aliphatic hydrocarbons, alcohols, aldehydes, ketones, and esters (Salthammer, 2022). Short-term exposure to high indoor concentrations of VOCs can cause health impacts such as headaches, nausea, respiratory infections, allergy, and asthma (Tsai, 2019). Some VOCs commonly present in indoor air, such as benzene, formaldehyde, and toluene, are carcinogenic to humans and are regulated by various national/international agencies (Tsai, 2019). A recent study suggested an association of neurodevelopmental delays with low-level indoor exposure to some VOCs in early life in Japan (Madaniyazi et al., 2022).

It has been demonstrated in many studies that VOC concentrations in indoor air are commonly several times higher than outdoor levels, attributed to a variety of emissions sources (Harb et al., 2018; Shin and Jo, 2012). Indoor VOC concentrations may show significant seasonal differences as their emissions are highly dependent on temperature (Bari et al., 2015; Pei et al., 2020). Indoor VOCs can be subject to photochemical reaction with indoor ozone to generate secondary organic aerosols and aldehydes (Lakey et al., 2017; Pytel et al., 2022). Of the wide range of indoor sources, interior finishes and materials, such as painting, wood floors, furniture, and appliances, constitute important VOC sources (Pang et al., 2007; Persson et al., 2019). Therefore, high indoor concentrations of VOCs have been found in new (or newly renovated) houses. Still, they can be released continuously and slowly over a long time, posing a persistent health threat to people (Pei et al., 2016; Zhang et al., 2021). Huang et al. (2019) found that floor coatings

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and solvent-based adhesives were the key VOC sources for architectural decorations in China. A study examined the longitudinal variations of indoor VOC concentrations in new apartments over a 24-month period in Korea, and most VOC concentrations showed a decreasing trend (Shin and Jo, 2013). Gallon et al. (2020) found that the future indoor air quality in a building at different construction stages depends not only on the emissions from construction materials but also on the implementation process.

Tremendous amounts of VOCs are emitted from various sources with China's rapid urbanization and industrialization (Mo et al., 2021; Zhang et al., 2017). In the meanwhile, more and more synthetic building materials and consumer products are used in new or renovated indoor places in China, implying significant reservoirs of VOCs for the indoor environment. A recent study found that the concentrations of total VOCs in 20 % of the residences in eight Chinese cities exceeded the national standard (Pei et al., 2020). VOCs in indoor air of new residences in China Indoor VOCs related to interior finishes in China have been characterized in numerous studies, (Dai et al., 2017; Du et al., 2014), highlighting indoor emissions of these pollutants. However, few have characterized the dynamics of their emissions and pollution during the finishing process. There are few studies focusing on the health risks of occupational interior finishers. China enacted in 2020 a new and more rigorous national Standard for Indoor Environmental Pollution Control of Civil Building Engineering (GB50325–2020) (Bai et al., 2022). It is necessary to evaluate its influence on the occurrence of VOCs in indoor air in China.

In this study, we investigated VOCs in indoor and outdoor air at different stages during the whole renovation processes of two urban residences. Formaldehyde was detected in selected stages. The main objectives are to reveal the temporal variations in the concentration and composition of VOCs, to identify the key emitters of VOCs and the potential links between indoor and outdoor VOCs during home renovation period, and to assess the health risks of interior finishing workers' exposure to VOCs. Currently, the risks are little known for this cohort. Such a study would expand our understandings of VOCs associated with interior finishing. It also provides suggestions for reducing human exposure and health risks.

Materials and methods

Sampling design

The sampling was conducted in Guangzhou, a megacity in South China. Guangzhou has a subtropical monsoon climate, with an average annual temperature of 22.5 ℃ and relative humidity (RH) of 76 % (GSB, 2021). Two residences (named Home A and Home B, with a distance of about 5 km) were selected (Fig. S1 in Supplementary Information). Home A is a three-bedroom apartment (80 m^2) on the 19th floor of a building adjacent to the urban main road. Home B is a two-bedroom apartment (74 m^2) on the third floor, with a big living room window facing a small garden. The floorplans are shown in Fig. S2. The remodeling and renovations of the two homes started from June 2021 lasting for approximately six months, during which the houses were not occupied. Samples were collected at different stages during the interior finish period (from wall plastering to furniture and appliance installation), particularly when suspicious sources were introduced. An additional sampling at each home was done six months after the finishing (occupied). Eight and seven sampling events were involved in homes A and B, respectively (Table 1). Air samples were obtained indoors (including the master and secondary living/dining room) and outdoors (near the two sites), respectively. The doors and windows were shut 1 h before sampling, and the rooms were kept closed during the sampling. The quality of the interior finishes and materials used at the two residences were representative of the average interior finishing level in this city. Nearly all the wood-based furniture in the two homes is made up of composite lumbers.

Table 1
Sampling information related to the interior finishes at two residences in Guangzhou City, China.

Sampling event (date)	Interior finish	Description
Home A		
E1 (10–29–2021)	Plastering	Wall plastering (ready for painting) a few days ago. Wall ceramic tiles caulking in kitchen, bathroom, and balcony one week ago.
E2 (11–01–2021)	Wall painting	Interior wall painting one day ago.
E3 (11–06–2021)	Wall painting & kitchen cabinet	The sixth day after wall painting. Kitchen cabinet (partly finished) three days ago.
E4 (11–10–2021)	Wood flooring tiles	Wood flooring tiles in bedrooms and kid's room one day ago.
E5 (11–14–2021)	Furniture	Semi-finished furniture (which had been displayed in the store for months) in master and secondary bedrooms one day ago.
E6 (11–20–2021)	Furniture	Customized furniture in living room and kid's room, a bed & mattress to each bedroom, and the rest kitchen cabinet a few days ago.
E7 (12–03–2021)	Household appliances & furniture	Household appliances and finished furniture (dining-table, chairs, and couch) in living room a few days ago. A desk in secondary bedroom. The house was ready for occupancy.
E8 (05–30–2022)		Six months after interior finishes and approximately five months after occupancy.
Home B		
E1 (10–30–2021)	Wall plastering	Wall plastering (ready for painting) a few days ago. Ceramic tiles flooring in all rooms two weeks ago. Interior doors one week ago.
E2 (11–03–2021)	Wall painting	Interior wall painting one day ago.
E3 (11–07–2021)	Wall painting & tile caulking	Wall painting five days ago. Ceramic tiles caulking one day ago.
E4 (11–14–2021)	Household appliances & furniture (move-in)	Couch and TV bench, washing machine & dryer in living room a few days ago (packed). Small domestic appliances in master bedroom (not opened). Toilet finished several days ago.
E5 (11–23–2021)	Furniture	Customized furniture (cabinets and wardrobe) in living room, master bedroom, and kitchen a few days ago. Small cabinet in bathroom one day ago.
E6 (12–06–2021)	Household appliances	Household appliances a few days ago. Mattress in secondary bedroom (packed).
E7 (29–05–2022)		Approximately six months after interior finishes and five months after occupancy.

Sampling and analysis

The procedure was performed according to the guidelines of the national standard of China (GB 50325–2020) and United States Environmental Protection Agency (USEPA) Method TO-17 (Bai et al., 2022; Huang et al., 2021). Air samples were collected on Tenax TA tubes (6.35 × 88.9 mm, 60–80 mesh, 200 mg, Markes International Ltd, UK) at a flow rate of 250 mL/min for 20 min, by two low-flow air sampling pumps (VAPex, Casella, UK). Before sampling, Tenax-TA tubes were preconditioned for 3 h at 320 °C in 50 mL/min flow of N_2, sealed with Markes Difflok caps, and stored in a sealed metal container at −4 °C in a refrigerator. The sampling height was approximately 1.2 m above the floor. All the doors and windows were closed one hour before sampling and kept closing during the entire sampling period. After sampling, the

sorbent tubes were sealed with Markes brass storage caps fitted with PTFE ferrules, wrapped with aluminum foil, and immediately transported to the laboratory in a clean container. Outdoor air samples were concurrently collected following the same protocols. The indoor temperature, relative humidity (RH), and barometric pressure were also measured at the sampling time (Table S1). The tubes were capped and analyzed in 72 h. The indoor temperature and relative humidity were also recorded (cos-03, Renzhi Inc., China). Solutions of mixed VOC standards containing fifteen compounds (Table 1) were produced by Beijing Manhage Bio-Technology Co. Ltd. These VOC species were chosen because they align with the updated Chinese indoor environmental building standards, in which these VOCs are priority chemicals. VOCs were analyzed with a thermal desorption system (TD100-xr, Markes International Ltd, UK) coupled to a gas chromatography-mass spectrometry (GC–MS, QP2020 NX, Shimadzu Corporation, Japan) equipped with an electron impact ionization source. The conditions of the thermal desorption system and GC–MS are given in Table S2. The total VOC (TVOC) concentration was also determined by quantifying all compounds eluted from hexane to hexadecane using toluene conversion. The calculations were performed using the Shimadzu TVOC Calculation Tool. Formaldehyde concentrations were monitored at the end of finishes and the intervention stages using a portable formaldehyde detector (PPM Formaldemeter-htV-m, PPM Technology Ltd, UK). This instrument measures formaldehyde using an electrochemical formaldehyde sensor consisting of two electrodes made of noble metals. The measurement range for PPM Formaldemeter was 0–10 ppm (0–12.3 mg/m^3) with a resolution of 0.01 ppm and a precision of 2 %. PPM Formaldemeter has been used for measuring formaldehyde previously (Dugheri et al., 2018; Zhou et al., 2018).

Quality control

Field blanks were taken and analyzed in each sampling event, and 15 in total were prepared. A laboratory blank was also analyzed daily using a blank tube before sample analysis. BTEX were found in the blanks with amounts <10% of those in the samples. The limits of detection (LODs) of target species were determined as three times the standard deviation of the repeated measurements of working standards with the lowest concentration, which ranged from 0.03 to 0.26 μg/m^3 (Table S3). A standard solution containing the target compounds was injected routinely for GC–MS maintenance, and their relative deviations were less than 5 %. The PPM Formaldemeter was calibrated before each sampling event with the manufacturer's supplied calibration standard in accordance with the instructions.

Data analysis

Concentration data in this study did not follow a normal distribution. Correlation analysis (spearman) was conducted by the SPSSPRO software package 1.1.11. Python's Matplotlib library was employed for graph creation. Mann−Whitney U test for statistical differences between data groups performed by Python's NumPy and SciPy libraries, and a confidence level of 95 % was applied.

Cancer and non-cancer risk assessment

Cancer and non-cancer risks associated with indoor VOC inhalation exposure were assessed for occupational interior finishers and occupants, respectively. The adjusted exposure concentration (EC_i) was calculated by Eq. (1) (USEPA, 2014; Xu et al., 2021) :

$$EC_i = \frac{CA_i \times ET \times EF \times ED}{AT} \quad (1)$$

where CA_i is the measured indoor concentration of compound i (μg/m^3); ET is the exposure time (h/d); EF is the exposure frequency (d/yr); ED is exposure duration (yr); AT is averaging time (h). For occupational interior finishers, the average concentrations during the interior finish period are used; for occupants, the halves of the concentrations six-months after the renovation are used according to the study by Liang et al. 2014a.

The ET for interior finishers is estimated to be 9 h/d based on the China statistical yearbook (2021) (NBSC, 2022). The ET for occupants is estimated to be 15 h/d according to the Exposure Factors Handbook of Chinese Population. The EFs are estimated as 350 and 310 d/yr, and the EDs are estimated as 24 and 30 yr for adult residents and interior finishers, respectively. An average lifetime of 70 years is assumed for AT.

The lifetime excess cancer risk was calculated by Eq. (2)

$$LCR_i = IUR_i \times EC_i \quad (2)$$

where LCR_i is the cancer risk associated with compound i and IUR_i is the estimated inhalation unit risk (m^3/μg) for compound i (Table S4). The non-cancer inhalation health risk was assessed by the hazard quotient (HQ) and hazard index (HI), which were calculated by Eqs (3) and (4)

$$HQ_i = \frac{EC_i}{RfC_i} \quad (3)$$

$$HI = \sum HQ_i \quad (4)$$

where RfC_i is the chronic inhalation reference concentration of compound i (Table S4). The USEPA deems health risks to be significant if cancer risk exceeds the acceptable risk (1×10^{-6} to 1×10^{-4}). A HQ or HI <1 indicates a low non-cancer risk.

Results and discussion

Concentrations and compositions

Overall concentrations and compositions

Descriptive statistics for the indoor and outdoor VOC concentrations at the two residences are shown in Table 2. The indoor concentrations of total target VOCs during the interior finishing period had a median of 50.71 μg/m^3 in Home A and 57.81 μg/m^3 in Home B. During this period, the median outdoor levels were 31.83 and 39.89 μg/m^3, respectively. The VOCs were classified into BTEX and aliphatic hydrocarbons (AHs), and other VOCs. BTEX made the largest contributions to both the indoor and outdoor VOCs (on average 58.7 % in homes A and 57.9 % in Home B, followed by AHs (32.8 % and 35.6 %). Other VOCs contributed only minor fractions. For the individual VOCs, toluene was the most abundant (35.9 %) and was found in all the samples, followed by tetradecane (19.8 %), and xylene (13.2 %) in Home A. Toluene (32.8 %), hexane (18.9 %), xylene (15.9 %), and tetradecane (12.2 %) are major species in Home B. These VOCs were detected in over 82 % of the samples in the two homes. The dominance of toluene in indoor air may be accounted for its various sources such as building materials, paints, furnishing materials, tobacco smoke, and cleaning materials (Gao et al., 2021a, 2021b), which has also been reported in new buildings previously (Fan et al., 2017; Yan et al., 2019; Yin et al., 2019). Tetradecane and xylene are used in lubricants and greases, adhesives and sealants, and coating products (ECA, 2023; Yu et al., 2022). Zhang et al. (2021) reported a higher level of xylene than toluene in new school and residential rooms in China and attributed this to the wide use of xylene in paint. The indoor formaldehyde concentrations were between 30 and 40 μg/m^3 in Home A and 40 and 50 μg/m^3 in Home B, slightly higher than or comparable to the outdoor levels (30 μg/m^3 at both sites). Home A was more furnished (with more finishing materials and new furniture) than Home B, in which pre-owned furniture was used in bedrooms. However, there were no statistically significant differences in the indoor levels of most VOCs, except for hexane ($p = 0.012$, higher in Home B) and hexadecane ($p = 0.027$, higher in Home A). In addition to the interior finishes, house ventilation is also a significant factor influencing indoor VOC levels

Table 2
Descriptive statistics for the indoor and outdoor concentrations(μg/m^3) VOCs and formaldehyde at the two residences.

VOCs	Home A						Home B					
	Indoor			Outdoor			Indoor			Outdoor		
	range	mean	median	range	mean	median	range	mean	median	range	mean	median
Benzene	0.64–11.73	2.99	2.25	1.13–4.19	2.63	2.59	0.38–78.42	5.87	2.69	1.17–5.69	2.93	2.81
Toluene	1.93–451.9	54.34	15.55	1.69–36.54	14.99	14.09	0.45–1388	85.18	22.79	3.36–92.97	29.50	18.16
Ethylbenzene	0.0–14.0	4.22	3.07	0.45–6.34	2.80	1.79	0.07–9.38	3.53	2.79	0.0–1.75	1.04	1.10
Xylene	0.57–47.77	12.11	5.82	1.09–13.28	5.74	4.67	0.27–37.58	12.81	11.15	0.0–4.62	2.32	2.20
BTEX	6.59–468.8	73.67	40.76	5.52–54.07	26.16	21.25	2.63–1475	107.39	41.12	8.06–94.78	35.79	26.04
Hexane	0.0–23.12	5.83	4.51	1.75–7.91	4.32	3.92	0.0–2661	101.01	5.88	2.08–141.7	31.68	11.39
Undecane	0.0–2.7	0.62	0.43	0.0–0.71	0.16	0.06	0.0–2.73	0.58	0.31	0.0–0.86	0.17	0.00
Tetradecane	0.43–165.4	24.15	11.71	0.15–5.95	1.42	0.59	0.0–48.67	11.48	6.81	0.05–14.13	3.36	1.33
Nonane	0.0–1.08	0.19	0.06	0.0–0.77	0.19	0.09	0.0–45.43	1.56	0.15	0.0–0.58	0.15	0.07
Hexadecane	0.0–17.59	5.35	3.57	0.16–2.59	0.69	0.35	0.0–20.35	3.80	2.03	0.34–2.71	1.17	0.78
AHs	3.81–198.2	36.13	20.70	2.78–14.08	6.79	5.58	3.1–2757	118.43	23.72	4.12–147.1	36.54	20.12
Styrene	0.0–28.98	5.50	2.57	0.0–5.63	2.09	1.64	0.0–20.7	3.60	1.39	0.0–1.84	1.00	1.22
2-Ethylhexanol	0.0–7.82	0.88	0.24	0.0–2.43	0.59	0.07	0.0–9.54	1.19	0.86	0.0–1.12	0.37	0.24
Butyl acetate	0.0–10.26	1.79	0.83	0.0–8.96	2.75	1.86	0.0–8.03	1.47	0.81	0.0–1.04	0.51	0.59
Trichloroethylene	0.0–1.12	0.24	0.10	0.0–0.78	0.23	0.12	0.0–2.18	0.39	0.15	0.0–0.54	0.09	0.00
Sub-total	0.15–32.38	8.42	6.12	0.5–12.19	5.67	4.20	0.12–24.43	6.67	3.46	1.04–3.29	1.98	1.79
TVOC	219.2–4326	1341	1023	245.2–728.6	414.5	343.9	233.95–14,546	1459	912.8	219.7–577.1	434.3	444.5
Formaldehyde[a]	30.0–40.0	38.33	40.0	30.0–40.0	33.3	30.0	40.0–50.0	41.67	40.0	30.0–40.0	33.3	30.0

[a] Formaldehyde was detected only at the end of interior finishes (E7 and E8 of Home A, E6 and E7 of Home B).

(Caron et al., 2020; Ye et al., 2014). The concentrations of TVOCs ranged from 219.2 to 4326 μg/m^3 in Home A and from 234.0 to 14,546 μg/m^3 in Home B. There was no significant difference in the TVOC concentrations in the two homes.

The mean individual indoor concentrations of formaldehyde (35.7 μg/m^3), benzene (4.34 μg/m^3), toluene (61.55 μg/m^3), and xylene (19.14 μg/m^3) at the end of the interior finishes (ready for delivery) at the study residences were all significantly lower than the national standards (70, 60, 150, and 200 μg/m^3, respectively). However, the concentrations of TVOCs (459.6–2856 μg/m^3, with a mean of 1070 μg/m^3) at this stage were higher than the national standard (450 μg/m^3) in more than half of the rooms. The indoor concentrations of BTEX in the present study (with a mean of 90.53 μg/m^3) were lower than most of the values in newly built or renovated residences reported in China, although most of the measurements in the literature were done after (rather than during) the interior finishes (Table S5). The BTEX concentrations substantially decreased compared to those in 2012 in this city (290.6 μg/m^3) (Du et al., 2014). The TVOC concentrations were significantly lower than the concentrations a decade ago but higher compared to the recent measurements in China (Table S5). The formaldehyde levels here were close to the median (40 μg/m^3) in urban indoor air in southern China (Dai et al., 2018) but lower than the median (154 μg/m^3) in newly renovated residences before 2015 (Huang et al., 2017). Although only two residences were involved, the lower levels in the present study were a reflection of the increasingly strict standards and public health awareness about indoor air quality in China. However, the comparable TVOC concentrations implied more substituted chemicals in interior finish materials in addition to the target chemicals, which needs further work to identify their indoor occurrence and health risk.

The indoor/outdoor (I/O) ratios of VOCs in Home A ranged from 0.47 to 27.03 (Table S6). The highest ratio was observed for tetradecane, followed by hexadecane (13.84). In Home B, the highest ratio was observed for xylene (4.3), tetradecane (3.2), and ethylbenzene (3.0). The ratios for toluene, benzene, and hexane were also less than 2, indicating more outdoor sources for these species. It should be noted that the outdoor VOCs were collected near the homes and may be affected by the indoor emissions, potentially resulting underestimated I/O ratios.

Concentrations and compositions in the microenvironments

Overall, the distribution profiles of these VOCs among the rooms were compound-specific. In Home A, the concentrations of toluene, the dominant VOC, decreased in the order of secondary bedroom > master bedroom > kitchen > living room > kid's room (Fig. S3), which were all obviously higher than the outdoor levels. The master and secondary bedrooms differed in wardrobes, floor area, and ventilation. Higher levels of ethylbenzene and xylene were present in the living room. The concentrations of tetradecane in the kid's room were noticeably high compared to those in other rooms, and the indoor concentrations were much higher than the outdoors. The result indicated predominant indoor emissions of tetradecane in Home A, although it is listed as a compound present in the exhaust of diesel vehicles (Chin and Batterman, 2012; Xu et al., 2020). The new wood cabinets in the kid's room may be the source of tetradecane, which may be used in the adhesives, sealants, polishes, and waxes (ECA, 2023). The kid's room cabinets were from a manufacturer different from the furniture in the bedrooms and kitchen and were assembled differently. Styrene and hexadecane showed similar patterns (with higher levels also in the kitchen), but they were different from those of BTEX. Relatively, the mean concentrations of benzene, hexane, and some minor compounds varied less among the microenvironments (including outdoors), indicating a lack of strong indoor sources. The mean concentrations of TVOCs were highest in the kid's room, which has more wood-based furniture than other rooms.

In Home B, many VOCs and TVOCs showed the highest concentrations the bathroom, in which there were only a toilet and a cheap small bathroom cabinet. Emissions from toilet glue or the cabinet board sheets should be their sources. The kitchen displayed the second highest levels for most VOCs. The higher levels were very likely due to emissions from the cabinet and the small space of the kitchen (5.5 m^2). Previous research has also found kitchen cabinet is a significant source of indoor VOCs thanks to the fact that most of them are made from engineered wood products. It can continue to release VOCs into the home for months or even years after manufacturing in a process as "off-gassing" (Harb et al., 2018; Wang et al., 2021). The VOC levels in the master bedroom were higher than in the kid's room. Furniture in the kid's room is second-hand and has been used for years, but a new wardrobe in the master bedroom was installed. At Home B, the outdoor air did not show a remarkable reduction in the concentrations of hexane, toluene, and benzene compared to the indoor levels (excluding concentrations in the bathroom). The outdoor air samples at this site were collected near the window, which was more likely to be influenced by indoor emissions.

Temporal variations

Home A

Fig. 1 displays the temporal variations of VOC concentrations in the rooms in Home A. In the first sampling event (E1), when the plaster walls were nearly cured, the VOC concentrations in the rooms were generally lower (< 10 μg/m^3 for individual VOCs and < 426.8 μg/m^3 for TVOCs), except for the higher toluene and TVOC concentrations in the kitchen (137.1 and 946.5 μg/m^3) and living room (56.67 and 1023 μg/m^3). Lower VOC concentrations at the wall plastering stage have also been observed in an early study (Liang, 2020). The higher concentrations in the kitchen were likely a result of emissions from caulk used to install ceramic tiles in the kitchen and bathroom a week before E1. The higher concentrations in the living room may be due to the interior finish materials, which were placed there temporarily. The concentrations in E2 (after interior painting) increased for partial VOCs, especially for xylene, tetradecane, and styrene. The marked rise in xylene levels was consistent with the fact that many manufacturers in China have replaced benzene with xylene as a solvent in paint (Zhang et al., 2021). Chang et al. (2019) recently observed a significant increase in the concentrations of toluene and xylene after wallpapering (painting). The TVOC concentration in E2 was, on average, two times higher than that in E1. Some VOCs, such as benzene, xylene, hexane, and undecane, did not show significant increases in their concentrations in E2 compared to E1. The carcinogenic properties of benzene have long been recognized, and benzene exposure has been linked to an increased risk of leukemia (Tsai, 2019). Hence, benzene is very likely not added to the latex paints. The results indicated that some VOCs were added to the latex paints or primers, although the manufacturer states that no VOCs have been detected in the products. By comparison, the concentrations of carcinogenic styrene in E2 increased noticeably. In E3, a week after the painting, the indoor levels continued to rise for most VOCs in the rooms. Then, the living room showed the most substantial increases in the concentrations (approximately 2.5 times for nearly all the VOCs), in particulate for toluene with an increase of 12 times. This was likely due to the interior finish materials, packaging materials, or unopened household appliances in the living room. It could also be attributed to the installation of kitchen cabinets a few days ago, as the kitchen is frequently open to the living room.The measurements in E4 were done on the second day after installing wood flooring tiles in the bedrooms and kid's room. The concentrations of most VOCs in E4 between these three rooms were comparable. Flooring resulted in increases in the concentration of toluene in E4 relative to E3 in these rooms. However, the concentrations of other VOCs (including TVOCs) mostly declined, suggesting that the wood flooring tiles were not a significant source of these VOCs. Compared to those in E3, the concentrations of all the VOCs in E4 in the living room substantially decreased (from 2905 to 477.3 μg/m^3) with the cleaning of part of the finishing products. This also signified that the peak values in E3 were a result of short-term abrupt emissions. On the day before E5, two new finished wardrobes, which had been displayed in the store for months, were installed in the two bedrooms. The concentration of toluene increased dramatically (from 83.08 in E4 to 302.94 μg/m^3 in E5), and the TVOC concentration also increased (to 1948 μg/m^3); whereas the concentrations of other VOCs changed slightly. The samples of E6 were collected a few days after two new storage cabinets in the living room and beds and mattresses in the bedrooms were installed. The concentrations in E6 indicated that the newly introduced beds or mattresses resulted in significant increases in the concentrations of AHs, styrene, 2-ethylhexanol, and butyl acetate but not BTEX in the bedrooms. This finding was inconsistent with a previous observation that new mattresses led to an elevation of the toluene concentrations in rooms (Beckett et al., 2022). Nevertheless, there was only a moderate increase in the TVOC concentration, indicating a lack of strong emission from the beds and mattresses. In the living room, most VOC concentrations increased in E6 compared to E5, especially for toluene, hexadecane, and hexane, indicating emissions from the storage cabinets. Zhang et al. (2021) did not find an increase in the VOC concentrations related to new furniture installation; while increases in part of rooms of new apartments were observed by Beckett et al. (2022). VOC concentrations were obviously higher at the stages of door and furniture installation than plastering and painting (Liang, 2020; Liang et al., 2014b). The sampling of E7 followed the installation of new domestic appliances and furniture in the living room, a bed in the kid's room, and a cheap desk in the secondary bedroom. In E7, the VOC levels in the bedrooms, kid's room, and living room decreased substantially compared to E6 (about two weeks before E7), implying lowered emissions from the interiors. This could be attributed to the cleaning of various waste related to the interior finishes from the rooms. This result also indicated that introducing the finished furniture pieces, such as the dining table, chairs, and couches, emitted few VOCs. An exception was toluene in the secondary bedroom, in which its concentration increased from 7.8 to 43.1 μg/m^3. This was clearly due to the emissions from the lower-end desk. In E8, approximately six months after the interior finishes, the concentrations of most VOCs in the bedrooms, kid's room, and kitchen decreased 79 %−83 % compared to the levels in E7. In the living room, however, the levels of most VOC increased (on average 1.8 times), suggesting there were still stronger emissions compared to other rooms. In terms of the compounds, the levels of ethylbenzene and xylene increased in most rooms. A study on the emission kinetics of VOCs from new timber frame houses observed an overall decreasing trend in the concentrations during the construction process (lasting for about two years), except for formaldehyde (Plaisance et al., 2017).

During the sampling period, concentrations in the kitchen showed different temporal patterns among the VOCs, which were affected by both the installation of cabinets (E1 and E6) and various packed or unpacked kitchen appliances. Fig. 1 also shows that in the two bedrooms, the temporal variations of BTEX and AHs differed, but the temporal variations of other VOCs were mostly similar. The temporal variations between the VOCs were different in the kid's room and partly similar in the kitchen. Unlike in other rooms, the variations in the living room were generally similar. In summary, the temporal variations between the rooms were not similar for most VOCs. The findings demonstrated that indoor VOC concentrations were spatially heterogeneous during the interior finish period because the emissions were room-dependent. It is worth noting that the VOC concentrations and the variations were also affected by the room ventilation rates (Caron et al., 2020; Deng et al., 2012) and temperature and humidity that are dependent on the sun lighting conditions (Bari et al., 2015). The outdoor concentrations showed similar temporal variations for most VOCs, suggesting a common source. This site is located in a zone with a heavy traffic fleet; traffic exhaust may therefore serve as a significant source of VOCs.

Home B

Generally, the associations of the VOC concentrations with the interior finishes in Home B were less definite than in Home A. The concentration of BTEX in E1 in the master bedroom (45.63 μg/m^3), secondary bedroom (28.53 μg/m^3), and living room (35.22 μg/m^3) were comparable, which were higher than those in Home A (Fig. 2). However, not all the target VOC concentrations in E2 increased after the wall painting, and similar results were observed in E3, five days after the painting. This was different from most cases in Home A and suggests that the latex paint used in Home B may not be the primary source of these VOCs. In contrast, the TVOC concentrations during this period showed increasing trends, similar to those in Home A. The finding also implied the use of other chemicals in the paint. In E4, in which most VOCs (including TVOC) decreased, the toilet installation did not result in an increase in their concentrations. An exception is the dramatic increase in the hexane concentrations, and the highest concentration was present outdoors. This result indicated an emission episode of hexane, which may be emitted from cooking activities at this residential site as

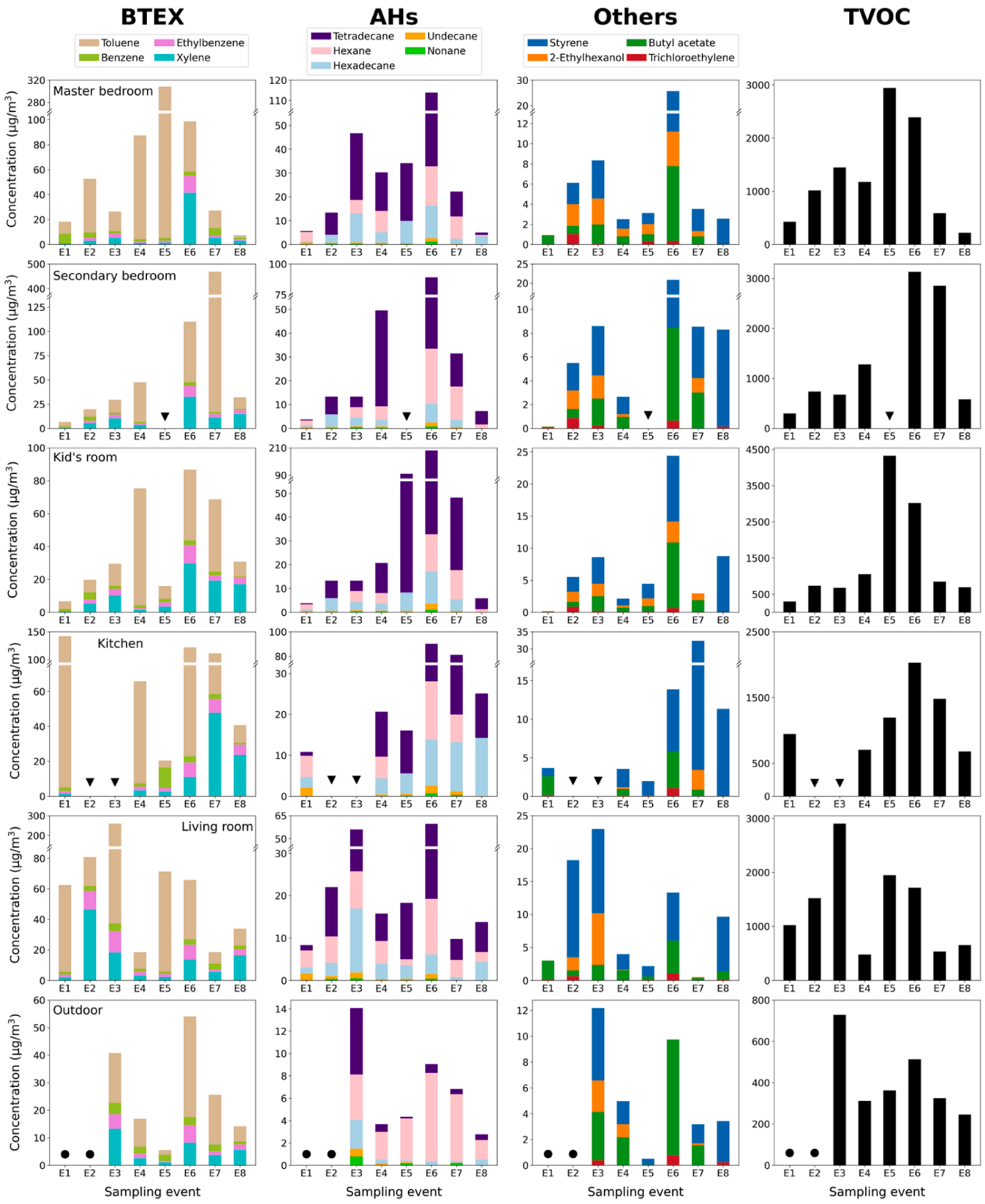

Fig. 1. Temporal variations of indoor and outdoor concentrations of VOCs at Home A. The triangles signify the samples were ruined in instrumental analysis, the dots signify the samples were not collected.

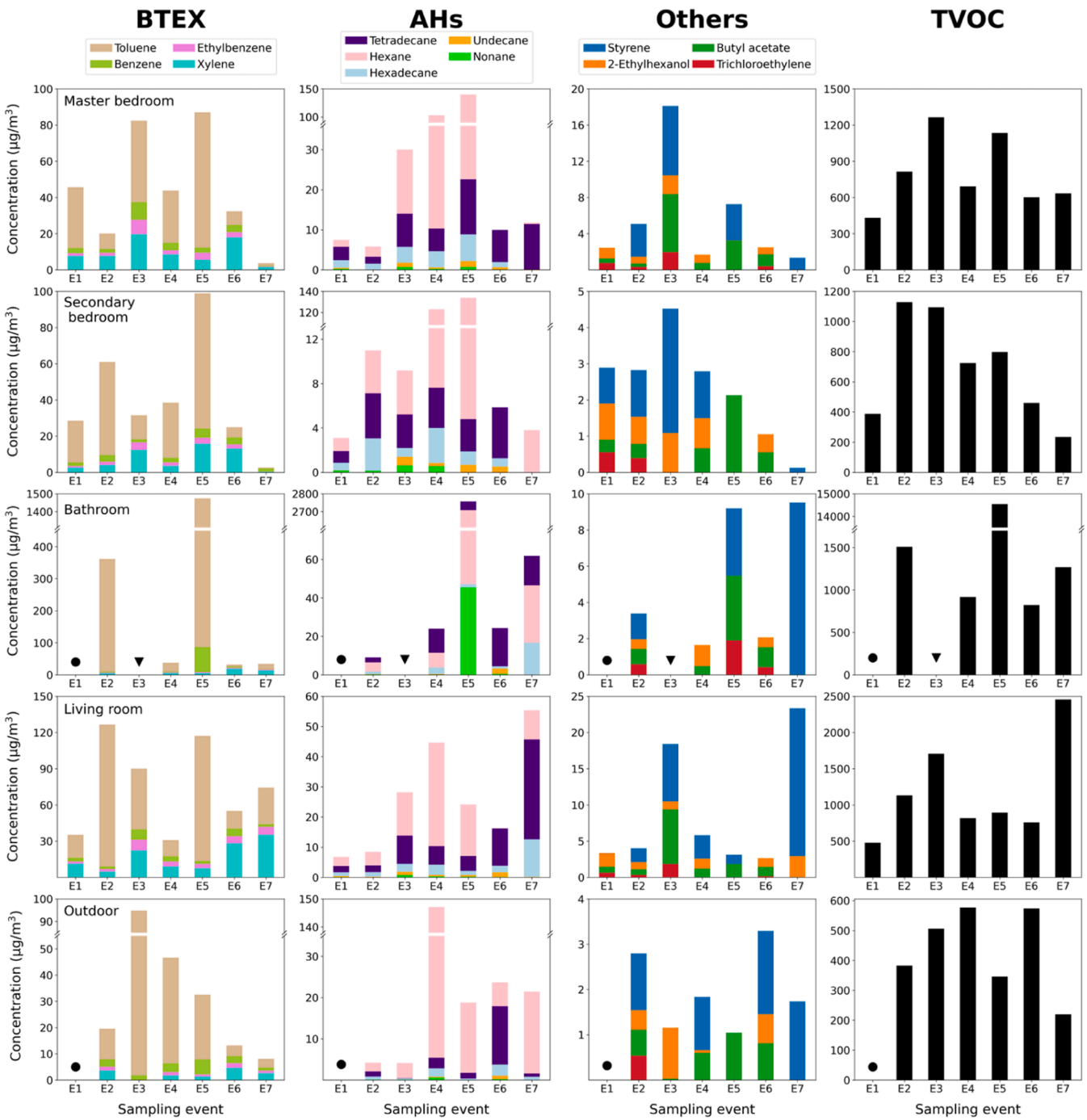

Fig. 2. Temporal variations of indoor and outdoor concentrations of VOCs at Home B. The triangles signify the samples were ruined in instrumental analysis, the dots signify the samples were not collected.

suggested previously (Cheng et al., 2016). In E5, a few days after installing nearly all the new furniture species in Home B, there was a remarkable increase in most VOC concentrations. Surprisingly, the concentrations of TVOC did not increase significantly in the rooms (except for the bathroom). Extremely high concentrations in E5 were found in the bathroom. This is definitely the emissions from the lower-end small bathroom cabinet. With the attenuation of emission from the interiors, most VOC levels in E6 and E7 declined substantially in the rooms. Nevertheless, the concentrations of some VOCs in the living room, kitchen, and bathroom in E7 (approximately six months after the interior finishes and five months after the occupancy) were higher than or comparable to those in E6 (Fig. 2 and Fig. S4). The VOCs in E7 have a characteristic of high contributions from styrene, hexane, and TVOC, differing from the compositions during the interior finish period (E1-E6) at this residence. Such differentiation in the VOC patterns was not observed in Home A, with a similar duration of occupancy to Home B. Styrene is an essential component of materials used in a variety of domestic products (Arya et al., 2021; Pal et al., 2023; Wi et al., 2021). There may be additional but unknown emission sources in Home A. Unlike at Home A, the outdoor VOC concentrations at Home B had different temporal variations, suggesting multiple sources including indoors and outdoors.

Correlations

Indoor VOCs may originate from indoors, outdoors, or both. Tetradecane, which showed the highest average I/O ratio, can be a marker of indoor emissions of VOCs. Relationships between tetradecane and other VOCs for each room were performed to understand their sources. Several minor compounds had weak correlations with tetradecane in most cases, and their relationships were not shown in Fig. S5. In the master bedroom, tetradecane did not correlate with benzene and toluene. Benzene had the lowest mean I/O ratio and was largely derived from outdoors. The strong emission of toluene related to the semi-finished wardrobe in bedrooms in E5 as well as its outdoor origins may influence the relationship. Tetradecane had no significant correlation with hexane, which was indicative of the presence of outdoor origins of hexane at this residence, e.g., industrial and vehicular sources (Bari et al., 2015), in agreement with the I/O ratios. Tetradecane showed significant correlations with other main VOCs ($r^2 > 0.700$, $p < 0.036$). Similar results were also observed in the secondary bedroom. The correlation with toluene was strong ($r^2 = 0.976$, $p < 0.001$) if an outlier (caused by the lower-end desk in E7) was excluded, indicating a main indoor source of toluene in this room. The master and secondary bedrooms use the same brand of wardrobe but different beds. The master bedroom window faces the city's main road and is more affected by vehicular emissions. There are fewer significant relationships with tetradecane in the kid's room, kitchen, and living room compared to the bedrooms, suggesting varying origins during the interior finish period. Overall, tetradecane had good relationships with ethylbenzene, hexane, hexadecane, and TVOC in most rooms. In the outdoor environment, we use benzene (a group 1 carcinogen in humans) as an indicator of outdoor origin. A recent study indicates the significant (though not dominant) role of outdoor benzene emission from traffic and industry in contributing to indoor concentrations, especially in developing countries, with the regulation on its indoor uses globally (Liu et al., 2020). Significant relationships were found for xylene and TVOC. In Home B, the correlations with tetradecane and hexane (with the lowest average I/O ratio) were much less significant than those in Home A (Fig. S6). Significant relationships with tetradecane were found for ethylbenzene and xylene in the living room. This suggests the differences in the emission sources of the VOCs at this residence.

Health risks

Cancer and non-cancer risks of exposure to indoor VOCs and formaldehyde are summarized in Table 3. The average HIs of VOCs for interior finishers were 0.19 in Home A and 0.38 in Home B, lower than those for formaldehyde (0.44 and 0.49), indicating a low non-cancer risk of occupational exposure. Benzene was responsible for approximately 80 % of the HIs for the VOC exposure, although its use in many interior finish materials has been restricted. The highest exposure risk occurred at the wall painting stage in Home A and the bathroom cabinet installation stage in Home B. A recent study found higher risks of exposure to VOCs at carpentry and painting stages for interior construction in another Chinese city (Liang, 2020). The non-cancer risks were also low for people living in homes A (HI = 0.79) and B (HI = 0.87), with formaldehyde being the primary contributor.

Table 3
Lifetime excess cancer risk and non-cancer risk (hazard quotient) of exposure to VOCs and formaldehyde for interior finishers (occupational exposure only) and occupants in Guangzhou.

Compound	Interior finishers		Resident	
	Home A	Home B	Home A	Home B
Cancer risk				
Formaldehyde	5.11E-05	5.68E-05	4.81E-05	5.35E-05
Benzene	3.56E-06	6.98E-06	5.95E-06	6.45E-06
Ethylbenzene	1.48E-06	1.20E-06	4.80E-06	4.40E-06
Trichloroethylene	1.62E-07	2.88E-07	2.37E-07	1.26E-07
Styrene	1.06E-07	4.72E-08	6.65E-07	9.00E-07
Sum	5.64E-05	6.53E-05	6.00E-05	6.55E-05
Non-cancer risk				
Formaldehyde	4.37E-01	4.85E-01	4.11E-01	4.57E-01
Benzene	1.52E-01	2.98E-01	2.56E-01	2.75E-01
Trichloroethylene	1.97E-02	3.52E-02	2.90E-02	1.54E-02
Xylene	1.47E-02	1.53E-02	7.90E-02	9.40E-02
Toluene	2.14E-03	3.27E-03	1.19E-03	2.11E-03
Ethylbenzene	1.98E-03	1.60E-03	6.40E-03	5.85E-03
Hexane	1.20E-03	2.16E-02	1.03E-03	1.59E-02
Styrene	7.19E-04	3.22E-04	4.52E-03	6.15E-03
Hazard index (HI)	6.29E-01	8.61E-01	7.90E-01	8.70E-01

The cumulative excess risks for interior finishers attributed to occupational exposure to the VOCs (LCRs = 5.3×10^{-6} in Home A and 8.5×10^{-6} in Home B) were within the acceptable range proposed by the USEPA. When formaldehyde is considered, the risks were 5.6×10^{-5} and 6.5×10^{-5} in the two homes). For occupants, the cumulative cancer risks of these known carcinogens were estimated to be 6.0×10^{-5} in Home A and 6.6×10^{-5} in Home B. The health risks for urban occupants may be overestimated because it may need a longer time for the indoor concentrations to level off after the interior finishes (Huang et al., 2020; Zhang et al., 2020). However, the health risks for interior finishers in Chinese cities may be underestimated as the exposure concentrations during the execution and installation processes may be much higher than the measurements a few days later. Most interior finishers in China do not wear personal protective equipment, virtually increasing their exposure from the respiratory tract and skin. Furthermore, the combined cancer risk of interior finishers (including household exposure to VOCs) would exceed the protective benchmark (10^{-4}). The result highlights the concern about the occupational exposure and health of interior finishers in China. Furthermore, formaldehyde remains the priority chemical to be controlled and removed in new or renovated homes in China.

Conclusion

This work presents the occurrence, temporal variation, and health risks of VOCs in indoor air associated with residential interior finishes. The declined concentrations of VOCs in the present study reflected China's increasingly strict standards and public health awareness about indoor air quality. However, the TVOC concentrations implied the need for measurement of other VOCs in present interior finish materials. VOC concentrations and their temporal variations during the interior finishes indicated room-dependent emissions. Furniture is the most important emission source of VOCs in newly renovated residences. The related non-cancer risks of VOC exposure were lower for both interior finishers and occupants. However, this study raises concerns about the excess cancer risk of occupational exposure of interior finishers in China. Little attention has been paid to this cohort.

Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author did not use any generative AI and AI-assisted technologies. The author reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRedit authorship contribution statement

Jin-Long Mai conducted the investigation, data analysis and prepared the draft. Wei-Wei Yang developed the methodology, prepared all figures and tables. Yuan Zeng and Yu-Feng Guan supervised the instrumental analysis and data analysis. She-Jun Chen designed and supervised the research and revised the manuscript. All authors reviewed the manuscript.

Data availability

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.heha.2023.100087.

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