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Characteristics Analysis of Volatile Organic Compounds Pollution in Residential Buildings in Northeast China Based on Field Measurement

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Abstract: A total of 8 mechanically ventilated residential buildings and 8 naturally ventilated residential buildings were selected to analyze the pollution characteristics of indoor VOCs under different ventilation modes in the severe cold area of northeast China. On typical meteorological days in each season, VOCs were detected on site, and ventilation modes were investigated by long-term online monitoring. The test results showed that the TVOC (total volatile organic compounds) concentrations varied greatly in different seasons or different functional rooms, and the TVOC concentration was the highest in winter, with a value of 0.994 mg/m^3. The kitchen was the place with the most serious VOC pollution, and the TVOC concentration could reach 1.403 mg/m^3. Benzene series and methylsiloxane had the highest detection rates, but the detected concentrations were low, and the average concentrations were 0.025 mg/m^3 and 0.013 mg/m^3 respectively. Among the VOC types with a detection rate greater than 50%, the average proportions of aldehydes, alkanes, and benzene series were 18.7%, 15.39%, and 14.38%, respectively. And their mass ratios were also high, which were 14.90%, 30.85%, and 15.70%, respectively. The annual daily average ventilation duration of mechanically ventilated residential buildings was 7.84 h longer than that of naturally ventilated residential buildings. The median TVOC concentrations of mechanically ventilated residential buildings and naturally ventilated residential buildings were 0.621 mg/m^3 and 0.707 mg/m^3, respectively. The fresh air system was applicable in the severe cold area of northeast China.

Keywords: VOCs; field measurement; long-term online monitoring; ventilation modes; benzene carcinogenic risk

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1. Introduction

Residential buildings are the main places of people's daily lives, and their indoor air quality is closely related to the health of every occupant. With the concepts of sick building syndrome (SBS) and building-related diseases (BRI) proposed, more and more experts and scholars in related fields pay attention to the research of indoor air quality and pollutants. According to statistics, about 87% of human time is spent indoors, while for the elderly, infants, and other special groups, the proportion of time spent indoors can be as high as 95% [1–3]. On the one hand, with the development of society and the improvement of living standards, people's requirements for the quality of the living environment are increasing, and the use of beautification and decorative materials leads to the accumulation of a large number of chemicals indoors. On the other hand, now the occupants pay more attention to their living environment and have more urgent requirements for a healthy and comfortable residential environment. At present, there are different levels of research on various gaseous pollutants at home and abroad, among which volatile organic compounds are ubiquitous in daily life. For example, benzene and toluene are common indoor pollutants, which have a huge impact on the environment and human health [4,5]. Therefore, volatile organic compounds are considered one of the important parameters for evaluating indoor and outdoor ambient air quality [6].

In 1989, the World Health Organization proposed the concept of volatile organic compounds (VOCs), and according to relevant experiments, it was found that VOCs have great harm to human health. One year later, Norbäck et al. [7] conducted a study on people with sick building syndrome to investigate the relationship between the syndrome and exposure to environmental and personal factors. The results of the study showed that the sick building syndrome was the result of multiple factors and was significantly associated with volatile hydrocarbon exposure. Other factors associated with the sick building syndrome were smoking, psychosocial factors, and experience of static electricity at work. Some other studies have found that VOCs are highly toxic and are a source of carcinogens that can cause respiratory diseases [8,9]. The harm caused by VOCs to human health is mainly reflected in the irritation of odor, eye, and respiratory tract [10,11]. Kadosaki et al. [12] also pointed out that more than 20 VOCs detected in indoor air have carcinogenic or mutagenic effects. There are many types of VOCs in indoor air, and it is relatively difficult to determine them qualitatively and quantitatively one by one. Therefore, the quantitative index of total volatile organic compounds (TVOC) is often used to characterize the total mass concentration of VOCs in indoor air [13]. Indoor VOCs mainly come from building materials and daily necessities. Farrow et al. [14] found that a higher level of TVOC was associated with air fresheners and aerosols. In addition, the use of office equipment such as printers and scanners, and human activities such as cooking and smoking also produced a variety of VOCs [15]. Tan et al. [16] found that the detection of organic pollutants in indoor air focuses on five pollution indicators, namely formaldehyde, benzene, toluene, xylene, and total volatile organic compounds, by analyzing the relevant literature on pollutants in the indoor environment since 2008. Benzene, toluene, and xylene are colorless and volatile toxic liquids with a strong pungent aromatic odor. In daily life, indoor benzene mainly comes from decorative materials, wood-based furniture, adhesives, air disinfectants, and insecticides [17–19]. At the same time, some researchers have measured family kitchens in different regions of China and found that TVOC concentrations basically exceeded the standard seriously [20,21].

Material emissions and environmental parameters are important factors impacting indoor air quality [22]. Ventilation is one of the most direct and effective methods to remove indoor gaseous pollutants when the VOC emission sources such as indoor building materials and furniture cannot be changed [23,24]. Ventilation can be mainly divided into natural ventilation using wind pressure and thermal pressure after opening windows by natural force, and mechanical ventilation using the fresh air system by artificial means [25]. In China, only a few residential buildings use mechanical ventilation, while the use of natural ventilation will lead to insufficient ventilation [26]. Moreover, many studies have found that considering thermal comfort, the proportion of occupants who open windows in cold outdoor climates is low [27–31]. While mechanical ventilation can operate continuously to ensure ventilation rate, filters can be used to control outdoor pollutants and discharge indoor pollutants [25]. Wallner et al. [32] investigated indoor air pollution in 62 mechanically ventilated buildings and 61 naturally ventilated buildings, and the results showed that almost all indoor air quality and indoor climate parameters in mechanically ventilated buildings were significantly better than those buildings relying on open windows and doors for ventilation.

In northeast China, there are mostly severe cold weather in winter. Affected by heating, the problem of outdoor pollution is aggravated by burning coal. In addition, the air tightness of buildings in northeast China is better. Especially in winter, the willingness of occupants to open windows is not high, and the window opening time is also short, and insufficient fresh air will bring more serious indoor pollution problems. In this study, the indoor VOC data of 16 residential buildings in northeast China in different seasons were collected via field measurement, and the characteristics of residential VOC pollution in northeast China were analyzed. At the same time, the residential ventilation modes were investigated using long-term online monitoring to explore the impact of different ventilation modes on indoor VOC pollution. The main purpose of this study is to understand the characteristics of indoor VOC pollution and occupants' ventilation habits in northeast China and to identify potential benzene carcinogenic risk of residential buildings with different ventilation modes.

2. Test Methods

2.1. Sampling Location and Outdoor Meteorology

Northeast China is located in the temperate climate zone with four distinct seasons. The summer is hot and rainy (mainly from June to August), the transition seasons are clear and short (mainly from April to May and September to October), and the winter is cold and long (mainly from November to March of the following year). The outdoor temperatures in summer, transition seasons, and winter were 24.3 °C, 16.6 °C, and −3.13 °C, respectively, and the outdoor humidities were 73.23%, 52.35%, and 44.91%, respectively. In this study, 16 residential buildings were selected in three cities in northeast China to conduct VOC detection on site and long-term online monitoring of ventilation modes, and analyze the current status of indoor VOC pollution in residential buildings. The three cities were Shenyang, the largest old industrial city, Yingkou, an open coastal city, and Fushun, which was surrounded by mountains and hills on three sides. The residential buildings installed with the fresh air system were mechanically ventilated residential buildings (NO. M1–M8), and the others were naturally ventilated residential buildings (NO. N9–N16). All the residential buildings' decorations were completed more than one year after the start of the study. The types of residential buildings included one-bedroom, two-bedroom, three-bedroom, four-bedroom, and villas, with a building area ranging from 55 m^2 to 300 m^2. The floors of buildings covered low, middle, and high positions. The detailed residential information is shown in Table 1.

Table 1. Residential information.

No.	City	Ventilation Mode	Construction Year	Decoration Year	House Type	Residential Area (m^2)	Decoration Way	Elevation (m)	Furniture Surface Area (m^2)
M1	Yingkou	mechanical ventilation	2016	2016	three bedroom	120	diatom ooze + composite wood	69.2	21.31
M2	Yingkou	mechanical ventilation	2016	2016	two bedroom	90	diatom ooze + composite wood + ceramic tile	55.2	44.93
M3	Yingkou	mechanical ventilation	2012	2013	four bedroom	160	Wallpaper + diatom ooze + solid wood +ceramic tile	69.2	43.10
M4	Yingkou	mechanical ventilation	2016	2017	villa	300	Wallpaper + latex paint + solid wood + ceramic tile	52.4	43.50
M5	Shenyang	mechanical ventilation	2016	2016	one bedroom	55	latex paint + composite wood	94.4	38.22
M6	Shenyang	mechanical ventilation	2016	2016	one bedroom	55	latex paint + composite wood	74.8	43.41
M7	Shenyang	mechanical ventilation	2016	2016	two bedroom	65	latex paint + composite wood	122.4	36.32
M8	Shenyang	mechanical ventilation	2016	2016	one bedroom	52	latex paint + composite wood	139.2	34.62
N9	Shenyang	natural ventilation	2011	2011	four bedroom	145	Wallpaper + latex paint + solid wood + ceramic tile	55.2	42.35
N10	Shenyang	natural ventilation	2004	2004	three bedroom	140	latex paint + solid wood	72	63.98
N11	Shenyang	natural ventilation	2013	2013	three bedroom	134	latex paint + solid wood + ceramic tile	122.4	52.97
N12	Shenyang	natural ventilation	2012	2012	three bedroom	120	latex paint + composite wood + ceramic tile	94.4	60.42
N13	Fushun	natural ventilation	2012	2012	two bedroom	70	latex paint + composite wood + ceramic tile	66.4	37.52

Table 1. *Cont.*

No.	City	Ventilation Mode	Construction Year	Decoration Year	House Type	Residential Area (m^2)	Decoration Way	Elevation (m)	Furniture Surface Area (m^2)
N14	Fushun	natural ventilation	2003	2004	three bedroom	95	latex paint + composite wood + ceramic tile	52.4	36.33
N15	Fushun	natural ventilation	2011	2011	two bedroom	110	latex paint + composite wood + ceramic tile	52.4	33.66
N16	Fushun	natural ventilation	2013	2013	two bedroom	90	latex paint + composite wood + ceramic tile	94.4	21.29

2.2. Sampling Schedule and Method

VOCs came from interior decoration materials and furniture, smoking, and cooking was also major contributor to VOCs concentration. Meanwhile, outdoor fuel combustion and transportation were also sources of VOC pollution. This study adopted the method of detection on site to test the concentration of VOCs under closed conditions. The closed condition was the standard condition stipulated in GB/T 18883-2002 "Standard for Indoor Air Quality" [33] issued by the Ministry of Health of China. The doors and windows of the rooms were closed for 12 h before the test and kept closed during sampling. In each season, 16 residential buildings were selected for VOC detection on typical meteorological days, and the indoor air was sampled by the atmospheric sampler. The sampling site is shown in Figure 1. The bedrooms, living rooms, and kitchens of 16 residential buildings were sampled once in summer, once in transition seasons, and once in winter, totaling 144 samples. The performance parameters of the sampler are shown in Table 2.

Figure 1. Sampling.

Table 2. Performance parameters of sampler.

	Performance Parameter	Model
Atmospheric sampler	Flow range: 0.1~1.2 L/min	Beijing Labor Insurance QC-2B
	Flow error: $\leq\pm5\%$	
	Flow stability: $\leq5\%$	

Before and after sampling, the sampling flow rate of the air sampling pump is calibrated with a verified higher-level flowmeter under the sampling load condition, and the average value of the two times is taken as the actual value of the sampling flow rate. The atmospheric pressure and temperature at calibration are similar to those at sampling. The error between two calibrations should not exceed 5%.

According to the standard GB/T 18204.2-2014 "Hygienic Inspection Methods for Public Places Part 2: Chemical Pollutants" [34] issued by the National Health and Family Planning

Commission, the method of Tenax tube active sampling + gas chromatography–mass spectrometry (GC-MS, Model 8890-5977B, Agilent Inc., Singapore) was used to analyze the types and concentrations of indoor VOCs. Indoor VOCs were sampled with Tenax-TA tubes, the sampling flow was 0.5 L/min, the sampling time was 20 min, and the total sampling volume was 10 L. Tenax-TA tubes were wrapped in tin foil before and after sampling to ensure that they were not contaminated by the surrounding air. After sampling, the Tenax-TA tubes were sent to the laboratory for unified analysis by GC-MS. The VOCs were desorbed from the adsorbent material of Tenax-TA tubes by thermal desorption. The mass spectrometer was operated in selected ion monitoring (SIM) mode and scan mode (mass range 35–400 AMU). The mass spectrometry database NIST11 was used for qualitative analysis, and the signal-to-noise ratio of VOCs analysis was 3. VOCs were quantified with toluene as the equivalent.

To understand the ventilation behaviors of occupants, the Xiaomi window sensor was used to collect information on the opening and closing status of windows online. The installation effect of the long-term online monitoring of residential buildings with the Xiaomi window sensor is shown in Figure 2. The window sensor is divided into two parts. During installation, the two parts shall be glued to the window frame and the edge of the window, respectively, and correspond neatly. The two parts are attracted by magnetic force. The internal magnetic detector converts the magnetic signal into an electrical signal to indicate the state of the windows. When the windows are closed, the distance between the two parts decrease, the magnetic force increase, and the sensor sends the closing signal through the network. When the windows are opened, the distance between the two parts increase, the magnetic force decrease, and the sensor sends the opening signal through the network. The device can capture the changing state of windows and upload it to the platform through the online data acquisition system, so as to obtain the real data of the opening and closing windows of the monitoring residential buildings.

Figure 2. Xiaomi window sensor.

For the operation performance monitoring of the fresh air system, an online monitoring system of the fresh air system was adopted. It consists of sensors, data acquisition modules, and data upload modules, as shown in Figure 3. The pressure sensor and temperature and humidity sensor can collect data on the tuyere pressure, temperature, and humidity of the fresh air system, and transmit the data to the data acquisition module for calculation and processing according to the internal program. Finally, the data upload module wirelessly transmits the data to the cloud to realize the real-time monitoring of the fresh air system. When the air pressure difference value was greater than 10 Pa, it was determined that the fresh air system was turned on. The enthalpy value of the supply and exhaust air obtained by the calculation and processing could be used to calculate the enthalpy exchange efficiency of the fresh air system, so as to judge whether the fresh air system was energy saving.

Figure 3. Fresh air system sensor.

2.3. Chemical and Risk Analyses

In this paper, the detection rate, mass ratio, and benzene carcinogenic risk of indoor VOCs in residential buildings in northeast China were studied. The detection rate is defined as the ratio of the number of samples in which a certain compound is detected to the total number of samples. The mass ratio is defined as the sum of the median concentrations of a certain class of VOCs divided by the sum of the median concentrations of all VOCs. In health risk assessment, carcinogenic risk refers to the probability of a certain group of people suffering from cancer predicted by the model when they are exposed to a certain dose of a pollutant during their life expectancy. The health risk assessment model and the Crystal Ball software (11.1.3.0.0, Oracle, Redwood City, CA, USA) proposed by the US Environmental Protection Agency were used to evaluate the health effects of indoor benzene on personnel respiratory exposure. Through the seamless connection with Excel, Crystal Ball software made use of the powerful data processing function of Excel and combined the advantages of Monte Carlo simulation to quantitatively analyze the carcinogenic risk of benzene.

3. Results and Discussion

3.1. Results of TVOC Measurement

Under closed conditions (residential buildings closed for more than 12 h), indoor TVOC concentration detection results of residential buildings in different seasons and different functional rooms are shown in Figure 4. The values in the boxplot from bottom to top represent the minimum value, quarter digit value, median value, mean value (hollow square), three-quarter digit value, and maximum value of TVOC concentration, respectively. The trend of the median value and the mean value of TVOC concentrations in different seasons or different functional rooms was basically the same. However, the mean value was more susceptible to the influence of the maximum value, so the median value was taken as the representative data of the TVOC concentration level. The median concentrations of indoor TVOC in summer, transition seasons, and winter were 0.643 mg/m^3, 0.772 mg/m^3, and 0.994 mg/m^3, respectively. The median concentrations of TVOC in the bedroom, living room, and kitchen were 0.626 mg/m^3, 0.707 mg/m^3, and 1.403 mg/m^3, respectively. No matter whether in different seasons or different functional rooms, the indoor TVOC concentrations exceeded the standard value of 0.60 mg/m^3 stipulated in GB/T 18883-2002 "Standard for Indoor Air Quality" [33]. Yin et al. [35] sampled the indoor VOCs in residential buildings in northwest China. The study found that the median TVOC concentration in all tested homes was 0.333 mg/m^3 under the closed condition and no significant difference in the TVOC concentration in different types of rooms. In general, the indoor TVOC pollution of residential buildings in northwest China is less than that in northeast China. Du et al. [36] investigated the concentration levels of BTX in homes with new renovations in urban and suburban areas in Guangzhou, China. The average concentrations of benzene, toluene, m/p-xylene, and o-xylene were 0.019 mg/m^3, 0.173 mg/m^3, 0.058 mg/m^3, and 0.041 mg/m^3, respectively, which were higher than that in northeast China.

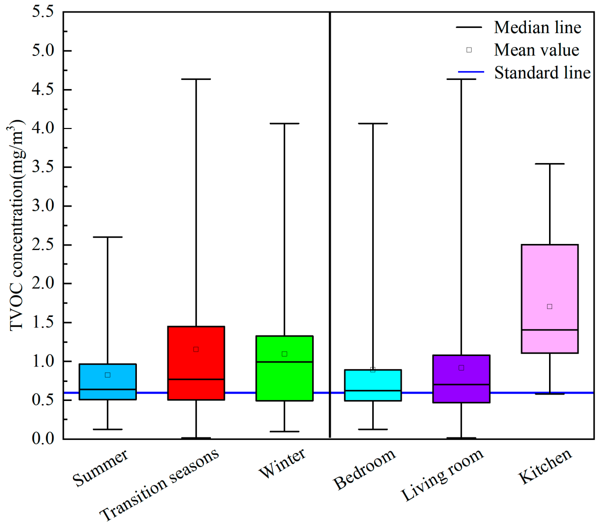

Figure 4. TVOC concentrations of residential buildings in different seasons and different functional rooms.

The indoor TVOC concentration in winter was significantly higher than that in summer and transition seasons. In summer, the residential buildings only ensured to be closed for the minimum required 12 h. In transition seasons, the residential buildings did not have more ventilation requirements and would keep closed for a long time, so the exceeding standard rate was higher than that in summer. In winter, the ventilation rate of residential buildings was lower, the indoor closing time was longer, and the indoor heating temperature was high, resulting in higher indoor TVOC concentration. The kitchen was the most polluted place in the residential buildings, and the TVOC concentration exceeded the standard by 2.3 times. The quarter-digit value of TVOC concentration in the kitchen was higher than the three-quarter-digit value of TVOC concentration in the bedroom and living room. Chinese family kitchens were generally small in size. Chinese cooking methods included frying, stir-frying, stewing, etc., which emitted a large amount of VOC pollution during the cooking process. As an important daily activity, family members spend about 3.6 h a day in the kitchen [37,38], and cooking for too long could lead to VOC accumulation.

3.2. The Detection Rates of VOCs

The number of VOCs detected by GC-MS in 16 residential buildings with a detection rate greater than 50.0% was 33, 29, and 29 in the bedrooms, living rooms, and kitchens, respectively. These VOCs were commonly found in residential buildings [39–41]. There were no VOCs with a detection rate of 100% in the bedrooms and living rooms. The highest detection rate of hexamethylcyclotrisiloxane and toluene in the bedrooms was 96.2%, and the average concentrations were 0.010 mg/m^3 and 0.045 mg/m^3, respectively. The highest detection rate of toluene in the living rooms was 90.9%, and the average concentration was 0.032 mg/m^3. The VOCs with a detection rate of 100% in the kitchens were benzene, toluene, and butyl acetate, with an average concentration of 0.011 mg/m^3, 0.038 mg/m^3, and 0.025 mg/m^3, respectively. In different seasons, only toluene was found to be the VOCs with a 100% detection rate in summer. In transition seasons, the detection rate of dodecamethylcyclohexasiloxane, toluene, and p-xylene was up to 95%. In winter, the detection rate of benzene, toluene, hexamethylcyclotrisiloxane, and octamethylcyclotetrasiloxane was up to 88.2%. However, the average indoor concentrations of the above VOCs were relatively low.

The concentration levels of benzene series and methylsiloxane with high detection rates and great harm to the human body in different functional rooms are shown in Figure 5. Exposure to volatile methylsiloxanes has become a public health concern, as volatile methylsiloxanes have been shown to bioaccumulate within living organisms and to induce toxicities in the human nervous, immune, and reproductive systems [42–45]. Benzene series mainly included benzene, toluene, p-xylene, and ethylbenzene, and methylsiloxane mainly included hexamethylcyclotrisiloxane, octamethylcyclotetrasiloxane, and dodecamethylcyclohexasiloxane. The average concentrations of benzene series and methylsiloxane were 0.025 mg/m^3 and 0.013 mg/m^3, respectively. The concentrations of these seven VOCs were all low, indicating that the above several VOCs with high detection rates were not the main pollutants in residential buildings.

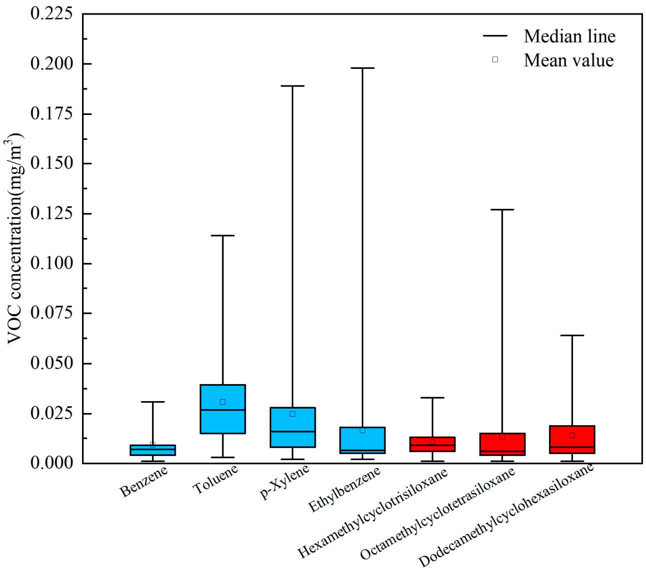

Figure 5. VOC concentrations with high detection.

3.3. The Types of VOCs

The proportions of VOC types with detection rates greater than 50.0% in different functional rooms are shown in Figures 6–8, respectively. The types of indoor VOCs could be mainly divided into alkanes, olefins, benzene series, alcohols, aldehydes, esters, ketones, methylsiloxane, etc. Among the 33 VOCs with a detection rate greater than 50.0% in the bedrooms, aldehydes were the most common, accounting for 18.183%, followed by alkanes (15.152%). Among the 29 VOCs with a detection rate greater than 50.0% in the living rooms, aldehydes were also the most common, accounting for 20.689%, followed by alkanes and benzenes series, both accounting for 13.793%. Among the 29 VOCs with a detection rate greater than 50.0% in the kitchens, there were three types of VOCs, which were aldehydes, alkanes, and benzene series, accounting for 17.241%. It could be seen that aldehydes, alkanes, and benzene series were common in the residential buildings of northeast China. One more nitrous oxide was detected in the bedrooms and living rooms than in the kitchens.

3.4. The Mass Ratios of VOCs

The mass ratios of VOCs with a detection rate of more than 50.0% in different functional rooms are shown in Figures 9–11. The mass ratio of alkanes was the highest, while the mass ratios of acids, aromatic hydrocarbons, and others were very low, and the mass ratio of methylsiloxane with a high detection rate was also low. In the bedrooms, the mass ratio of alkanes was 30.91%, followed by benzene series (16.80%) and then aldehydes (16.17%). In the living rooms, the mass ratio of aldehydes was 19.49%, followed by benzene series (19.27%) and then alkanes (15.34%). The mass ratio of alkanes in the kitchens was as high as 46.31%, followed by esters (15.48%), and then benzene series (11.02%). Statistics showed that alkanes, benzene series, aldehydes, and esters were the largest sources of VOCs in residential buildings in northeast China, including butane, hexane, benzene, toluene, hexal, nonal, ethyl acetate, butyl acetate, and so on, which were the characteristic VOCs of residential buildings.

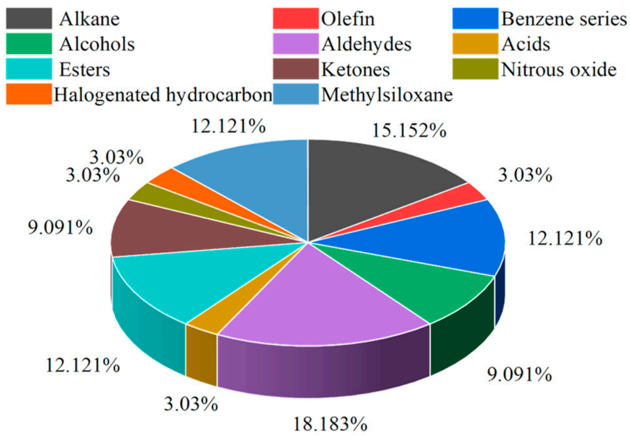

Figure 6. The proportions of VOC types with detection rates greater than 50.0% in the bedrooms.

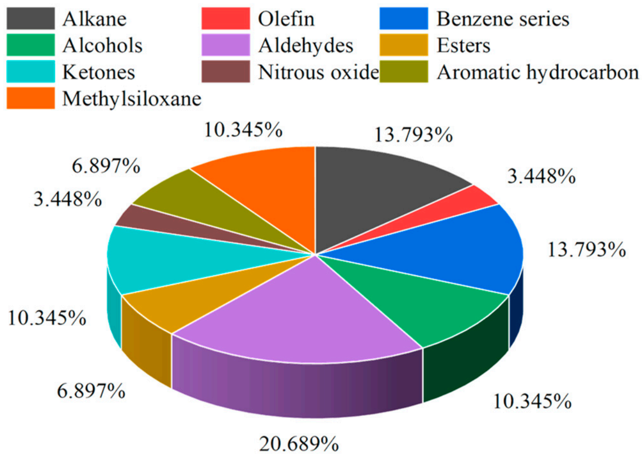

Figure 7. The proportions of VOC types with detection rates greater than 50.0% in the living rooms.

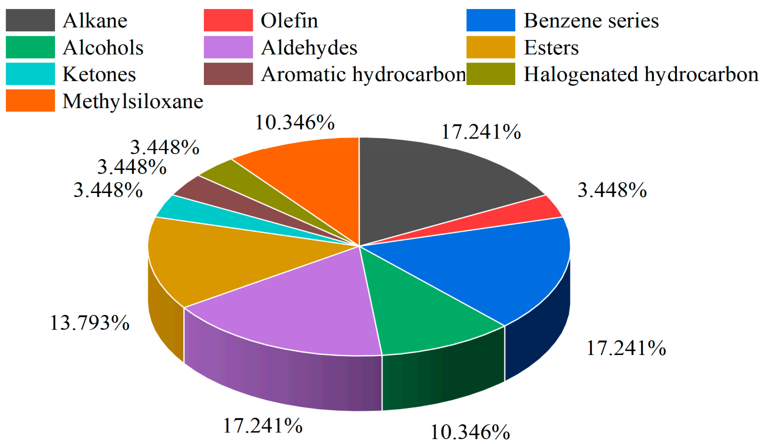

Figure 8. The proportions of VOC types with detection rate greater than 50.0% in the kitchens.

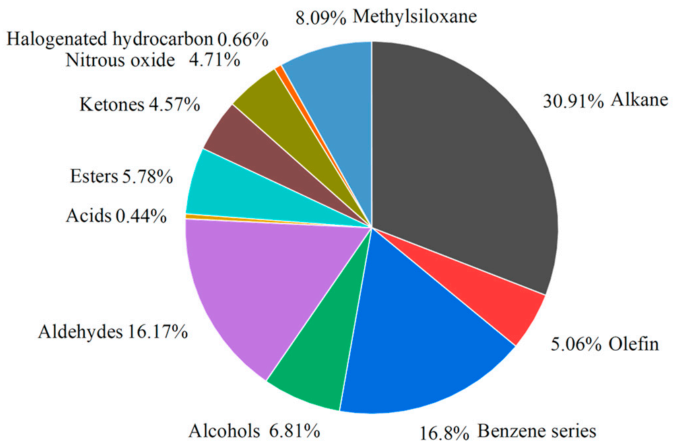

Figure 9. The mass ratios of VOCs with detection rate of more than 50.0% in the bedrooms.

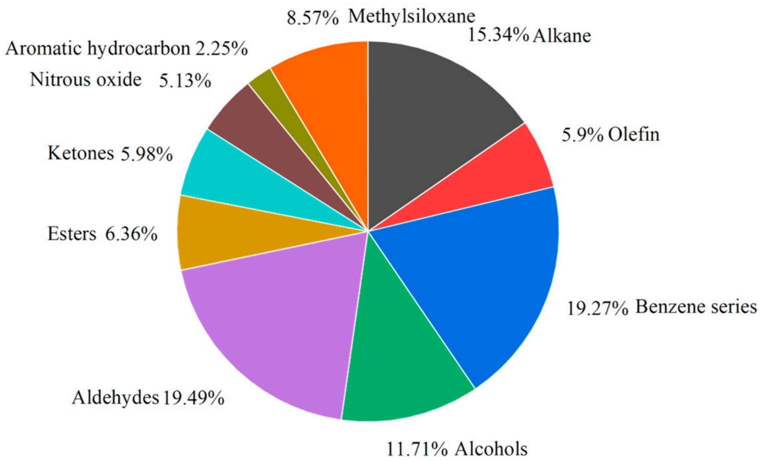

Figure 10. The mass ratios of VOCs with detection rate of more than 50.0% in the living rooms.

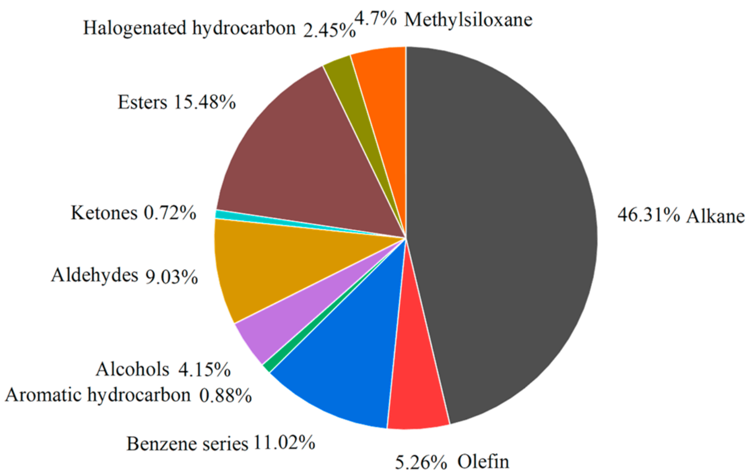

Figure 11. The mass ratios of VOCs with detection rate of more than 50.0% in the kitchens.

The detection rates of toluene were highest in the bedroom, living room, and kitchen, and the mass ratios of alkanes were higher in the bedroom, living room, and kitchen. The concentrations of the two pollutants are shown in Table 3.

Table 3. High detection rate and high mass ratio pollutant concentration in different functional rooms.

		Bedroom	**Living Room**	**Kitchen**
Toluene	Detection rate	96.2%	90.9%	100%
	Concentration	0.045 mg/m^3	0.032 mg/m^3	0.038 mg/m^3
Alkanes	Mass ratio	30.91%	15.34%	46.31%
	Concentration	0.020 mg/m^3	0.010 mg/m^3	0.058 mg/m^3

3.5. Influence of Ventilation Mode on Indoor TVOC Concentration

Mechanical ventilation and natural ventilation are the most important ventilation methods to solve the problem of indoor air pollution in residential buildings. In the severe cold area of northeast China, the air tightness of buildings was relatively good. Affected by the harsh outdoor environment, outdoor noise, and low outdoor temperature in winter, the occupants' willingness to open windows was relatively low, and the window opening time was also short. The lack of fresh air would bring more serious indoor pollution problems. Figure 12 shows the average TVOC concentration levels in the bedrooms and living rooms of mechanically ventilated residential buildings and naturally ventilated residential buildings. The indoor TVOC pollution of mechanically ventilated residential buildings was less than that of naturally ventilated residential buildings. The median concentration of TVOC in mechanically ventilated residential buildings was 0.621 mg/m^3, while that in naturally ventilated residential buildings was 0.707 mg/m^3. Figure 13 shows the ventilation duration of the residential buildings in different seasons. Two ventilation modes were used in the mechanically ventilated residential buildings in different seasons. Especially in winter, the outdoor temperature was low, and the average daily natural ventilation duration was only 0.71 h, while the average daily mechanical ventilation duration was 16.3 h, and the total ventilation duration was 29 times that of the naturally ventilated residential buildings. The annual average daily ventilation duration of mechanically ventilated residential buildings was 7.84 h longer than that of naturally ventilated residential buildings, which greatly affected the indoor pollution level.

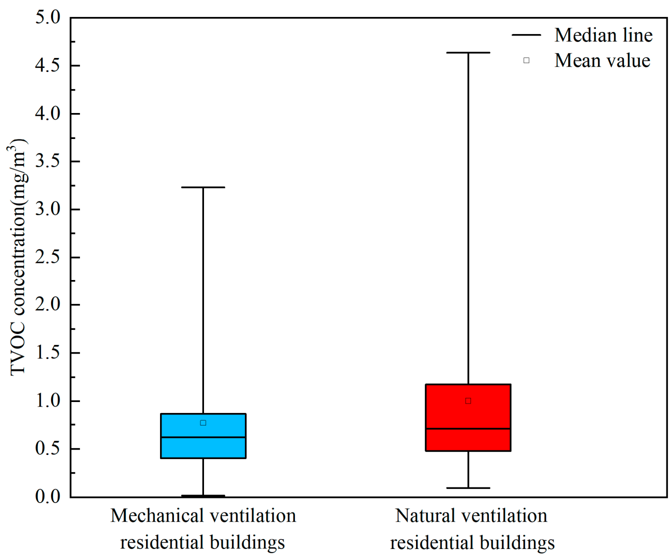

Figure 12. TVOC concentrations of residential buildings with different ventilation modes.

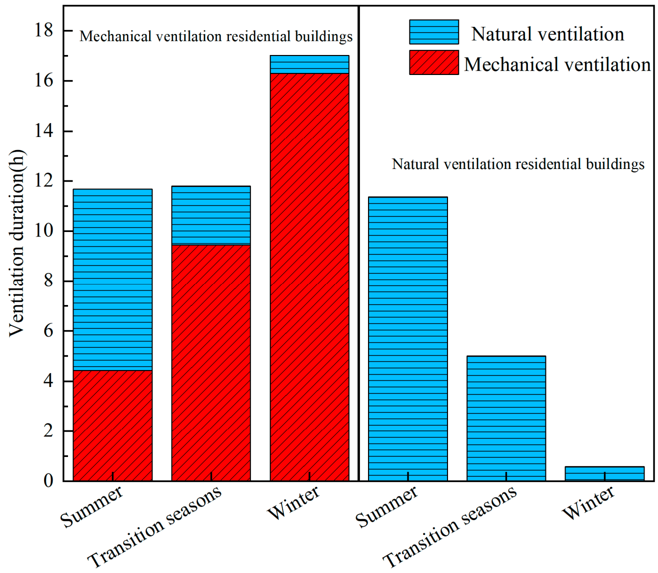

Figure 13. Ventilation duration of different ventilation modes.

3.6. Enthalpy Exchange Efficiency of Fresh Air System

The fresh air systems installed in the mechanically ventilated residential buildings selected in this study were total heat exchange. Exhaust air was used to preheat outdoor fresh air in winter, and in summer, exhaust air was used to cool outdoor fresh air, so as to achieve the purpose of energy saving. Testing enthalpy exchange efficiency was the main method to evaluate whether the total heat recovery fresh air system installed in cold areas could save energy. The frequency of using total heat recovery fresh air system is the highest in winter in northeast China, and the enthalpy exchange efficiency of each fresh air system in winter is shown in Figure 14. Among them, the average enthalpy exchange efficiency of the heat recovery fresh air system of 7 residential buildings was 72.0%, and the enthalpy exchange efficiency of each heat recovery fresh air system under heating conditions was higher than the requirement of 55.0% stipulated in the national standard GB/T 21087-2007 "Air-Air Energy Recovery Device" [46]. The heat exchange performances of the heat recovery fresh air systems were up to the standard. Zhao [47] determined the economic efficiency of the fresh air system used in five climate zones in China. The comparison showed that the fresh air system used in northeast China was the highest, which could improve indoor air quality and thermal comfort.

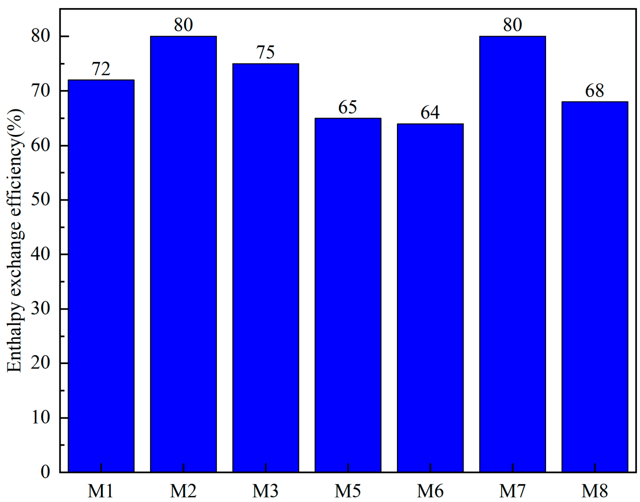

Figure 14. Enthalpy exchange efficiency of residential buildings.

3.7. Benzene Carcinogenic Risk

According to the regulations of the UPA, when the lifetime carcinogenic risk (*LCR*) is greater than 10^{-4}, it means that the carcinogenic risk is significant under this calculation condition; when the *LCR* is between 10^{-4} and 10^{-6}, the carcinogenic risk is acceptable; when the *LCR* is less than 10^{-6}, the carcinogenic risk is not significant, and 10^{-6} is also considered as a safety limit [48].

$$LADD = \frac{CA \times IR \times ET \times EF \times ED}{BW \times LT} \tag{1}$$

The average chronic daily intake (in mg/(kg·d)) of benzene exposure was calculated according to Formula (1). Exposure parameters mainly refer to the "Chinese Population Exposure Parameters Manual (Adult Volume)" [49] published in 2014. Where *CA* represents the benzene concentration (mg/m^3) obtained by the actual field measurement. The average benzene concentrations of mechanically ventilated residential buildings and naturally ventilated residential buildings were 0.0086 mg/m^3 and 0.0096 mg/m^3, respectively. *IR* represents the respiratory rate (m^3/h), and the average respiratory rate of adults is 0.83 m^3/h; *ET* is the exposure time (h/d), taking an average of 12 h/d; *EF* is the exposure frequency (d/a), taking an average of 313 d/a; *ED* is the continuous exposure time (a), and the average residence time of the occupants in residential buildings is 10 a; *BW* is body weight (kg), and the average body weight of adults is 60 kg; *Lt* is the expected life (a), taking 70 a (25550d).

$$LCR = LADD \times SF \tag{2}$$

Formula (2) was used to calculate the lifetime carcinogenic risk of benzene. Where *SF* is the slope factor, which is 0.029 mg/(kg·d) according to the regulations of the UPA. The benzene concentration was defined as a hypothetical variable, the lifetime carcinogenic risk was defined as a predictor variable, the number of iterations was set as 5000, and the confidence interval was set as 5% to 95%. The calculated average lifetime carcinogenic risks of benzene in mechanically ventilated residential buildings and naturally ventilated residential buildings were 5.08×10^{-6} and 5.63×10^{-6}, respectively, which were both higher than the international safety limit of carcinogenic risk of 1.0×10^{-6}, indicating that the tested occupants were at carcinogenic risk and the risk was acceptable. Through the comparative analysis of health risks, it could be seen that even if the mechanically ventilated residential buildings were at the carcinogenic risk, they were still lower than the naturally ventilated residential buildings.

4. Conclusions

In this study, the indoor VOC pollution of 8 mechanically ventilated residential buildings and 8 naturally ventilated residential buildings in northeast China was investigated via field measurement and long-term online monitoring. The main findings are as follows.

The concentration levels of TVOC in different seasons or different functional rooms were significantly different. The TVOC concentration in winter was the highest, which was 0.994 mg/m^3. The kitchen was the place with the most serious VOC pollution, and the concentration of TVOC could reach 1.403 mg/m^3. Chinese family kitchens were small, and the characteristic cooking methods and cooking time led to the accumulation of VOCs. No matter whether in different seasons or different functional rooms, the indoor TVOC concentrations exceeded the standard value of 0.60 mg/m^3 set by national standards. It could be seen that indoor VOC pollution was serious in northeast China.

Through analysis, the number of VOCs with a detection rate greater than 50.0% was 33, 29, and 29 in the bedrooms, living rooms, and kitchens, respectively. These VOCs were commonly found in residential buildings. Among them, aldehydes, alkanes, and benzene series accounted for a higher proportion, accounting for 18.7%, 15.39%, and 14.38%, respectively. The highest detection rates were mainly benzene series and methylsiloxane, with average concentrations of 0.025 mg/m^3 and 0.013 mg/m^3, respectively, indicating that

VOCs with high detection rates were not the main indoor pollutants in residential buildings. Meanwhile, in the VOCs with high detection rates, the mass ratios of aldehydes, alkanes, and benzene series were also higher, which were 14.90%, 30.85%, and 15.70%, respectively. The mass ratio of esters was detected in the kitchens up to 15.48%. Therefore, alkanes were the VOC types with the highest pollution concentration in residential buildings in northeast China.

The TVOC concentration levels of residential buildings with different ventilation modes were different. It could be seen from the detection results that the indoor TVOC pollution of mechanically ventilated residential buildings was lower than that of naturally ventilated residential buildings. The median indoor TVOC concentrations of mechanically ventilated residential buildings and naturally ventilated residential buildings were 0.621 mg/m^3 and 0.707 mg/m^3, respectively. Mechanically ventilated residential buildings use two ventilation modes in different seasons. Especially in winter, when the outdoor temperature was low, the average daily natural ventilation duration was only 0.71 h, while the average daily mechanical ventilation duration was 16.3 h, and the total ventilation duration was 29 times that of naturally ventilated residential buildings. The annual daily average ventilation duration of mechanically ventilated residential buildings was 7.84 h longer than that of naturally ventilated residential buildings, which greatly affected the indoor pollution level. The average enthalpy exchange efficiency of the fresh air system in northeast China was 72%, which met the requirements of the national standard. The mechanical ventilation had applicability in the severe cold area of northeast China.

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