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Characteristics of Formaldehyde Pollution in Residential Buildings in a Severe Cold Area—A Case in Liaoning, China

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Abstract: The negative impact of indoor formaldehyde pollution has become a growing interest, especially in severe cold areas, since most residential buildings do not have enough ventilation and people are unwilling to open windows. In order to explore the status and the influencing factors of indoor formaldehyde pollution in severe cold areas and predict the formaldehyde concentrations in these areas, a study of 60 residential buildings in Liaoning, China, was carried out using the method of phenol reagent spectrophotometry. While testing the formaldehyde concentration, the infiltration air change rate of the room was also tested using CO_2 as a tracer gas. The correlation between formaldehyde concentration and its influencing factors was analyzed by SPSS software. Multiple linear regression equations were established for the linear regression analysis. The measured data were used to assess the formaldehyde cancer risk of residents in Liaoning. The test results showed that the most serious rates of average formaldehyde pollution occurred in summer with a concentration of 0.097 mg/m^3, and the bedroom was the room most seriously polluted by formaldehyde in autumn with a concentration of 0.104 mg/m^3. According to the correlation analysis, the formaldehyde concentration was significantly correlated with the indoor temperature, years of decoration, and the infiltration ventilation rate. The linear regression equation for predicting the formaldehyde concentration was established. According to the risk assessment of the test results, residents in Liaoning are already at risk of cancer caused by formaldehyde.

Keywords: formaldehyde; indoor air; measurement; numerical analysis; risk assessment

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1. Introduction

In modern society, most people's work and life are gradually moving indoors, leading to the fact that people can spend more than 90% of their time indoors, which makes it inevitable that they breathe in a large amount of indoor air [1]. According to statistics, adults breathe 10 to 15 times per minute, with 0.5 L of air being inhaled each time. Calculated based on the average lifespan of 70 years, each person will breathe in 270,000 m^3 of air in their lifetime. The air drawn into the alveoli through human respiration has a total surface area of 60 to 80 m^2 [2]. Then it is physically diffused into the body for exchange, and the pollutants contained in the air also enter the body. Poor indoor air quality (IAQ) can cause people to develop serious diseases such as sick building syndrome (SBS), which has become an increasingly global problem. Therefore, it is widely believed that IAQ has a great impact on the physical and mental health of people both at home and abroad [3,4]. At present, Chinese residents are facing serious indoor and outdoor IAQ problems and are in need of guidance on indoor pollution removal methods and ventilation strategies.

As a common indoor air pollutant, formaldehyde is listed by the International Agency for Research on Cancer (IARC) as a category 1 carcinogen in humans and can irritate the eyes and upper respiratory tract [4]. Many other studies have found that formaldehyde is highly toxic and a carcinogen that can cause respiratory diseases [5,6]. With the increasing improvement of living standards, people care more and more about the indoor visual environment. This has led to more and more complex and diverse interior decoration. Therefore, the complex decoration materials in the relatively airtight indoor space have become the main source of pollution harming the human body [7]. Just like the deaths of Ali employees who rented rooms with excessive formaldehyde that led to leukemia [8], increasing attention and awareness have been paid to indoor pollutants such as formaldehyde. Currently, people are faced with the problem of exceeding the standard limit of indoor pollutants, which has once again initiated an upsurge of indoor air quality testing.

Studies have shown that common construction products such as wood-based materials, particleboard, furniture surface coatings, and combustion materials are typical indoor formaldehyde sources [9–11]. In addition to those sources, others include outdoor sources such as biomass burning and the conversion of biogenic emissions [12], chemical reactions in indoor spaces, various combustion processes, the operation of equipment such as air purifiers, and emissions from human activities such as saunas, cooking, and cleaning [13]. Due to the complex pollution sources of formaldehyde in residential buildings, there are many factors that affect the concentration of formaldehyde. In terms of interior decoration, the quality and quantity of man-made board, decorated material loading factor (wooden floors, cold-paint multi-layer wooden materials, and multi-layer materials for system furniture), furniture features (such as geometric features, product components, processing, and function), type of paint and coating of the surface area, external environmental factors (such as temperature and humidity), maturing time, and many other factors will affect the concentration of formaldehyde in indoor air [10,11,14–16]. Therefore, it is particularly important to study the emission characteristics of formaldehyde. Some scholars have studied the influence of relative humidity on the decomposition of formaldehyde. The results showed that when the relative humidity is between 25% and 50%, there is no significant difference in the effective change coefficient of formaldehyde [17]. However, 10 °C variations in temperature increased the formaldehyde emissions 1.9~3.5 times [18]. To explore the emission characteristics of indoor formaldehyde, an effective approach is the regression analysis method to separate the influence of different factors [19]. However, each region in different climatic zones has its own environmental conditions, and relatively few field tests and characteristic studies have been conducted on indoor formaldehyde concentrations for the severe cold areas of northeast China [20,21]. Thus, it is necessary to establish a regression equation that belongs to severe cold areas for predicting the formaldehyde concentrations in these regions.

In the present research, the status, influencing factors, and regression equation for indoor formaldehyde pollution were studied based on a group of 60 residential buildings in Liaoning, China. In total, 39 households were tested by on-site measurement and the data of the other 21 households were taken from our former research [22]. Referring to a method of linear regression [23], a multiple linear regression equation applicable to the Liaoning region was established. The formaldehyde concentration obtained from the test was used to calculate the current formaldehyde cancer risk of residents in Liaoning province.

2. Methods

2.1. Depiction of the Tested Household Conditions

To determine the status of the formaldehyde pollution in residential buildings in the Liaoning area, 60 residential buildings in Shenyang (the largest city in Liaoning province, 41°48′ N, 123°25′ E), Fushun (the typical old base of heavy industry in Liaoning, 41°52′ N, 123°55′ E), and Yingkou (the typical port city of Liaoning, 40°39′ N, 122°13′ E) were selected for the to be tested by on-site measurement of formaldehyde concentrations. In addition, 29 households were selected according to different environmental conditions for on-site measurement in the different seasons of the year. The selection of the sample size was carried out according to the maximum number of households that can be determined using the existing research funds. Due to certain difficulties in on-site measurement, the sample size selected in this paper was not small [23], and it also met the requirement that the ratio of variable to sample size should be at least five times when conducting multifactor regression analysis with a small sample size [24]. The climate of the selected region is characterized by cold and dry winters (November–March), short transition seasons (April–May, September–October), and hot and rainy summers (June–August). The houses tested were chosen according to the time since they were last decorated, number of floors, apartment type, floor area, and decoration method. Approximately half of all households had been decorated between 1 and 2 years from the start of the test. Various types of residential units were included in the study, including one- to four-bedroom homes, duplex apartments, and villas. The floors on which the residences were found cover low, medium, and high positions, with the highest being 32 floors. The decorating materials were mainly latex-painted walls, composite wood floors (tiles), and panel furniture. The information for the 29 households under long-term monitoring is shown in Table 1.

2.2. On-Site Measurement of Formaldehyde

At present, there are two existing indoor air quality standards in China, namely, GB/T 18883-2002 Indoor Air Quality Standard established by the Ministry of Health [25] (hereinafter referred to as the GB/T 18883 standard) and GB 50325-2020 Indoor Environmental Pollution Control Code for Civil Construction Projects issued by the Ministry of Construction [26] (hereinafter referred to as the GB 50325 standard). The differences between the two standards are shown in Table 2.

From the perspective of numerical comparison, the GB/T 18883 standard is more lenient, while the GB 50325 standard is stricter. From the perspective of the implementation conditions of the standards, the GB 50325 standard is the project acceptance standard, which does not consider indoor furniture, while the GB/T 18883 standard is the daily operating standard. Thus, there are some different requirements between them. What is more, their test preconditions are also different. The GB/T 18883 standard requires the sampling room to be airtight for 12 h before sampling, whereas the GB 50325-2020 standard only requires the sampling room to be airtight for 1 h before sampling. For this difference, Li et al. believed that the concentration of pollutants tested after 12 h of airtightness should be the highest concentration possible during people's stay indoors, which was considered the most adverse conditions [27]. For this reason, the standard referred to in this paper for the on-site measurement is the GB/T18883 standard, that is, the sampling rooms were kept airtight for 12 h before the measurements were taken.

The testing lasted for almost one year, starting from 20 December 2016 and ending on 30 October 2017. Typical days in each of the four seasons were selected for the on-site measurement under airtight conditions. The specific test time was from 20 December 2016 to 20 January 2017 in winter, 22 April 2017 to 4 June 2017 in spring, 15 July 2017 to 29 August 2017 in summer, and 11 October 2017 to 30 October 2017 in autumn.

The main functional rooms of a residential house can be divided into three parts: the bedroom, the living room, and the kitchen. Therefore, these three functional rooms were selected for the on-site measurement in this paper. The number of sample points in each test room was determined according to the area required in the GB 50325 standard. The sampling site should avoid vents and possible pollution sources, and the distance from the wall should be greater than 0.5 m. In principle, the height of the sampling site should be consistent with the height of the breathing zone. The relative height is between 0.5 m and 1.5 m, and should be arranged in the middle of the room as far as possible. In the sampling process, the sampler is placed on a bracket fixed a height at 1.4 m. When the sampling space is too small to place the bracket, the sampler is placed on a cabinet with a height of more than 1 m as far as possible.

Table 1. Household information.

NO.	City	Construction Year	Year of Decoration	Building Floor No.	No. of Floors	House Type	Residential Area (m^2)	Furniture Surface Area (m^2)	Decoration Type
N1	Shenyang	2011	2011	11	2	Four-bedroom	145	42.345	Latex paint + wallpaper + solid wood
N2	Shenyang	2012	2012	19	6	Two-bedroom	70	37.522	Latex paint + composite wood
N3	Shenyang	2013	2013	18	16	Two-bedroom	90	21.285	Putty powder + composite wood
N4	Shenyang	2009	2009	16	3	Two-bedroom	100	41.302	Latex paint + composite wood
N5	Shenyang	2013	2013	33	26	Three-bedroom	134	52.9676	Latex paint + solid wood
N6	Shenyang	2004	2004	9	8	Three-bedroom	140	63.975	Latex paint + solid wood
N7	Shenyang	2012	2012	28	16	Three-bedroom	120	60.415	Latex paint + composite wood
N8	Shenyang	2003	2003	6	6	Three-bedroom	110	46.3825	Latex paint + composite wood
N9	Shenyang	2015	2015	30	27	Two-bedroom	105	39.04	Latex paint + composite wood
N10	Shenyang	2011	2011	6	1	Two-bedroom	110	33.659	Latex paint + composite wood
N11	Shenyang	2008	2009	23	2	Penthouse	150	52.46	Putty powder + solid wood
N12	Shenyang	2002	2009	6	1	Two-bedroom	90	52.23	Putty powder + composite wood
N13	Shenyang	2003	2004	6	1	Three-bedroom	95	36.3275	Putty powder + composite wood
N14	Shenyang	2002	2012	6	1	Three-bedroom	125	34.03	Putty powder + composite wood
N15	Shenyang	2009	2009	28	13	Two-bedroom	90	40.28	Latex paint + composite wood
N16	Fushun	2016	2016	33	1	Two-bedroom	80	40.33	Latex paint + composite wood
N17	Fushun	2016	2016	33	6	Two-bedroom	75	28.243	Latex paint + composite wood
N18	Fushun	2016	2016	33	27	Single room	65	41.785	Latex paint + composite wood
N19	Fushun	2016	2016	33	1	Two-bedroom	65	39.905	Latex paint + composite wood
N20	Fushun	1996	2016	6	5	Two-bedroom	75	22.225	Latex paint + composite wood
N21	Fushun	2016	2016	28	4	Two-bedroom	65	22.38	Latex paint + composite wood
N22	Yingkou	2016	2016	7	7	Three-bedroom	120	21.308	Diatom ooze + composite wood
N23	Yingkou	2016	2016	2	6	Two-bedroom	90	44.928	Diatom ooze + composite wood + ceramic tile
N24	Yingkou	2012	2013	7	28	Four-bedroom	160	43.095	Wallpaper + textile + solid wood + ceramic tile
N25	Yingkou	2016	2017	-	3	Villa	300	43.5	Latex paint + wallpaper + solid wood + ceramic tile
N26	Shenyang	2016	2016	16	34	Single room	55	38.22	Latex paint + composite wood
N27	Shenyang	2016	2016	32	34	Single room	52	34.62	Latex paint + composite wood
N28	Shenyang	2016	2016	9	34	Single room	55	43.41	Latex paint + composite wood
N29	Shenyang	2016	2016	26	34	Two-bedroom	65	36.32	Latex paint + composite wood

Table 2. Differences between standards.

	GB/T 18883-2002 Indoor Air Quality Standard	GB 50325-2020 Indoor Environmental Pollution Control Code for Civil Construction Projects
Formaldehyde/mg/m^3	0.10	0.07
VOC/mg/m^3	0.60	0.50
CO_2/ppm	1000 ppm (daily average)	
$PM_{2\cdot5}$/mg/m^3	0.075 (daily average)	According to GB 3095-2012 Ambient Air Quality Standard, excellent < 0.035, good < 0.075, light pollution < 0.115, medium pollution < 0.15

According to the standard of GB/T 18204.2-2014 "Public Health Inspection Methods—Part 2: Chemical Pollutants" [28], the concentration of formaldehyde is determined by the phenol reagent (3-methyl-2-benzothiazolinone hydrazone, hereinafter referred to as MBTH) spectrophotometric method. Before sampling, the absorption liquid (MBTH) was configured, and 5 mL of the absorption liquid was put into the absorption tube, which had been washed and dried with distilled water in advance. Air sampling pumps were used to circulate 10 L air through the absorption tubes over 20 min at a rate of 0.5 L/min. After sampling, the formaldehyde absorbent was transferred into the colorimetric tube, and the absorbent was stabilized to 5 mL, 0.4 mL of ammonium ferric sulfate was added, and the solution was left to stand for 15 min during the experiment. Finally, a spectrophotometer (Figure 1a, Table 3) was used to measure the absorbance of the sample at the wavelength of 630 nm (the spectrophotometer should be preheated for 40 min), and this value was compared with the standard curve to calculate the formaldehyde concentration in the sample. This method provides acceptable accuracy with a coefficient of variation lower than 5%, and has been used in many studies [29–32]. However, during the testing process, both the preparation of the solution and the handling during sampling and assaying may have an impact on the final results. Considering other studies used sophisticated testing instruments for field testing, we should enhance the accuracy and science of the testing in future studies.

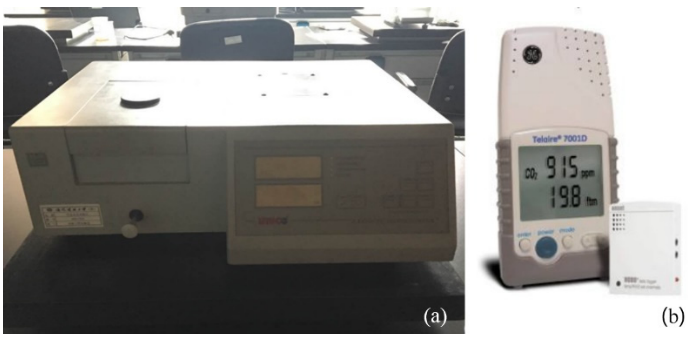

Figure 1. Test equipment: (**a**) spectrophotometer, (**b**) Telaire 7001 and HOBO.

Table 3. Equipment information.

Equipment	Manufacturer	Model
Spectrophotometer	UNICO (Shanghai)	2100PC
CO_2 gas detector	GE (USA)	Telaire 7001
Recorder	ONSET(USA)	HOBO U12

2.3. Measurement and Determination of Infiltration Rate

The tracer gas decay method according to the national standard testing GB/T 18204.1-2013 "Public Health Inspection Methods—Part 1: Test Method of Public Health Physical Factors" was used to determine the infiltration rate of each household for the different seasons [33]. CO_2 was selected as a tracer gas and the average method was used to analyze the test results. Due to the limited conditions, it was difficult to test the infiltration rate of the whole house, so only the bedroom was selected as the measurement point in this paper. The test procedure is as follows: close the windows and doors of the test room, release carbon dioxide into the bedroom, and turn on a fan to mix the tracer gas with the indoor air. When the CO_2 concentration in the test room reaches 2500 PPM, stop releasing the CO_2 and turn off the two mixing fans after 5 min. The Telaire 7001 sensor and HOBO (Figure 1b, Table 3) were used to continuously measure and record CO_2 concentration and temperature at two measuring points. The test was completed when the CO_2 concentration had decayed to the background level. The experiment was repeated twice to ensure data quality. The ventilation frequency N is calculated by Equation (1).

$$\mathrm{N} = \frac{\ln(C_1 - C_0) - \ln(C_\tau - C_0)}{\tau} \tag{1}$$

where the environment background concentration of the tracer gas is C_0, the mass concentration of the tracer gas in the room at the initial time (ppm) is C_1, the mass concentration of the tracer gas in the room at time τ (ppm) is C_τ, and the measurement time is τ.

2.4. Data Processing

The data processing adopted the method of overall statistical analysis to comprehensively analyze the variation trend of formaldehyde concentrations in the household and a macro analysis of the data was made. The Pearson's correlation analysis used SPSS software to analyze the correlation between the data and the significant differences between the two independent samples. When the p-value is less than 0.05, the statistical correlation is considered to be significant. At the same time, multiple regression analysis was carried out based on the data. Equation (2) adopted the regression model established in this test research group.

$$\mathrm{y} = y_0 + A_1 \exp(\mathrm{T}_0) + A_2 \ln(Y) + A_3 \ln(V_0) + 1000\mathrm{A}_4 d \tag{2}$$

where y represents the predicted indoor formaldehyde concentration under airtight conditions, y_0 represents the initial concentration of the indoor formaldehyde, and T_0 represents the standard indoor air temperature: $T_0 = T/15$ (T represents the sampling point temperature, and 15 °C was the base temperature because it was almost the lowest indoor air temperature found during the on-site measurements), Y represents the years of decoration for each household, V_0 is the standard infiltration rate of each household: $V_0 = V_\mathrm{i}/0.3$ (0.3 h^{-1} was the standard infiltration rate because it was the infiltration rate with the highest probability density according to the distribution fitting result), and d represents the source characteristics variable and is set as −1, 0, and 1 for households with low, modest, and high formaldehyde concentrations, respectively, and 1000 is a conversion factor to change from $\mathrm{mg/m^3}$ to $\mathrm{\mu g/m^3}$ for formaldehyde [23].

2.5. Health Risk Assessment

Equation (3) [34] was used to calculate the average chronic daily intake (CDI, mg/kg/day) for household formaldehyde exposure.

$$CDI = \frac{C \times IR \times ED \times EF}{BW \times ATL} \tag{3}$$

where C is the formaldehyde concentration of 0.081 $\mathrm{mg/m^3}$ obtained from the on-site measurement and IR is the respiration rate, which is 0.63 $\mathrm{m^3/h}$ for an adult male and

0.4 m^3/h for an adult female, respectively. The average of these, 0.52 m^3/h, was selected in this paper. *EF* is the exposure frequency (d/year), the test population is family members, and the average daily exposure is 16.3 h/d. *ED* is the duration of continuous exposure (year) and the average duration of residence was assumed to be 10 years. *BW* represents weight (kg), and the average adult weight is assumed as 60 kg. *ATL* represents the average lifespan (70 years). Equation (4) was used to calculate the lifetime carcinogenic risk (*LCR*) of formaldehyde.

$$LCR = CDI \times PF \tag{4}$$

where *PF* is the slope factor, referring to the carcinogenic risk slope factor proposed by the US Environmental Protection Agency (EPA) of 0.046 mg/(kg·d) [35].

3. Results and Discussion

3.1. Formaldehyde Concentrations

The key statistical parameters of each sampling site and the situation of exceeding the standard are shown in Table 4. The indoor formaldehyde concentrations of 60 households in the Liaoning area under airtight conditions are shown in Figure 2. As can be seen from the results, the average concentration of each sampling site in the residences in the Liaoning area does not exceed the standard, but is close to the limit. The average formaldehyde pollution in the bedrooms is more severe than in the other two sampling sites, mainly due to the smaller space and the presence of more furniture. The phenomenon of formaldehyde exceeding the standard limit was found in all three sampling sites, with the exceeding rate of the living room being highest; this may be connected with the wallpaper used for decoration in this part of the household. In general, the average concentration of formaldehyde in the Liaoning area is below 0.1 mg/m^3 after 12 h of airtightness, as stipulated in the GB/T18883 standard, but nearly one-third of the households experienced indoor formaldehyde concentrations that exceeded the standard.

Table 4. Statistical parameters and over-standard rate of formaldehyde in 60 households.

Formaldehyde	Bedroom	Living Room	Kitchen
Average	0.0816	0.0748	0.0721
Median	0.0820	0.0714	0.0642
Over-standard rate	28.07%	30.19%	28.21%

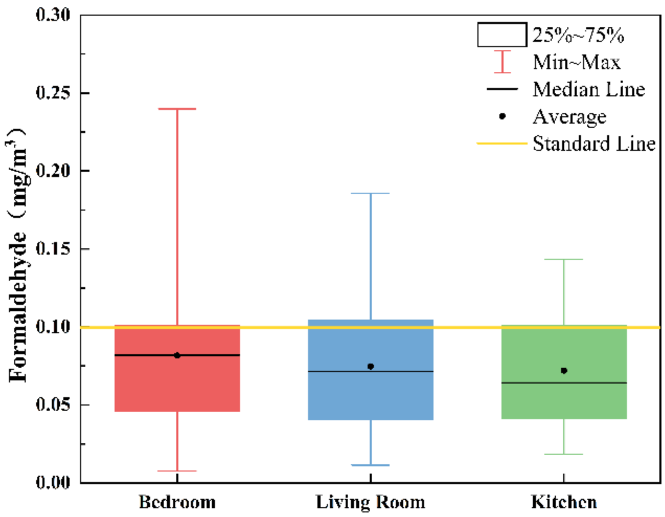

Figure 2. Indoor formaldehyde concentration in 60 households in Liaoning.

The above results include the formaldehyde concentration test results of each season. In order to explore the indoor formaldehyde concentration levels of the residential buildings in the Liaoning area over different seasons, 29 households were selected according to the different environmental conditions. The on-site formaldehyde measurement results under typical daily airtight conditions over the four seasons of the year are shown in Figure 3. It can be seen from the figure that the formaldehyde concentrations under airtight conditions changed with the seasons: they increased with the increase of the outdoor temperature and reached a peak in summer. In one household, the formaldehyde concentrations at the three sampling sites exceeded 0.2 mg/m^3 in the summer, twice the national standard limit. Table 5 shows the rates of formaldehyde under airtight conditions. According to the over-standard rate, formaldehyde pollution in autumn is relatively serious, and the average concentration of formaldehyde in the bedroom in autumn is 0.104 mg/m^3.

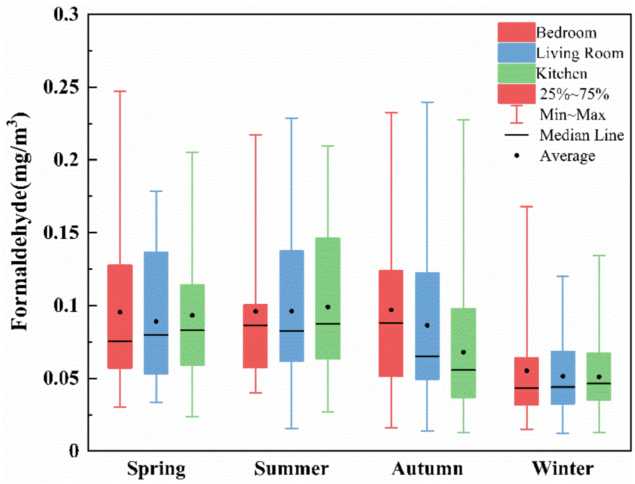

Figure 3. Indoor formaldehyde concentrations of 29 households over different seasons.

Table 5. Over-standard rate of formaldehyde concentrations in 29 households.

Formaldehyde	Winter	Spring	Summer	Autumn
Bedroom	12.5%	37.9%	26.1%	48.3%
Living room	6.25%	25.9%	34.8%	26.9%
Kitchen	3.2%	26.9%	30.0%	18.5%

Due to the lower outdoor temperatures in the autumn and the absence of district heating in Liaoning, the low indoor temperature in autumn leads to less ventilation behavior in residents' bedrooms, such as opening windows. At the same time, the temperature difference between the indoor and outdoor environment is lower, resulting in lower infiltration rates in the rooms. These factors caused the serious increases in formaldehyde concentrations in the bedrooms of Liaoning residents in the autumn. In summer, according to previous studies [22,36], residents of the Liaoning area use air conditioning less frequently in their bedrooms, and most of them achieve indoor thermal comfort by opening windows for ventilation combined with the use of electric fans. Therefore, bedrooms are more ventilated and have lower formaldehyde concentrations compared to other rooms. However, the overall average formaldehyde concentration in summer under airtight conditions is 0.097 mg/m^3, which is the highest among the four seasons. The reason was that the formaldehyde concentrations were very high (0.217 mg/m^3, 0.209 mg/m^3, and 0.180 mg/m^3) in the three houses decorated with wallpaper. There are several reasons for the lower formaldehyde concentration in the kitchen compared to other rooms. Firstly, from the on-site test process, we found that most households have a small kitchen space and almost no furniture except for cabinets. Secondly, most of the residents will open the cooker hood when cooking, resulting in frequent mechanical ventilation in the kitchen and more fresh air compared to other rooms. Some of the kitchen windows in older buildings can be less airtight and therefore have higher infiltration rates due to the use of cooker hoods over the years. Thirdly, the households tested included high-rise residences. The non-return valves in their hood ducts also result in more air changes in the kitchen due to thermal pressure [37]. These three points are the reason for the relatively low concentrations of formaldehyde in the kitchen. In winter, the temperature difference between the indoor and outdoor environment is larger and the number of infiltration air changes is higher compared to other seasons. The amount of fresh air is also greater in kitchens when using cooker hoods for mechanical ventilation. These factors lead to the lower formaldehyde concentrations observed in kitchens in the Liaoning area in winter than other rooms [38,39]. The test results show that the characteristics of seasonal changes in indoor formaldehyde concentrations in Liaoning are consistent with those in other climate zones in China, and are related to the indoor temperature and humidity [14,40]. However, the indoor formaldehyde concentrations were higher in Liaoning than in the southern region of China. Compared with the southwest region, the formaldehyde concentrations under airtight conditions are similar, but the situation varies from room to room, and the formaldehyde concentration in the kitchen is higher in the northwest region [41]. Thus, the formaldehyde concentrations in different regions of China have their own characteristics, so it is more important to develop the corresponding formaldehyde prediction and treatment methods according to the geographical characteristics.

3.2. Infiltration Rate

A distribution histogram of the ventilation rate of residential buildings in Liaoning province is shown in Figure 4. The average infiltration rate is 0.38 times per hour, and the median is 0.34 times per hour. Previous studies have shown that the concentrations of formaldehyde and TVOC are relatively lower when the infiltration rate of the residence is high [42]. However, in winter, a high infiltration rate will not only cause the invasion of outdoor PM2.5, but also reduce the indoor temperature and increase indoor energy consumption. If the infiltration rate is too low, it will lead to insufficient indoor fresh air volume and indoor pollutant accumulation. Therefore, determining a reasonable range of osmotic ventilation times has become a very important research topic.

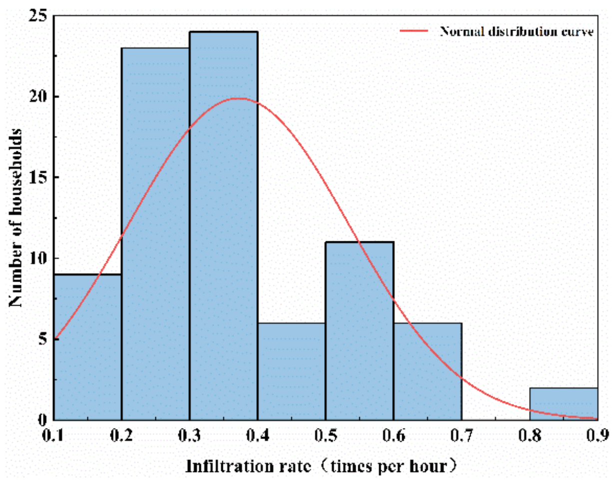

Figure 4. Distribution histogram of the infiltration rate.

3.3. Correlation Analysis

In order to explore the correlation between the influencing factors and the concentration of formaldehyde, SPSS software was used to analyze the correlation between formaldehyde concentration and infiltration rate, decorating material loading factor (the ratio between the total exposed area of decorating materials used and the net space volume of the room during interior decoration [26]), the years since decoration, and the indoor temperature. The results are shown in Table 6, from which it can be seen that formaldehyde is significantly positively correlated with indoor temperature, significantly negatively correlated with years since decoration, and infiltration, and weakly correlated with the decorating material loading factor, which was not statistically significant. Therefore, the decorating material loading factor was not considered when the regression equation of the Liaoning region was established.

Table 6. Correlation analysis.

Formaldehyde	Years of Decoration	Infiltration Rate	Indoor Temperature	Decorating Material Loading Factor
Pearson correlation coefficient	−0.11 *	−0.382 *	0.132 *	0.082
p-value	0.048	0.034	0.034	0.231

* Note: the correlation was significant at the 0.05 level (two-tailed).

3.4. Regression Analysis

According to the research mentioned above, the indoor formaldehyde concentration is significantly correlated with the logarithm of years of decoration, the logarithm of infiltration rate, and the index of indoor temperature under airtight conditions. The regression model was recalculated using the data obtained from the on-site measurement of residential buildings in Liaoning province, and the linear regression Equation (5) belonging to Liaoning province was established. The calculated parameters are shown in Table 7.

$$y = 16.6 + 4.7\exp(\mathrm{T_0}) - 0.674\ln(Y) - 17.3\ln(V_0) + 50d \quad (5)$$

Table 7. Parameters of the regression equation.

	Estimated Value (Std. Error)	T	Pr (>∣t∣)
y_0	16.6 (9.86)	1.671	0.009
A_1	4.7 (1.78)	2.644	0.01
A_2	−0.674 (2.87)	−0.235	0.015
A_3	−17.3 (4.77)	−3.626	0.001
A_4	50	13.766	0.000
R^2	0.776		
Adjusted R^2	0.764		
F-statistic	63.959		
p-value	0.000		
n	60		

In previous studies, regression Equation (6) [23] was established using the test results of formaldehyde concentrations and the influencing factors in all climatic regions in China, and is shown below.

$$y = 48.6 + 3.9\exp(\mathrm{T_0}) - 9.3\ln(Y) - 11.3\ln(V_0) - 48d \quad (6)$$

Because the equation was established based on data taken from all climatic regions in China, a large deviation will occur when it is used to predict the formaldehyde concentrations in Liaoning province alone. The test results from Liaoning province were used to verify the two regression equations. The verification results were compared and are shown in Figure 5. It can be seen from the results that there is a large deviation between Equations (5) and (6), so Equation (4) cannot accurately represent the characteristics of the Liaoning region.

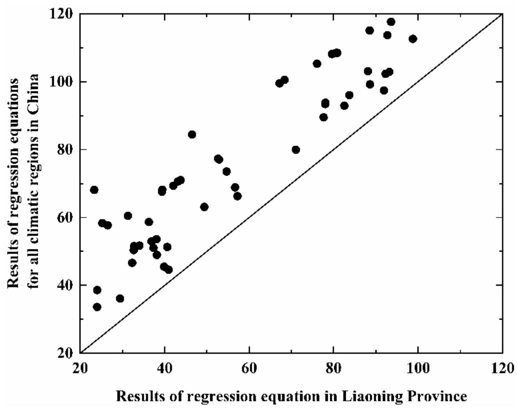

Figure 5. Comparison results of regression equations.

3.5. Health Risk Assessment

After calculation, the lifetime carcinogenic risk of formaldehyde in residential buildings in Liaoning province is 3.1×10^{-6}, which is higher than the international carcinogenic risk standard value of 1.0×10^{-6} set by the US Environmental Protection Agency [35]. Therefore, residents in the Liaoning region have a higher risk of cancer because of indoor formaldehyde. It is urgently necessary to study how to control indoor formaldehyde pollution. In future studies, more representative tests and long-term monitoring should be carried out on more households, and an affordable indoor formaldehyde pollution control scheme should be provided for residents in this area.

4. Conclusions

This paper examines the indoor formaldehyde pollution of 60 residential buildings in the Liaoning area, carries out tracking tests of formaldehyde in 29 of them over four seasons, and obtains the infiltration rate of residential buildings using the tracer gas decay method. The correlation and regression analyses of formaldehyde and its influencing factors were carried out with the test data, and the risk of formaldehyde-related cancer among residents in Liaoning province was evaluated. The research drew the following conclusions.

The average formaldehyde concentrations and the over-standard rate at the three sampling points of 60 residential buildings in Liaoning were 0.0816 mg/m^3 (28.07%) for the bedrooms, 0.0748 mg/m^3 (30.19%) for the living rooms, and 0.0721 mg/m^3 (28.12%) for the kitchens. Over the four seasons, the formaldehyde pollution was the most serious in summer, with an overall average formaldehyde concentration of 0.097 mg/m^3, and the formaldehyde pollution in the bedrooms of the three sampling points was the most serious in autumn, with an average concentration of 0.104 mg/m^3. The average infiltration rate in Liaoning was 0.38 times per hour.

There was a significant correlation between the concentration of formaldehyde and the years since decoration, the infiltration, and the indoor temperature in Liaoning, but a weak correlation was found between the concentration of formaldehyde and decorating material loading factor. According to the measured data to establish the regression equation for $y = 16.6 + 4.7\exp(T_0) - 0.674\ln(Y) - 17.3\ln(V_0) + 50d$, the LCR of formaldehyde in residential buildings in the Liaoning area is 3.1×10^{-6}, which is higher than the international carcinogenic risk standard value stipulated by the US Environmental Protection Agency, indicating that the residents in this area are at risk of cancer.

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