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Research Article

Accumulation and Diffusion of PM from Outdoor to Indoor by Clothing under Haze Conditions: A Case Study of Zhengzhou, China

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Clothing can absorb fine particulate pollutants from the atmosphere outdoors and then release them after entering the room in a form similar to three-handed smoke. In this study, the experimental site in Zhengzhou, a typical city with heavy pollution in central China, was used to investigate the adsorption and diffusion patterns of three different fabrics of polyester, polyester-cotton, and cotton clothing for fine particle pollutants, to guide people's behavior patterns and indoor air distribution, and to reduce indoor pollution exposure. The results showed that when garments of three different fabrics were exposed to moderate and heavy $PM_{2.5}$ pollution for 1 h, 2 h, and 3 h, respectively, and then transferred to the diffusion chamber, polyester always released the highest $PM_{2.5}$ concentration to indoor air during the same release cycle, followed by cotton and polyester-cotton. In addition, the concentration of indoor air pollutants will be periodically affected by the diffusion of fine particulate adsorbed by clothing fabrics. With the increase in outdoor pollution and exposure duration, the indoor $PM_{2.5}$ concentration takes longer to stabilize at certain levels after the clothing is transferred to the indoor side. Finally, the comparison of natural ventilation experiments proved that it is not feasible to rely solely on natural ventilation to improve the influence of clothing pollution sources on indoor air quality.

1. Introduction

Over the past two decades, with the rapid development of urbanization and industrialization, China, as the largest developing country in the world, has been faced with extremely serious air quality problems, and all parts of the country have been deeply affected by haze weather [1, 2]. Zhengzhou is a representative city of cold areas in central China, assuming the role of a national transportation hub. As a national center city, it has a large population and high density. The resident population of Zhengzhou has surpassed 13 million since 2020 and persists to grow at a rate greater than 1% per year, with its urbanization level reaching nearly 82 percent today, up from 58.4 percent in 2010. According to the CAQMA report (2016), Henan is one of the provinces with the most serious $PM_{2.5}$ pollution [3]. In addition, China's Ministry of Ecology and Environment reported the national ambient air quality situation in 2022, in which Zhengzhou's average $PM_{2.5}$ concentration in December was 76 $\mu g/m^3$, and its air quality was in the top twenty of the bottom 168 major cities in the country. In most polluted weather, fine particulate matter is the main contributor, which has attracted extensive attention from scholars [4–6]. Fine particulate matter ($PM_{2.5}$) is defined as particulate matter suspended in the air with an aerodynamic diameter of 2.5 microns or less. According to studies, fine particulate matter ($PM_{2.5}$) can be inhaled and deposited in the lungs, causing damage to human respiratory and cardiovascular systems or even leading to cancer, posing a threat to human health [7–12].

According to some scholars, the outdoor working hours of rural residents in China are 6 days per week on average, and the average outdoor activity time can be as high as 6.63 hours per day [13]. Although the outdoor activity time of urban residents will be significantly shortened, most are maintained within the time range of 1.5-3.5 hours per day [14–16]. Outdoor workers, such as sanitation workers, couriers, or construction workers, spend an average of 8-12 hours a day outside [17–19]. In addition, police officers, logistic personnel, and other special types of work are also engaged in outdoor labor for a long time. According to the characteristics of work type, the short-term rest space and duty room of relevant personnel are characterized by high-density small space. Outdoor particles are likely to be carried into the room by the human body and affect indoor air quality, causing damage to human health under such conditions. In fact, it is common for the concentration of indoor air pollutants to be several times higher than outdoor air pollutants, which is often caused by poor ventilation, overcrowding, and indoor pollution sources [20].

Most people spend 85-90% of their lives indoors [21], so it is crucial to study indoor particulate matter concentrations. Zhao et al. [22] found that the outdoor $PM_{2.5}$ concentration was much higher than the indoor $PM_{2.5}$ concentration under winter pollution conditions, and the I/O ratio was in the range of 0.6 to 0.8, which was also well illustrated by Ścibor et al.'s experiments [23]. A significant amount of $PM_{2.5}$ in the indoor environment is introduced from outdoors through natural ventilation, infiltration through cracks in building maintenance structures, and mechanical ventilation systems [24–27]. Another part comes from indoor emissions, such as smoking [28], cooking [29], human activities [30], and chemical reactions [31].

In the current studies, most studies on the coupling relationship between indoor and outdoor particulate concentrations focus on the permeability effect of outdoor particulate matter. As early as the 1950s, Gruber et al. analyzed and compared indoor and outdoor particulate concentrations for the first time in 1954 [32]. In the following time, numerous studies have shown that outdoor particles can significantly affect indoor particle concentration [33–35]. However, few studies on indoor pollution focus on particulate matter produced by indoor human activities. Gurung et al. [36] evaluated the impact of smoking behavior on the indoor environment. Zhou et al. [37] compared the effects of the outdoor environment and indoor human activities on indoor $PM_{2.5}$ concentration levels and found that smoking and cooking rapidly increased $PM_{2.5}$ concentration. Meanwhile, other human activities such as walking, dressing, and sweeping contributed to a 33 percent increase in $PM_{2.5}$ concentrations.

When exploring the influence of outdoor particles on indoor, most scholars adopt the method of measurement and obtain the law through long-term data monitoring. Zhao et al. [38] established the indoor and outdoor particle diffusion model based on the measured data and evaluated the relationship between indoor and outdoor particle concentration using the I/O ratio and found that indoor $PM_{2.5}$ lags about 2 hours compared with outdoor $PM_{2.5}$. Zhao et al. [22] continuously monitored indoor and outdoor $PM_{2.5}$ mass concentration in winter in Beijing and developed a prediction model based on mathematical statistics. Othman et al. [39] collected $PM_{2.5}$ concentration and dust in classrooms and analyzed that the primary source of indoor dust was road dust. When exploring the influence of human activities on indoor particulate matter, simulation was used to simulate human behavior in typical rooms to summarize the rules. Kamens et al. [40] set sampling points in three medium households and analyzed and studied typical activities, such as cooking, dust removal, or vacuum cleaning.

Above many types of research focus on the influence of human behavior as the pollution of the indoor environment but ignore the human body with clothing as adsorption of outdoor particulate matter pollution sources and secondary release of the effects into the room. In this work, experimental methods were carried out in the simulated cabin to control and adjust the exposure concentration and duration of clothing absorption of three different fabrics, polyester, polyester-cotton, and cotton, for exploring the law of diffusion after the accumulation of fine particulate matter by different clothing fabrics.

2. Method

2.1. Indoor Transport Model for PM

2.1.1. Model. The indoor particulate concentration depends on many factors as shown in Figure 1. Outdoor particulate matter can enter through natural or mechanical ventilation, penetrate through walls, or be generated by indoor personnel activities, such as cooking and cleaning. Another way is when people enter the room from the outside, and the clothing of the human body is used for particulate transport. The outdoor concentration of particulate matter determines the exposure environment of clothing, while the clothing fabric determines particulate matter's adsorption and diffusion ability. Therefore, experiments should be conducted to investigate the effect of clothing accumulation and diffusion of particulate matter on the indoor environment.

To explore the influence of clothing fabrics on the indoor environment, it is necessary to remove the effect of the outdoor environment and the error caused by indoor personnel activities in the data analysis process.

Based on $PM_{2.5}$ concentration in ordinary rooms and outdoor atmosphere, according to the mass conservation law of particulate matter, the dynamic balance equation of $PM_{2.5}$ is established as follows:

$$\frac{dC_{PM_{2.5},in}}{d\tau} = a \cdot P \cdot C_{PM_{2.5},out} + \frac{RL_f A_f}{V} + \frac{v_s}{V} - (a+K)C_{PM_{2.5},in} - \frac{v_k}{V}, \quad (1)$$

where $C_{PM_{2.5},in}$ is the $PM_{2.5}$ concentration in the diffusion chamber, a denotes air change times, P is the penetration coefficient, $C_{PM_{2.5},out}$ is the outdoor atmospheric $PM_{2.5}$

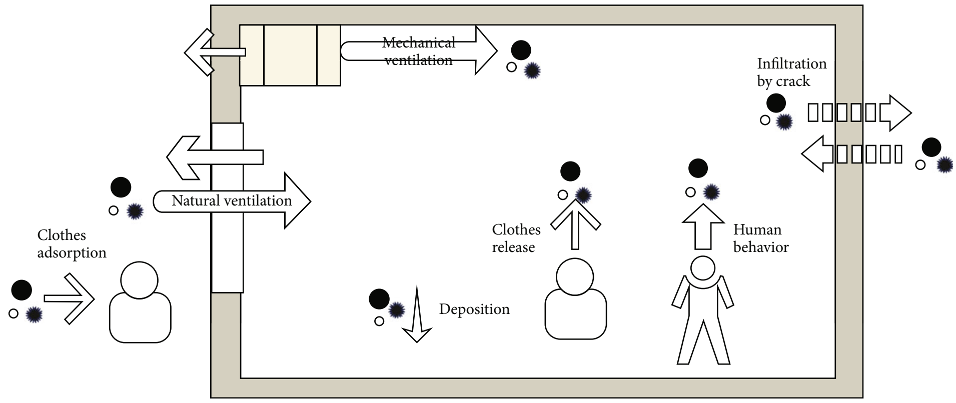


Figure 1: Schematic diagram of main sources of indoor particles.

concentration, R is the secondary suspension rate of $PM_{2.5}$, L_f is the mass load of floor particles, A_f is the floor area of the diffusion chamber, v_s is the diffusion rate of indoor particulate matter pollution sources, K is the sedimentation coefficient, v_k is the rate of other sedimentation, and V is the volume of the diffusion chamber.

Some scholars have pointed out that condensation, reaction, and other effects have no obvious influence on the change of indoor $PM_{2.5}$ concentration in a short period, so this study neglects the impact of relevant effects and simplifies the product differentiation of Equation (1) to obtain [41]

$$C_{PM_{2.5},in,\tau} = \frac{aPC_{PM_{2.5},out,\tau}}{a}\left(1 - e^{-\Delta\tau\cdot(a+K)}\right) + C_{PM_{2.5},in,\tau-1}e^{-\Delta\tau\cdot(a+K)}, \quad (2)$$

where $C_{PM_{2.5},in,\tau}$ indicates the indoor $PM_{2.5}$ concentration at a certain time, $C_{PM_{2.5},out,\tau}$ indicates the outdoor $PM_{2.5}$ concentration at a certain time, $C_{PM_{2.5},in,\tau-1}$ indicates the indoor $PM_{2.5}$ concentration at the previous moment of a certain time, and $\Delta\tau$ is the time interval.

2.1.2. Data Processing. This paper conducted an experimental study on the transport characteristics of indoor particulate matter in a real indoor environment. In the process of no mechanical ventilation and closed doors and windows throughout the experiment, indoor particulate matter concentration would still be affected by osmotic air volume. To eliminate the interference of this part on the experimental results, the air change times and the penetration coefficient P need to be solved to understand the outdoor infiltration characteristics of the experimental phase. The number of air change is obtained by detecting the CO_2 concentration and substituting it into the gas attenuation formula and dynamic equilibrium equation. The penetration coefficient P and sedimentation coefficient K are obtained from the dynamic equilibrium equation of $PM_{2.5}$ through a no-load experiment.

(1) Number of Air Changes a. In the diffusion chamber experiment stage, indoor CO_2 shows a trend of attenuation, and the known gas concentration decay formula is

$$C_{co_2\,in,\tau} = \left(C_{co_2\,in,0} - C_{co_2\,out}\right)\exp\left(-a\tau\right) + C_{co_2\,out}, \quad (3)$$

where τ denotes time, $C_{co_2\,in,\tau}$ denotes indoor CO_2 concentration at time, $C_{co_2\,out}$ denotes outdoor CO_2 concentration, $C_{co_2\,in,0}$ denotes indoor CO_2 concentration at initial time, and a denotes air change times.

Take the logarithm of the left and right sides of the equal sign in the above equation at the same time, and obtain the linear regression equation

$$\ln\left(\frac{C_{co_2\,in,0} - C_{co_2\,out}}{C_{co_2\,in,t} - C_{co_2\,out}}\right) = a\tau + b. \quad (4)$$

Assuming that the CO_2 concentration outside and inside the diffusion chamber is uniform, the dynamic equilibrium equation of indoor CO_2 concentration can be established by the conservation law as follows:

$$\left(\frac{dC_{co_2,in}}{d\tau}\right) = a\left(C_{co_2,out} - C_{co_2,in}\right) + \frac{E}{V}, \quad (5)$$

where E is the release rate of the indoor CO_2 release source; because there is no CO_2 release source in the diffusion chamber, so the last term in the formula is negligible, and the integral calculation of Equation (5) can be obtained as follows:

$$C_{co_2,in,t} = \int_{t_0}^{t} aC_{co_2,out,t}e^{-a(t-\tau)}d\tau + C_{co_2,in,t}e^{-a(t-t_0)}. \quad (6)$$

During the experiment, the outdoor weather conditions did not change significantly; the air change time a did not change significantly, which could be approximately regarded as a stable value. In addition, set the sampling time interval as a time step and define it as Δt, substitute it into Equation (6), and simplify it to obtain

$$C_{co_2,in,\tau} = C_{co_2,out,\tau}\left(1 - e^{-\Delta t \cdot a}\right) + C_{co_2,in,\tau-1} e^{-\Delta t \cdot a}, \quad (7)$$

where τ represents any sampling point in the experimental process and $\tau - 1$ represents the sampling point at a sampling time interval before any sampling point.

(2) Penetration Coefficient P and Sedimentation Coefficient K. The penetration coefficient P and sedimentation coefficient K are only related to the experimental environment, so the no-load experiment is carried out and obtained using Equations (1) and (2).

(3) Clothing Releases Particulate Matter. Using the air change times, penetration coefficient, and sedimentation coefficient above putting them into Equation (2) and inputting the initial value for iterative calculation, the hourly concentration change of indoor particulate matter can be obtained only under the influence of outdoor infiltration. The characteristics of particulate matter released by clothing can be obtained by subtracting the permeability value calculated simultaneously as the measured values of experimental instruments.

2.2. Experimental Methods

2.2.1. Experimental Steps. The field measurement method in the laboratory was used to investigate the accumulation and diffusion characteristics of different clothing fabrics on $PM_{2.5}$. In the generation chamber with the help of mosquito incense to simulate the pollution conditions of fine particulate matter in the atmosphere and artificial control to adjust the exposure time and exposure concentration of clothing and after the completion of the corresponding adsorption time, the clothing and the human model were transferred to the diffusion chamber which was purified in advance, and the experimental instruments were used to monitor the changes in the concentration of particulate matter in the room and to collect data.

2.2.2. Experimental Setting. The experiment site of this paper is located in an office in Zhengzhou City, central Henan Province, China. The climate characteristics of Zhengzhou in the past 40 years are shown in Figure 2.

Figure 3 shows the winter's average daily mass concentration of $PM_{2.5}$ outdoors in Zhengzhou. It can be seen from the figure that the weather with moderate outdoor pollution (115-150 $\mu g/m^3$) and heavy pollution (150-250 $\mu g/m^3$) in Zhengzhou in winter accounts for nearly half.

The volume of the generation chamber is 47.32 m^3, 5.2 m long, 3.5 m wide, and 2.6 m high, with a suspended ceiling and a tiled floor. This room is used to simulate the atmospheric environment during the experiment to achieve free control of clothing exposure concentration and duration. The volume of the diffusion chamber is 65.1 m^3, the length is 6.2 m, the width is 3.5 m, and the height is 3 m. The indoor ceiling is suspended, the floor is laid with ceramic tiles, and the three sides of the bulkhead are nonadsorption toughened glass. During the experiment, this room was used to simulate the indoor situation in the ordinary home and office environments and observe the regular characteristics of particles released by clothing indoors. During the experiment, the doors and windows of the diffusion chamber were kept closed, there was no mechanical ventilation, and the indoor wind speed was almost zero.

The number of sampling points depends on the size of the actual laboratory and the field situation. Two detection points are set for the occurrence chamber, and four detection points are set for the diffusion chamber. The average value is taken during data processing. The height of the sampling points in the occurrence chamber was consistent with the adult male chest cavity height, and the height range of 1.5 m was maintained. The height of the sampling point of the diffusion chamber is the same as the height of the mouth and nose of the human body sitting quietly at work, about 1 m.

According to the statistics of outdoor activity time of residents in cities and villages in China, the outdoor exposure time was divided into three types: 1 h, 2 h, and 3 h. With reference to ambient air quality standards (GB3095-2012) and ambient air quality index (AQI) technical regulations (HJ633-2012) published by China and the outdoor air pollution conditions in Zhengzhou City in winter, pollution conditions above moderate have an impact on the health of the wider population, and the $PM_{2.5}$ mass concentration in the occurrence chamber was set to two kinds based on the concentration values of $PM_{2.5}$ in the air quality index of different levels, which were 133 ± 15 $\mu g/m^3$ in the moderate pollution range and 200 ± 15 $\mu g/m^3$ in the severe pollution range.

The layout of the occurrence chamber and diffusion chamber is shown in Figure 4.

Since the experiments were not conducted in a clean room, even though the diffusion chamber was not mechanically ventilated and the doors and windows were closed throughout the experiments, the particle concentration in the room would still be affected by the infiltration airflow. In order to create atmospheric and clean environments through the generation and diffusion chambers, respectively, the outdoor infiltration characteristics of the building were studied through the use of an unloaded experiment. And the characteristics of the clothing cloth adsorption and release of particulate matter were obtained by means of instrumentation monitoring and data processing throughout.

2.2.3. Experimental Materials. In this paper, based on the special people who work outdoors for a long time and the clothing fabrics commonly worn by the general public in the autumn and winter seasons, three typical clothing fabrics of polyester-cotton, cotton, and polyester clothing were selected as research objects, and the size and thickness of clothing of different kinds of fabrics were close, so as to avoid as far as possible the impact of nonuniform clothing on the experimental results.

Studies by Wang et al. [42] and Stabile et al. [43] found that the particulate matter released from the combustion of

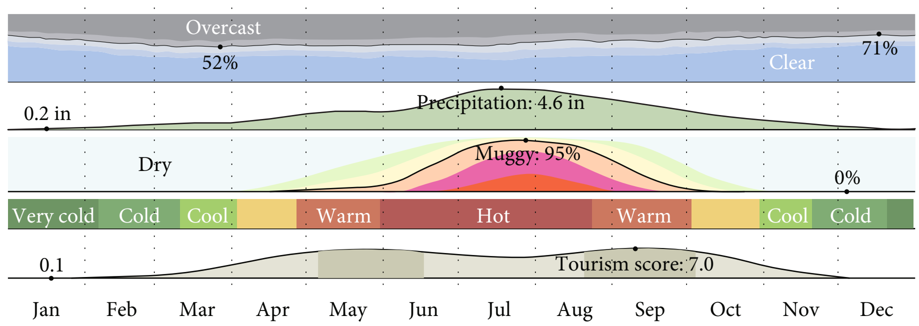


Figure 2: The climate characteristics of Zhengzhou (quoted from WeatherSpark).

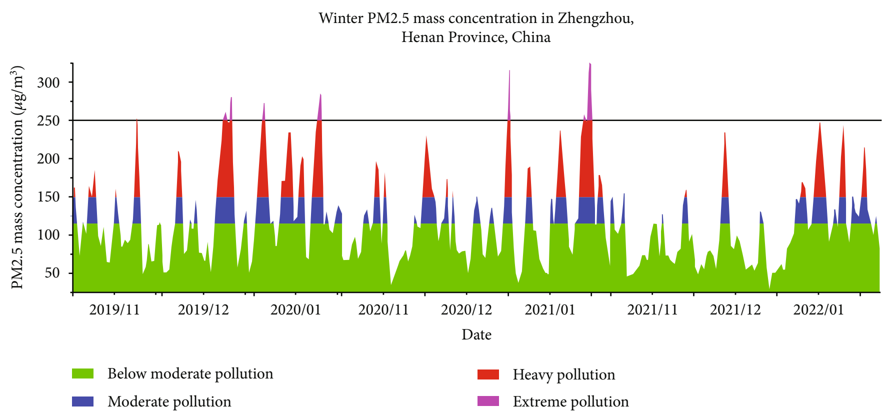


Figure 3: Outdoor $PM_{2.5}$ daily average mass concentration in winter in Zhengzhou.

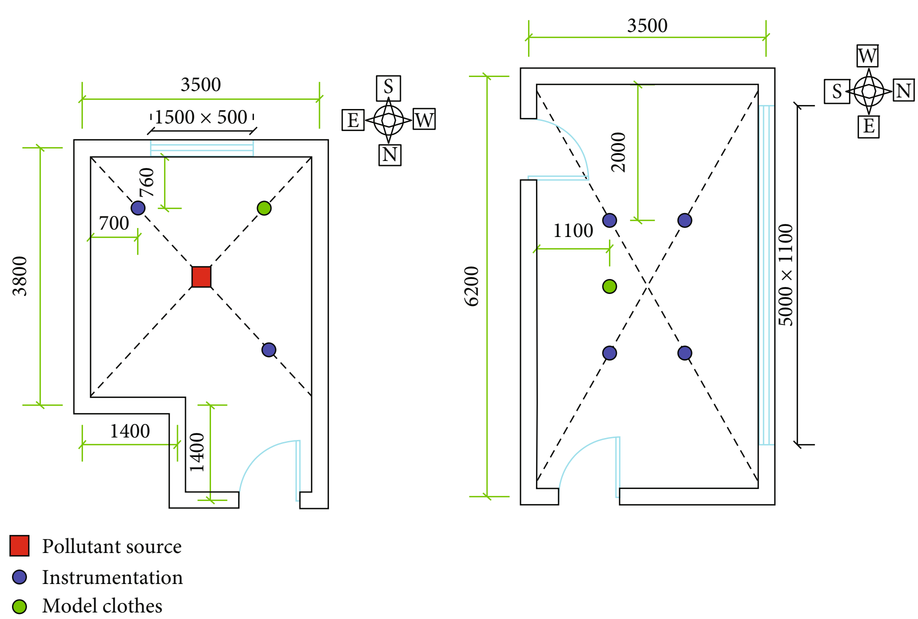


Figure 4: The layout of the occurrence chamber and diffusion chamber.

traditional solid mosquito coils consisted mainly of $PM_{2.5}$ and PM_{10}, which is similar to the particle size distribution of particulate matter under outdoor pollution conditions. Based on this characteristic of mosquito incense, Xiaofeng and Zhongping [44] used mosquito incense as an internal dust source and obtained some results when they investigated the attenuation law of indoor $PM_{2.5}$. Liu et al. [45] and Majumdar et al. [46] simulate $PM_{2.5}$ by burning mosquito-repellent incense to study its indoor diffusion rule, harmful effect on the human body, and biological effect.

Therefore, this experiment also uses mosquito coils as an indoor $PM_{2.5}$ generator and controls the constant indoor particulate matter concentration by the number of mosquito coils lit and the opening and closing of windows and doors.

In order to better simulate the tightness of real-life clothes on the human body and to avoid the impact of the experimenter on the indoor environment, this study adopts a half-length clothing model to conduct the adsorption and release of particulate matter experiment.

The physical picture of the above experimental materials is shown in Table 1.

2.2.4. Measuring Instruments and Accuracy. The main monitoring object of this experimental instrument is the concentration of particulate matter in the diffusion chamber while maintaining a relatively constant temperature and humidity in the chamber. The specific models and parameters of the instruments used are shown in Table 2.

2.3. Outdoor Penetration Correction

2.3.1. Number of Air Changes a. Linear fitting was performed according to Equation (3) to eliminate the influence of outdoor infiltration,as shown in Figure 5, and the indoor and outdoor osmotic air change times $a1$ were solved, as shown in Table 3. The R^2 was obtained by fitting, and the fitting degree of the model is above 0.85. The fitting effect is good, and the result is credible.

To further ensure the reliability of the obtained parameters, this experiment adopts the dynamic balance method for iterative calculation in addition to the gas decay method for the number of air changes. The sampling time interval of the instrument during the experiment is 1 minute; because the sampling time interval is short, in order to avoid the situation that the adjacent sampling value remains unchanged and the error increases, the average value of the data for 5 consecutive minutes is taken as the most sampled value; that is, the sampling time interval is set to 5 minutes and used as the time step. The data were processed to take the mean value and then put into Equation (7), and the results were calculated iteratively with the help of mathematical analysis software SPSS as follows.

The results show that the air change number $a2$ obtained by the dynamic balance method has a good effect and is close to $a1$ obtained by the gas decay method. The average value of the two is taken as the final value of the air change number a, as shown in Table 4.

2.3.2. Penetration Coefficient P and Sedimentation Coefficient K. During the experiment, three days were randomly selected for the no-load experiment. After indoor air was purified by an air purification and disinfection machine in a closed diffusion chamber, an air quality monitor was turned on to monitor indoor $PM_{2.5}$ concentration changes without putting contaminated clothing into the chamber. During the no-load experiment, there was no indoor pollution source, and the indoor $PM_{2.5}$ concentration change sources were only caused by outdoor infiltration. Therefore, the penetration coefficient K and sedimentation coefficient P can be calculated using this data part.

After obtaining the number of air changes a in the no-load experimental phase according to the method in Section 2.2.2, the parameters in the formula, i.e., penetration coefficient P and settling coefficient K, were obtained iteratively using SPSS software and the measured data, and it has been pointed out that P and K can be approximated as constants under the condition that the building room structure and the particle object remain unchanged. Therefore, the P and K calculated from three random no-load experiments were averaged, and the results were used as the determined parameter values throughout the experiment, the result as shown in Table 5.

All parameters were determined and put into Equation (2). With the help of the software Excel, enter the initial values of outdoor concentration and indoor concentration for continuous calculation, and the hour-by-hour concentration of indoor particulate matter can be obtained. The outdoor concentration here is the mass concentration of $PM_{2.5}$ in the atmosphere monitored by the monitoring station of water supply company 1319A, which is closest to the experimental point. The characteristics of particulate matter released and diffused in clothing and clothing rooms can be obtained by subtracting the concentration of particulate matter in the same period from the measured data.

3. Results and Discussion

3.1. Accumulation and Diffusion of $PM_{2.5}$ by Clothing Fabrics in Enclosed Spaces

3.1.1. Accumulation and Diffusion of $PM_{2.5}$ by Clothing Fabrics Based on Moderate Pollution Background. Clothing of different fabrics, under the conditions of moderate pollution of fine particulate matter concentration in the occurrence chamber, after 1 h, 2 h, and 3 h of exposure, respectively, was moved to the diffusion chamber that has been decontaminated in advance; the change of particulate matter concentration in the diffusion chamber after excluding the effect of outdoor infiltration is shown in Figure 6.

First of all, as can be seen from the concentration change curve in the above figures, after placing the clothing exposed to moderate pollution conditions in the occurrence chamber for 1 h, 2 h, and 3 h in the diffusion chamber within the same diffusion duration (<175 min), the overall concentration of particulate matter released at the same moment from the clothing of three fabrics showed a trend of polyester being the largest, cotton being the second, and polyester-cotton being the smallest.

Among the three fabric garments exposed to 1 h under moderate pollution, the rate of $PM_{2.5}$ release from polyester fabric at the early stage of diffusion was significantly more significant than the remaining two. The release rate only gradually slowed after 40 min, and its final stable concentration value reached 37 $\mu g/m^3$, slightly exceeding China's indoor 24-hour average concentration limit level 1 standard of 35 $\mu g/m^3$. Cotton and polyester-cotton caused the indoor space $PM_{2.5}$ concentration was elevated and finally stabilized at about 28 $\mu g/m^3$ and 22.5 $\mu g/m^3$, where the average release rate of diffusion of cotton is greater than that of polyester-

Table 1: Experimental materials.

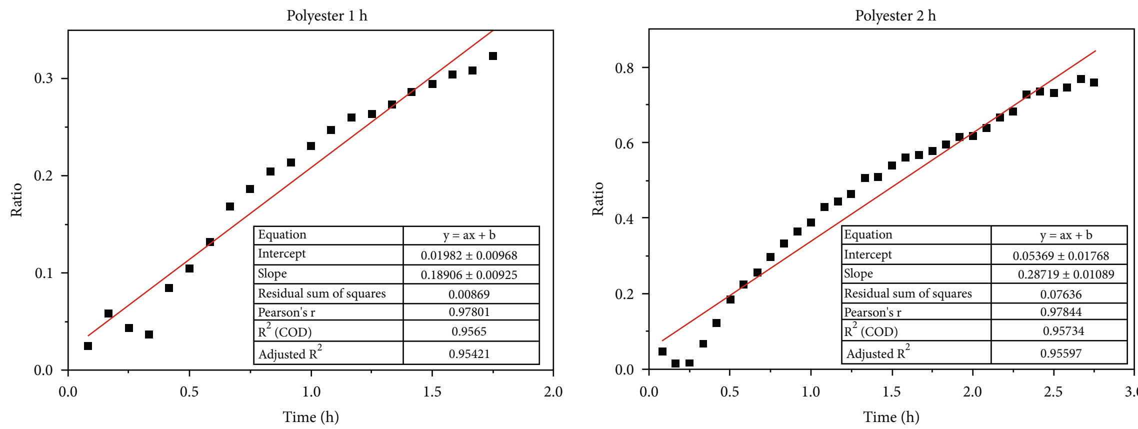
Experimental materials	Real figure	Note
Clothing materials		Fabric polyester-cotton: 60% polyester and 40% cotton Cotton: 100% cotton Polyester: polyester fiber
Male model		Height can be adjusted freely, shoulder width 45 cm, bust circumference 96 cm, and body height 90 cm
Traditional mosquito-repellent incense		Disc type mosquito incense, mugwort clear fragrance type, and cypermethrin content 0.08%

Table 2: Specific models and parameters of experimental measuring instruments.

Instrument model	Detection object	Measuring range	Distinguishability	Precision
BLATN BR-SMART hand-held air quality monitor 	$PM_{2.5}$, PM_{10}, HCHO, and VOCs	0–999 $\mu g/m^3$	1 $\mu g/m^3$	±15% measured value
WFWZY-1 universal wind speed and temperature autometer 	Wind speed	-20~80°C	0.01°C	±0.5°C
	Temperature	0.05~30 m/s	0.01 m/s	±0.05 m/s
JZ322 PC-8Z integrated air micro station 	Wind direction	0~359°	1°	±3°
	Wind speed	0~70 m/s	0.1 m/s	±0.3 m/s
	Temperature	40°C~80°C	0.1°C	±0.2°C
	Humidity	0~100% RH	0.1% RH	±5% RH
	Pressure	300~1100 hPa	0.1 hPa	±0.3 hPa
	Rainfall	0~999.9 mm	0.2 mm	±10%
	Radiation	0~2000 W/m^2	1 W/m^2	<5%
	Ultraviolet	0~500 W/m^2	1 W/m^2	<5%

cotton, but the changing trend of both has some similarity. In addition, we can find that when the diffusion duration reaches about 125 min, the growth of pollutant concentration released by the three fabrics of clothing is significantly slowed down, and the indoor $PM_{2.5}$ concentration tends to be stable.

Among the three fabric garments exposed for 2 h in the background of moderate pollution, the release rate of fine particulate matter was relatively close among the three at the early diffusion stage. The release rate of polyester was relatively uniform throughout, and the concentration of



(a) (b)

Figure 5: Example of air change times of linear fitting for moderate (a) and severe (b) pollution.

Table 3: Number of air changes by dynamic balance method.

Pollution levels	Fabric type	Exposure time	Number of air changes *a*2	R^2
Moderate pollution	Polyester	1 h	0.157	0.947
		2 h	0.303	0.989
		3 h	0.461	0.939
	Polyester and cotton	1 h	0.239	0.972
		2 h	0.381	0.972
		3 h	0.247	0.983
	Cotton	1 h	0.411	0.996
		2 h	0.204	0.972
		3 h	0.465	0.991
Heavy pollution	Polyester	1 h	0.282	0.994
		2 h	0.179	0.907
		3 h	0.271	0.987
	Polyester and cotton	1 h	0.237	0.894
		2 h	0.242	0.994
		3 h	0.253	0.908
	Cotton	1 h	0.623	0.980
		2 h	0.179	0.987
		3 h	0.644	0.994

$PM_{2.5}$ in its diffusion chamber was finally stabilized at about 45 ug/m^3, which was significantly larger than the indoor 24 h average concentration limit level 1 standard set by China. The release rate of polyester-cotton slowed significantly when the diffusion length reached about 60 min, while cotton also showed a significant slowdown trend at 100 min, and the characteristic curves of $PM_{2.5}$ release of both had some similarities. In addition, when the diffusion time reached 145 min, the fine particulate matter concentration in the diffusion chamber where the clothing of the three fabrics was located tended to stabilize, with the final stabilization values of cotton and polyester-cotton fluctuating around 33 $\mu g/m^3$ and 25 $\mu g/m^3$, respectively.

Among the three fabric garments exposed to the moderate pollution background for 3 h, the three fabric garments always showed a constant release of $PM_{2.5}$ during the whole 175 min dispersion period of the experimental monitoring. In addition, the characteristic curves of the released particulate matter of cotton and polyester-cotton still have some similarities at the early diffusion stage.

3.1.2. Accumulation and Diffusion of $PM_{2.5}$ by Clothing Fabrics Based on the Background of Heavy Pollution. Different fabrics of clothing in the occurrence of the cabin concentration of fine particles for heavy pollution conditions, respectively, after 1 h, 2 h, and 3 h exposure, were moved to the diffusion chamber that has been decontaminated in advance, excluding the influence of outdoor infiltration of the diffusion chamber particle concentration changes which are shown in Figure 7.

Table 4: The number of air changes a.

Pollution levels	Fabric type	Exposure time	$a1$	$a2$	a
Moderate pollution	Polyester	1 h	0.189	0.157	0.1730
		2 h	0.287	0.303	0.2950
		3 h	0.486	0.461	0.4735
	Polyester and cotton	1 h	0.243	0.239	0.2410
		2 h	0.349	0.381	0.3650
		3 h	0.232	0.247	0.2395
	Cotton	1 h	0.402	0.411	0.4065
		2 h	0.177	0.204	0.1905
		3 h	0.459	0.465	0.4620
Heavy pollution	Polyester	1 h	0.279	0.282	0.2805
		2 h	0.179	0.179	0.1790
		3 h	0.298	0.271	0.2845
	Polyester and cotton	1 h	0.260	0.237	0.2485
		2 h	0.246	0.242	0.2440
		3 h	0.275	0.253	0.2640
	Cotton	1 h	0.561	0.623	0.5920
		2 h	0.174	0.179	0.1765
		3 h	0.649	0.644	0.6465

Table 5: Penetration coefficient P and sedimentation coefficient K.

Date	Penetration coefficient P	Sedimentation coefficient K	R^2
2021.3.26	0.430	0.206	0.949
2021.3.27	0.394	0.216	0.988
2021.3.28	0.429	0.225	0.992
Mean value	0.4177	0.2157	—

As can be seen from the above figure, after exposure to heavy pollution conditions for 1 h, 2 h, and 3 h of clothing and clothing placed in the diffusion chamber, in the diffusion cycle of 175 min, the same pattern of fine particles was released from clothing and clothing after exposure to the background of moderate pollution; the three types of clothing fabrics also show an overall trend of the maximum concentration of particles released from polyester, followed by cotton and the smallest polyester-cotton.

The characteristics of the release of fine particulate matter from the three fabric garments exposed for 1 h under the background of heavy pollution have great similarity to those under moderate pollution for 1 h. For example, the release rate of $PM_{2.5}$ from polyester at the beginning of diffusion is significantly greater than the remaining two, and the release rate gradually slows down after 50 min; the average release rate of cotton is greater than that of polyester-cotton, but the changing trend of both has some similarity. In addition, when the diffusion duration reached about 150 min, the growth of pollutant concentrations released by the three fabrics of clothing also slowed down significantly, and the indoor particulate matter concentrations stabilized, which was 25 min longer than the time to reach stability in the background of moderate pollution. The final concentration values of the three were also stabilized at about 29 μg/m^3, 10 μg/m^3, and 7 μg/m^3, respectively.

Among the three fabric garments exposed to heavy pollution for 2 h, the release rate of fine particulate matter at the beginning of diffusion was significantly greater in polyester than in cotton and polyester-cotton. Although the difference in the concentration of released particulate matter between cotton and polyester-cotton during the diffusion cycle is significant, they are similar in that they both have a linear trend, unlike the logarithmic function-like change curve characteristic of polyester. In addition, as with the other experimental results mentioned above, the $PM_{2.5}$ concentrations emitted from the three fabrics ceased to increase at 165 min of diffusion and stabilized at 24 μg/m^3, 11.5 μg/m^3, and 3 μg/m^3, respectively.

After placing the clothing garments exposed to heavy pollution conditions in the occurrence chamber for 3 h in the diffusion chamber, the characteristic curve of $PM_{2.5}$ release from polyester remained similar to a logarithmic function, while cotton and polyester-cotton were characterized by a straight line. During the experimental monitoring process (<175 min), the three fabric garments continued to release fine particulate matter, and no concentration stabilization time point has yet occurred.

3.2. Diffusion Stabilization Period under Different Exposure Times. After being exposed for 1, 2, and 3 hours, respectively, under the conditions of $PM_{2.5}$ moderate and heavy pollution in the cabin, the same kind of clothing fabric is moved to a clean diffusion cabin to release fine particles. The regular characteristics are shown in Figure 8.

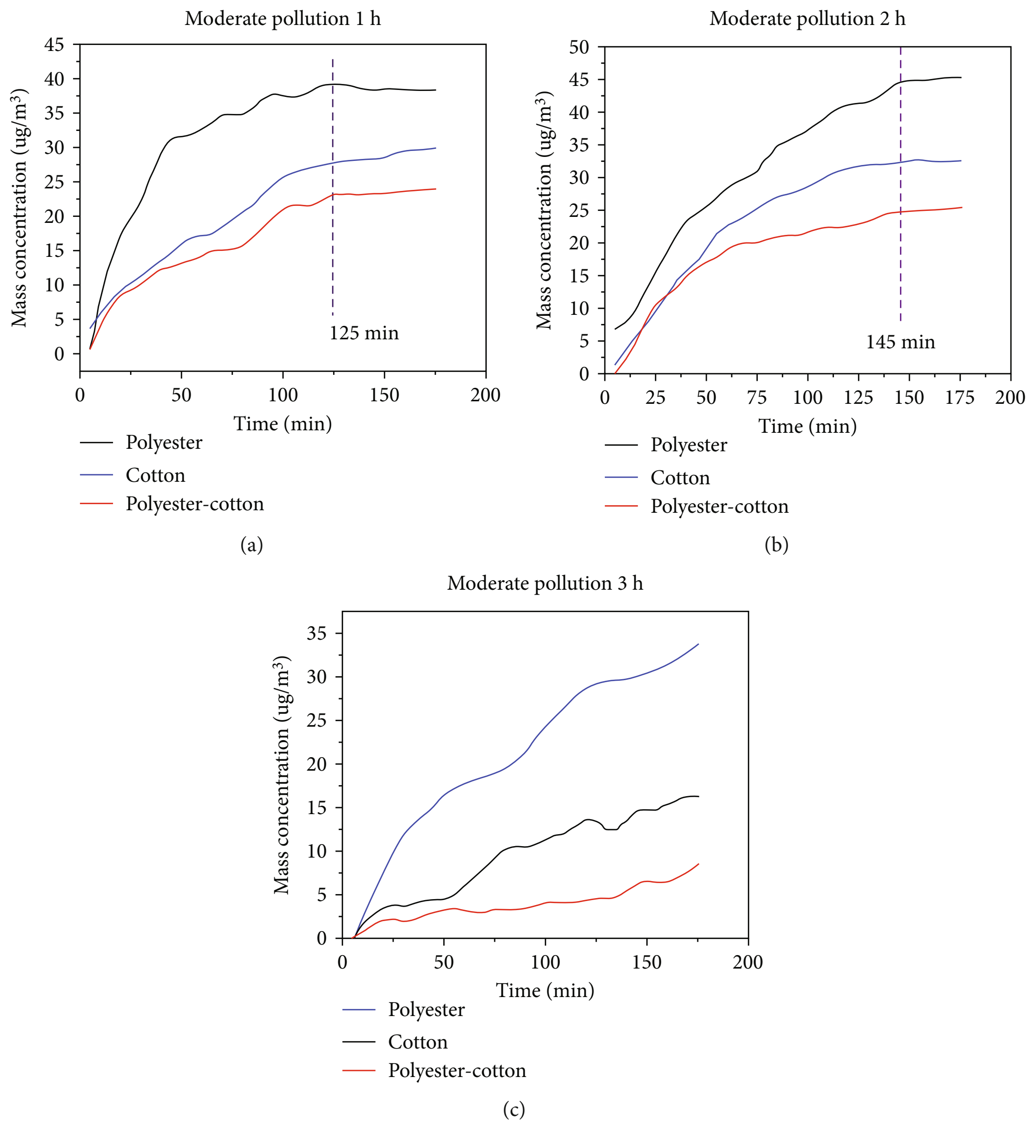


Figure 6: Exposure to moderate pollution background for 1 h (a), 2 h (b), and 3 h (c).

3.2.1. The Rediffusion Stability Period of Polyester Fabric Clothing under Different Exposure Times. The polyester fabric garments were exposed for 1, 2, and 3 hours in the chambers with moderate and severe pollution, respectively, and then placed in the diffusion chamber for continuous diffusion for 175 minutes. The change of $PM_{2.5}$ concentration in the diffusion chamber with time is shown in Figure 8.

As shown in the figure, the concentration of $PM_{2.5}$ in each group of diffusion chambers gradually increased with the exposure time. The changing trend was roughly in the form of a logarithmic function. During the exposure periods of 1 h and 2 h under moderate and severe pollution conditions, there was a stable concentration stage during the experimental monitoring process. The experimental group with an exposure time of 3 h maintained an increasing trend. Among them, the stable phenomenon occurs about 125 minutes after 1 hour of moderate pollution, 145 minutes after 2 hours of moderate pollution, 150 minutes after 1 hour of heavy pollution, and 165 minutes after 2 hours of heavy pollution. That is, the longer the exposure time, the more severe the exposure, and the longer the time for releasing particulate matter from clothing, which is consistent with our daily cognition. However, it is worth noting that the total amount of particulate matter released from clothing exposed under heavy pollution conditions is generally less than that of moderate pollution. The final stable value of exposure for 2 hours under heavy pollution is also less than 1 hour. This experimental phenomenon has a certain deviation from people's daily cognition.

3.2.2. The Rediffusion Stability Period of Polyester-Cotton Fabrics and Garments under Different Exposure Times. The polyester-cotton clothing was fully exposed in the moderate and heavy pollution occurrence chamber for 1 h, 2 h, and 3 h and then put into the diffusion chamber for 175 min, and the $PM_{2.5}$ concentration in the diffusion chamber changed with time, as shown in Figure 9.

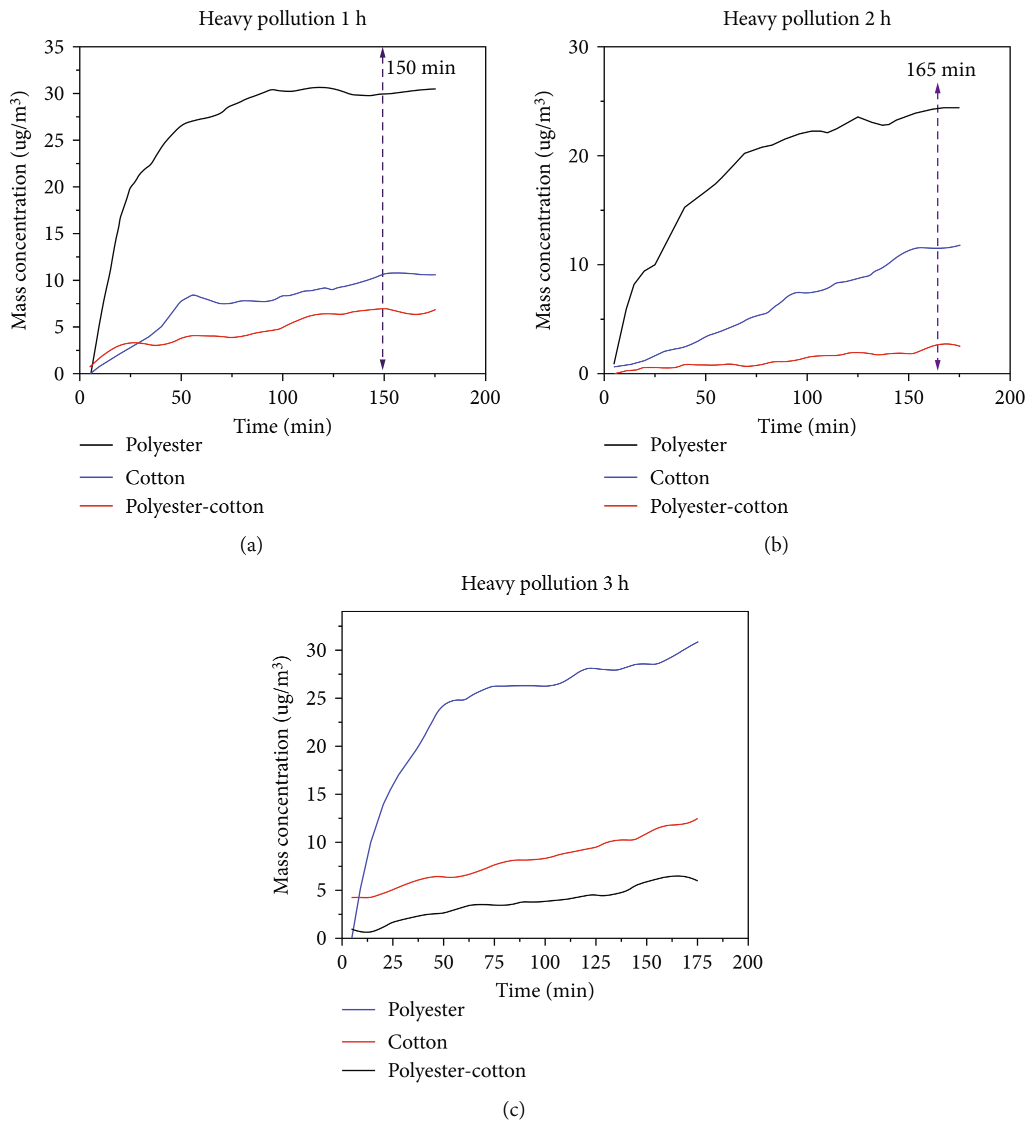


Figure 7: Exposure to heavy pollution background for 1 h (a), 2 h (b), and 3 h (c).

As shown in the figure, the $PM_{2.5}$ concentration in the experimental room of each group gradually increased with the length of exposure, in which the 1 h and 2 h changes of moderate pollution were in the form of similar logarithmic functions. The polyester change characteristics are similar, and the remaining four groups show the overall trend of the primary function. During the experimental monitoring, there was a stabilization phase of concentration during the 1 h and 2 h of exposure to moderate and heavy pollution conditions. The experimental group with 3 h of exposure always maintained an increasing trend. The stabilization phenomenon occurred at 125 min for 1 h of moderate pollution, 145 min for 2 h of moderate pollution, 150 min for 1 h of heavy pollution, and 165 min for 2 h of heavy pollution, respectively. The longer the exposure time, the more severe the exposure to pollution and the longer the time for releasing particulate matter from clothing. In addition, we found that the total amount of particulate matter released from clothing exposed under heavy pollution conditions was less than that of moderate pollution overall. The final stability value of 2 h of exposure under heavy pollution was also less than 1 h, which is also consistent with the above-mentioned situation occurring with polyester fabrics. Xiaowei et al. and Yan [47, 48] found that the influence of fabric surface roughness on particle settlement is related to fabric tightness value, wind speed, and particle size through model chamber analysis. Therefore, the cause of this situation needs to be further studied by setting up the particle deposition experimental bench.

3.2.3. The Rediffusion Stability Period of Cotton Fabric Clothing under Different Exposure Times. Cotton clothing was exposed for 1 h, 2 h, and 3 h in the moderately and severely polluted cabins, respectively, and then placed in the diffusion cabin for 175 minutes for continuous diffusion. The $PM_{2.5}$ concentration in the diffusion cabin changes with time, as shown in Figure 10.

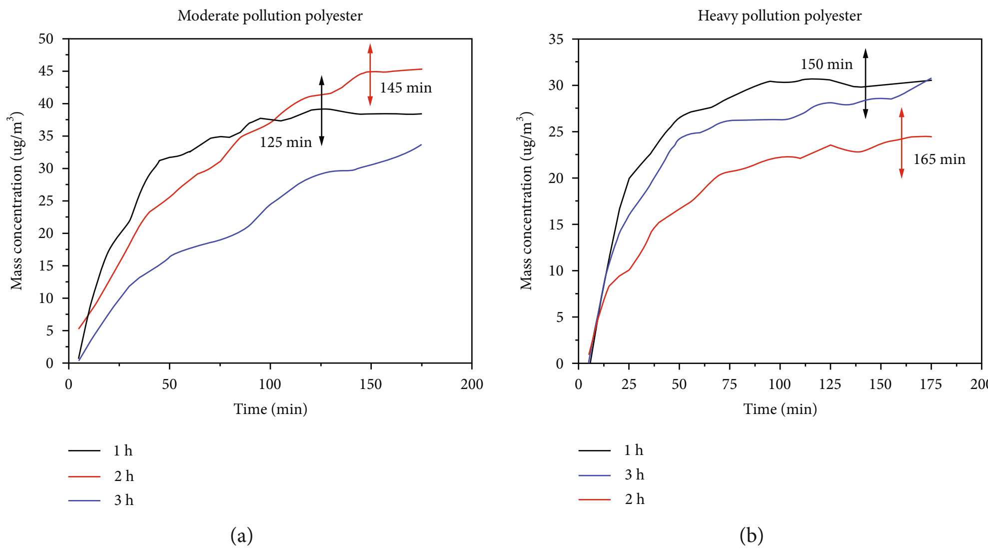


Figure 8: Polyester in moderate (a) and heavy (b) pollution.

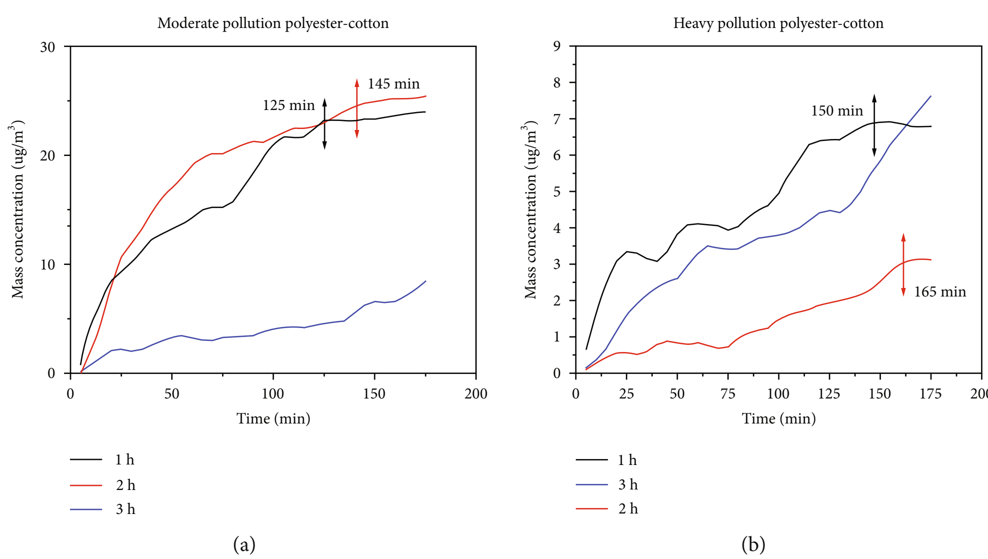


Figure 9: Polyester-cotton fabric clothing in moderate (a) and heavy (b) pollution.

As shown in the figure, the concentrations of $PM_{2.5}$ in the experimental rooms of each group gradually increased with the exposure time, and the overall change trend was in the form of a linear function. During the 1 h and 2 h exposures under moderate and severe pollution conditions, a stable concentration stage also appeared during the experimental monitoring process, and the appearance time was the same as the above-mentioned polyester and polyester-cotton fabrics; the clothing exposed for 3 h also always released $PM_{2.5}$ during the diffusion period, so its final stable value cannot be determined. However, from the exposure time of 1 h and 2 h, it can be seen that the last stable value of 2 h is greater than 1 h whether it is moderate or heavy pollution.

3.3. Accumulation and Diffusion of $PM_{2.5}$ by Clothing Fabrics Based on Natural Convection. Figure 11 shows the changes in pollutant concentrations in the room when each of the three types of clothing is placed in the diffusion chamber, where the windows and doors are opened for natural ventilation.

The figure shows that when the doors and windows are opened, the indoor pollutant concentration increases significantly at the beginning of twenty minutes under the influence of outdoor pollutants. Polyester and cotton materials stabilize at about forty minutes, while polyester-cotton materials can reach stability after about twenty minutes of growth. The stable values in the three cases were not much different from the outdoor air pollutant concentrations, and the changing trend was the same.

The placement of polyester and polyester-cotton material diffusion cabin pollutant concentration is slightly lower than the outdoor pollutant concentration, while the placement of cotton material diffusion cabin pollutant concentration in a

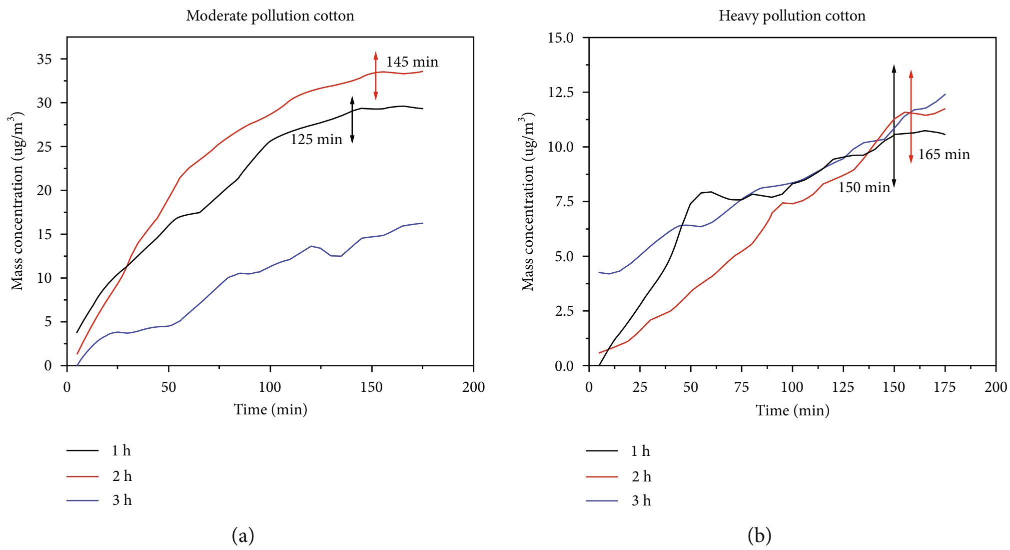


Figure 10: Cotton fabric clothing in moderate (a) and heavy (b) pollution.

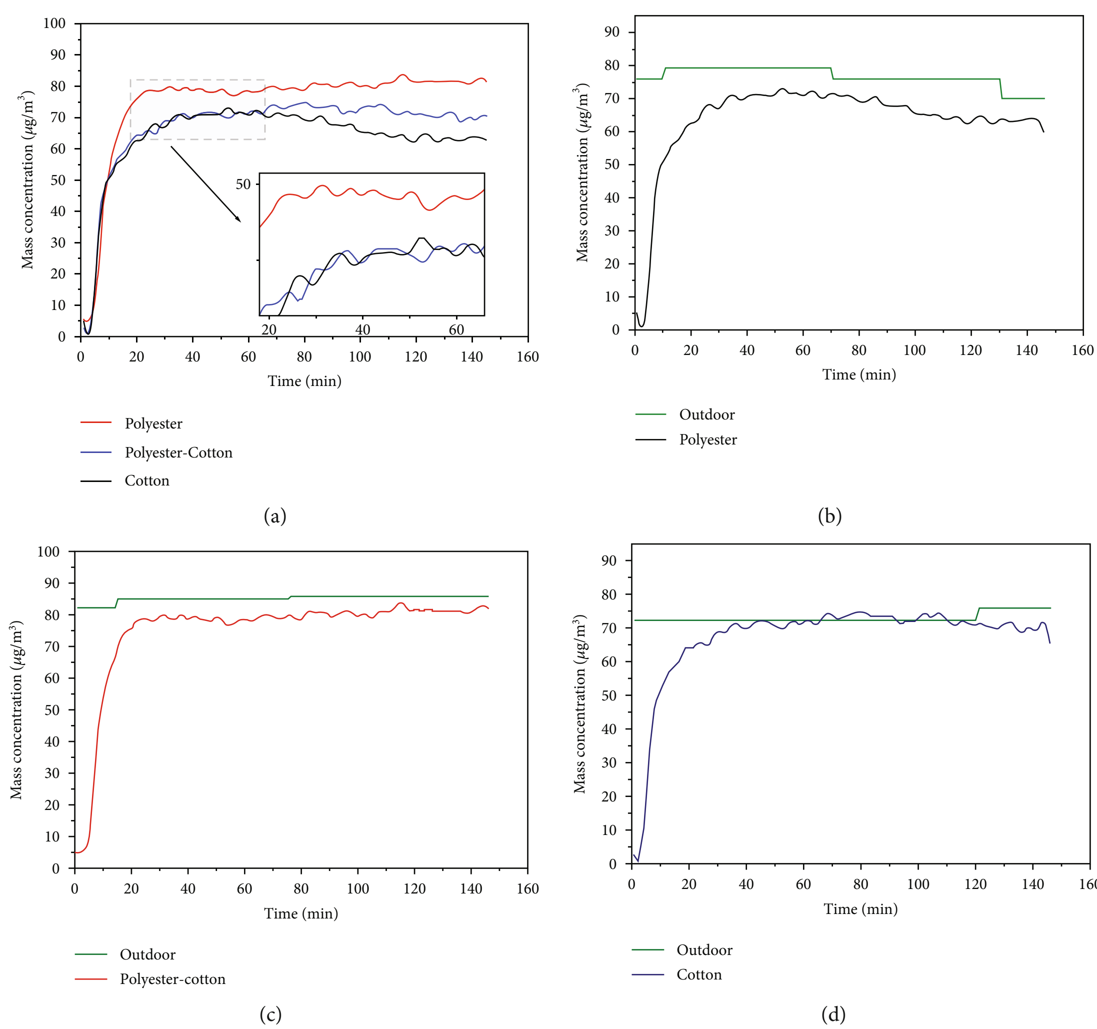


Figure 11: Comparison under natural convection conditions.

period is even higher than the outdoor pollutant concentration, which also means that natural ventilation alone is unable to improve the impact of clothing pollution sources on indoor air. Other means, such as air purifiers and mechanical ventilation, are needed to solve the problem.

4. Conclusions

In this study, theoretical analysis and experimental tests were conducted to determine the law of indoor rediffusion of three common garment fabrics, polyester-cotton, cotton, and polyester, when exposed to different levels and lengths of $PM_{2.5}$ pollution outdoors, and the main conclusions are as follows.

The adsorption and diffusion effects of different types of clothing can cause different degrees of pollution in the indoor environment, and in the same release cycle, the polyester clothing released the largest of $PM_{2.5}$, the polyester-cotton is second, the cotton is the smallest.

Clothing in the outdoor adsorption of fine particles into the indoor diffusion will stop after a period of time to external release, and the release time is proportional to the exposure concentration and exposure length. In addition, in the experiment, it was found that under the same exposure length, the diffusion effect of clothing exposed to a heavy pollution environment is weaker than that of moderate pollution indoors, and the reasons for this need further study.

Natural ventilation on indoor measurement of air pollution dilution of experimental studies has proved that relying only on natural ventilation cannot improve the impact of clothing pollution sources on indoor air quality. To solve the problem, it still needs to use other means such as air purifiers or mechanical ventilation.

Nomenclature

$C_{PM_{2.5},in}$:	The $PM_{2.5}$ concentration in the diffusion chamber ($\mu g/m^3$)
P:	Penetration coefficient
$C_{PM_{2.5},out}$:	The outdoor atmospheric $PM_{2.5}$ concentration ($\mu g/m^3$)
R:	Secondary suspension rate of $PM_{2.5}$ (%)
L_f:	The mass load of floor particles ($\mu g/m^2$)
A_f:	The floor area of the diffusion chamber (m^3)
v_s :	The diffusion rate of indoor particulate matter pollution sources ($\mu g/s$)
K:	The sedimentation coefficient
v_k:	The rate of other sedimentation ($\mu g/s$)
V:	Space volume (m^3)
τ:	Time (s)
$C_{PM_{2.5},in,\tau}$:	The indoor $PM_{2.5}$ concentration at a certain time ($\mu g/m^3$)
$C_{PM_{2.5},out,\tau}$:	The outdoor $PM_{2.5}$ concentration at a certain time ($\mu g/m^3$)
$C_{PM_{2.5},in,\tau-1}$:	The indoor $PM_{2.5}$ concentration at the previous moment of a certain time ($\mu g/m^3$)
$\Delta\tau$:	The time interval (s)
E:	The release rate of the indoor CO_2 release source
$C_{co_2\,in,\tau}$:	The indoor CO_2 concentration at τ time ($\mu g/m^3$).

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of 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.

Authors' Contributions

Ruixin Li was responsible for the project administration, writing of the original draft, funding acquisition, and methodology. Yuxin MA was responsible for the writing of the original draft, validation, methodology, investigation, and formal analysis. Jiacong Chen was responsible for the project administration, data curation, software, and investigation and wrote, reviewed, and edited the manuscript. Olga L. Bantserova was responsible for the supervision, resources, and conceptualization. Jiayin Zhu was responsible for the supervision, resources, and conceptualization. Yabin Guo was responsible for the supervision and resources. Yu Chen was responsible for the supervision and resources.

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