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# Indoor Air Quality and Personnel Satisfaction in Different Functional Areas of Semi-Underground Buildings

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**Abstract:** With the increasing application of semi-underground buildings, it is of greater significance to understand indoor air quality and personnel satisfaction in different functional areas within such buildings. In this study, a semi-underground building in Xi'an was taken as an example to test and study the indoor air quality in different functional areas, and a questionnaire survey based on the satisfaction of indoor personnel was conducted at the same time. The comprehensive results showed that the places with the highest concentrations of $PM_{2.5}$ exceeding the standard limit in the semi-underground building were the milk tea shops, hair salons, and driving schools, presenting 1.01 times, 1.15 times, and 1.08 times the standard limit, respectively. Hair salons were the sites with the highest pollution. The second most frequent pollutants were formaldehyde (HCHO) and total volatile organic compounds (TVOCs). In contrast to the wind speed parameters, the indoor concentrations of pollutants were higher than those outdoors. The upper limits of personnel satisfaction for particulate matter with a diameter less than 1.0 microns ($PM_{1.0}$), particulate matter with a diameter less than 2.5 microns ($PM_{2.5}$), and TVOCs were all higher than the standard limits. The upper limits of personnel satisfaction for $PM_{10}$, HCHO, wind speed, carbon monoxide (CO), and carbon dioxide ($CO_2$) were all below the standard limits. This provides data support and reference values for the widespread development and application of semi-underground buildings.

**Keywords:** semi-underground buildings; functional areas; air quality; satisfaction; evaluation



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## 1. Introduction

With the establishment of and increase in diverse new cities worldwide [1], various types of buildings are changing rapidly, causing massive changes in people's work and personal lives. With the continuous improvement of living standards and pursuits, people's requirements for their living environments are also increasing considerably [2]. Relevant studies in the literature have shown that there are a variety of toxic and harmful pollutants in buildings [3–5], such as total volatile organic compounds (TVOCs); formaldehyde (HCHO); carbon monoxide (CO); particulate matter with a diameter of fewer than 10 microns ($PM_{10}$), 2.5 microns ($PM_{2.5}$), or 1.0 microns ($PM_{1.0}$); and microorganisms. These pollutants bring different degrees of harm to people's physical and mental health [6,7]. In recent years, the incidence rate of sick building syndrome (SBS) has been increasing especially rapidly [8], damaging the health of children and elderly individuals. Therefore, good indoor environments are always a topic of concern [9].

At present, a large number of experiments have been conducted on indoor environments [10–13], mainly focusing on the sources, effects, and distributions of indoor pollution sources [10]; the impact of ventilation forms on the distribution of indoor pollution sources [11]; the correlation between personnel movement and indoor pollutants [12]; and the differentiation of pollutant types in underground buildings and overground buildings [13]. However, the existing research has mainly focused on overground and underground buildings, and there has been a lack of research on semi-underground buildings.

The characteristics of semi-underground buildings are a combination of those of overground and underground buildings, inheriting some of the advantages and disadvantages of both while also presenting differences [14]. Semi-underground buildings are gradually being promoted and used due to their unique architectural design and convenient access. At present, semi-underground buildings have been widely used as residential buildings [15], granaries [16], and stations [17], among other things. For this type of building, people are more concerned about issues of heat and humidity [18–21], and relevant research has been conducted through simulation and experimental methods. A schematic diagram of a semi-underground building examined in one such study is shown in Figure 1. There has been relatively little research on semi-underground buildings; in particular, there has been insufficient research on indoor environments comprising different functional areas.

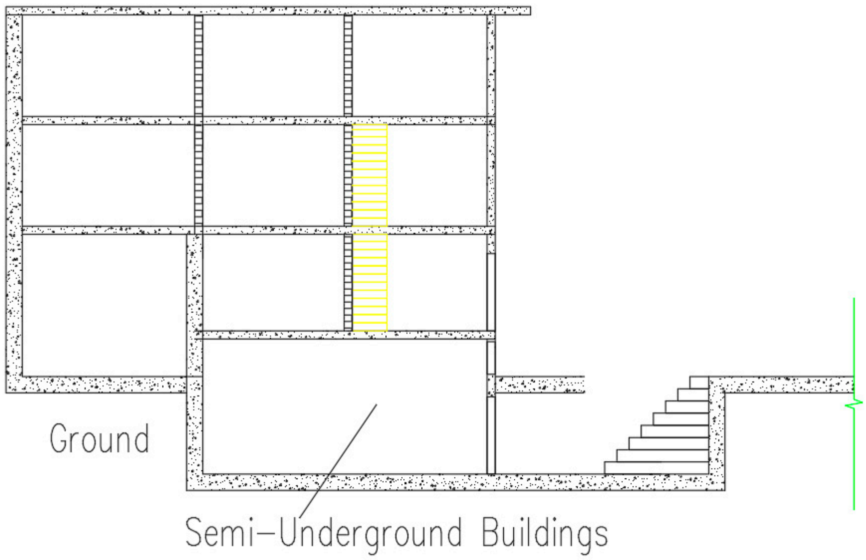



**Figure 1.** Floor plans and section of a semi-underground building.

In addition, the formulation of national indoor hygiene standards for pollutant concentration limits mainly considers the perspective of personnel health and rarely involves the subjective feelings of indoor personnel [22]. Human subjective consciousness can directly judge the quality of an indoor environment, more accurately reflecting the actual situation. Therefore, only by combining subjective and objective evaluation methods can the current situation and existing problems regarding indoor air quality be truly understood. However, there is currently a lack of research combining the two methods in semi-underground buildings, especially in the evaluation of different functional areas. Thus, such research is of great significance and guiding value given the increasing prevalence of semi-underground buildings.

People spend 90% of their time indoors [23]; therefore, the indoor environment is of utmost importance. Based on the practical situation described above, in this study, a research method combining experimental testing and a questionnaire survey is used to study the pollutant concentration and personnel satisfaction in different functional areas of semi-underground buildings. The relationships between pollutant standard limits and human satisfaction concentrations are also discussed. This study provides a data reference for the widespread development and application of semi-underground buildings in the future.

## 2. Methods

### 2.1. Survey Site

A semi-underground building in Xi'an was taken as an example in this study. The building includes different functional areas, such as milk tea shops, hair salons, driving schools, supermarkets, stationery stores, pharmacies, and bookstores. This study took milk tea shops, hair salons, driving schools, supermarkets, and stationery stores as the test objects and monitored the indoor pollutant concentrations. Additionally, a questionnaire survey was conducted to assess the satisfaction of personnel in the different functional areas with their indoor environment at different times of day (8:00–9:00 AM, 12:00–13:00 PM, 17:00–18:00 PM).

### 2.2. Testing Content

The concentrations of CO, carbon dioxide ($CO_2$), TVOCs, HCHO, $PM_{1.0}$, $PM_{2.5}$, and $PM_{10}$, the wind speed, and the temperature and humidity in different functional areas of the semi-underground building during different business hours were continuously monitored. Sampling points were arranged in areas with a high personnel density in the center of the testing site, and the sampling height was at the height of the crowd's respiratory belt (1.2–1.5 m). The monitoring period was from 12 April to 13 April 2024. Continuous monitoring was applied during the testing times (8:00–9:00 a.m., 12:00–13:00 p.m., 17:00–18:00 p.m.). To ensure the accuracy of the test results, the same two groups were tested separately, and the average value was taken for calculation.

### 2.3. Testing Instruments

A GRIMM1.109 portable aerosol particle size spectrometer was used to test the mass concentration of particles. The measurement range of this device is 0.1 to 100,000 $\mu g/m^3$, with a repeatability of 5%. The temperature, humidity, and $CO_2$ levels were tested by using an IAQ-Calc7525 indoor air quality detector. For this device, the temperature range is 0 to 60 °C, with an error of ±0.6 °C; the relative humidity range is 5 to 95% RH, with an accuracy of ±3.0% RH; and the $CO_2$ range is 0 to 5000 ppm, with an accuracy ±3.0% of the reading or ±50 ppm. An HD37AB1347 device was used to measure the wind speed and CO. Its speed range is 0.1~5 m/s, with an accuracy range of ±3%; its CO concentration range is 0 to 500 ppm, with an accuracy of ±3 ppm + 3% of the measured value. The formaldehyde (HCHO) level was tested by using a Branton BR-smart-126 air quality detector; its measurement range is 0 to 3.0 $mg/m^3$, with a resolution of 0.01 $mg/m^3$. A PGM-7600K volatile gas detector was used to test for TVOCs; its measurement range is 0.1 to 15,000 ppm, with an accuracy of 10% or ±2 ppm of the reading.

### 2.4. Evaluation Criteria

#### 2.4.1. Pollutant Standards

The concentration limits for each pollutant are shown in Table 1, according to GB/T 18883-2022 "Standards for Indoor Air Quality" [24].

**Table 1.** Concentration limits for various pollutants.

| Standard | Index | Limit | Note |
|---|---|---|---|
| Standards for Indoor Air Quality (GB/T 18883-2022) | Temperature (°C) | 22~28 | Summer |
| | Relative humidity (%) | 40~80 | Summer |
| | Wind speed (m/s) | ≤0.3 | Summer |
| | CO ($mg/m^3$) | ≤10 | 1 h |
| | $CO_2$ (%) | ≤0.10 | 1 h |
| | TVOCs ($mg/m^3$) | ≤0.60 | 8 h |
| | HCHO ($mg/m^3$) | ≤0.08 | 1 h |
| | $PM_{10}$ ($mg/m^3$) | ≤0.10 | 24 h |
| | $PM_{2.5}$ ($mg/m^3$) | ≤0.05 | 24 h |

2.4.2. Subjective Questionnaire

A subjective survey was conducted in the form of a questionnaire, with reference to the relevant literature [25], and the voting scale method was used to characterize the comfort of the indoor environment in the semi-underground building based on the respondents' satisfaction. The subjective evaluation was divided into 7 levels, and Table 2 shows the voting scale of personnel satisfaction with the indoor air quality in this study.

**Table 2.** Voting scale for personnel satisfaction with the indoor air quality.

| Satisfaction | Very Bad | Bad | Moderately Bad | Moderate | Moderately Good | Good | Very Good |
|---|---|---|---|---|---|---|---|
| S | −3 | −2 | −1 | 0 | +1 | +2 | +3 |

When the voting value is S = 0, it is considered a critical point, indicating that satisfaction with the indoor air quality is moderate [26]. When S > 0, it indicates that the respondents are satisfied with the air quality; the larger the value of S, the more satisfied they feel. On the contrary, when S < 0, it indicates that the respondents are dissatisfied with the air quality; the smaller the value of S, the less satisfied they feel.

## 3. Results and Discussion

### *3.1. Average Concentration Distributions of Indoor Pollutants*

The average concentration distributions of the major pollutants in a semi-underground building with different functions are shown in Table 3.

**Table 3.** Average concentrations of major pollutants in a semi-underground building.

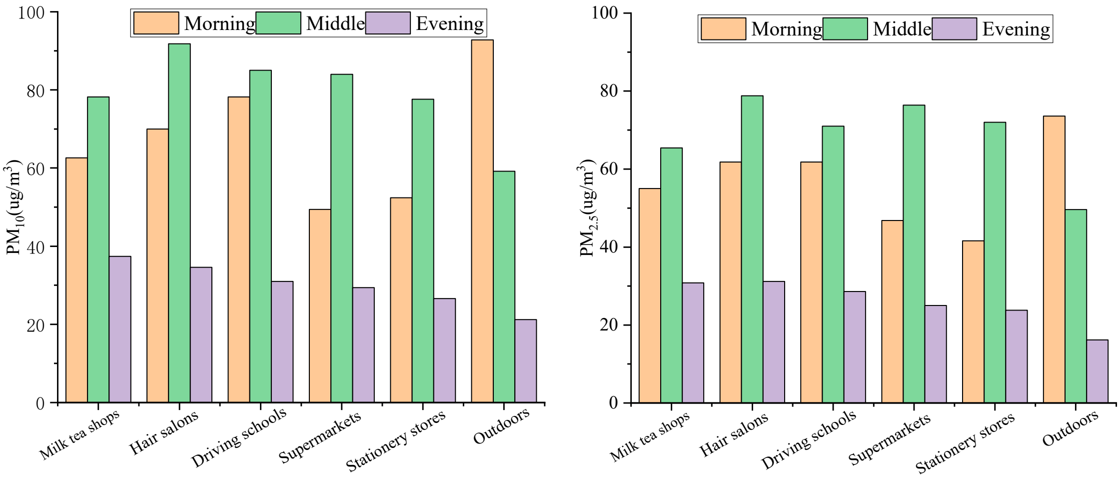
| Average | Milk Tea Shops | Hair Salons | Driving Schools | Supermarkets | Stationery Stores | Outdoors |
|---|---|---|---|---|---|---|
| $PM_{1.0}$ (ug/m$^3$) | 29.89 | 32.94 | 30.65 | 26.38 | 24.22 | 28.41 |
| $PM_{2.5}$ (ug/m$^3$) | 50.40 | 57.27 | 53.80 | 49.40 | 45.80 | 46.47 |
| $PM_{10}$ (ug/m$^3$) | 59.40 | 65.47 | 64.73 | 54.27 | 52.20 | 57.73 |
| HCHO (mg/m$^3$) | 0.08 | 0.08 | 0.02 | 0.03 | 0.03 | 0.01 |
| TVOCs (mg/m$^3$) | 0.61 | 0.53 | 0.36 | 0.28 | 0.24 | 0.16 |
| Wind speed (m/s) | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.51 |
| CO (mg/m$^3$) | 0.42 | 0.58 | 0.42 | 0.42 | 0.42 | 0.13 |
| $CO_2$ (%) | 0.08 | 0.09 | 0.08 | 0.08 | 0.09 | 0.05 |
| Temperature (°C) | 25.74 | 26.61 | 27.07 | 27.13 | 26.61 | 26.81 |
| Relative humidity (%) | 46.57 | 46.86 | 46.27 | 46.07 | 45.33 | 36.19 |

From Table 3, it can be seen that in the semi-underground building, with the exception of some pollutant indicators exceeding the standard in the milk tea shops, hair salons, and driving schools, the indoor environment meets the requirements throughout the different functional areas. This is because the advantages brought by the structural characteristics of the semi-underground building allow for sufficient air circulation with the surface environment. Half of the building is on the ground, while the other half of it is underground, enabling full air circulation with the surface environment. As a result, the frequency of fresh and polluted air exchange within the building is accelerated, thereby reducing the accumulation of pollutants [14]. The places in the building where the concentration of $PM_{2.5}$ exceeded the standard limit were the milk tea shops, hair salons, and driving schools, with values 1.01 times, 1.15 times, and 1.08 times the standard limit values [24], respectively. Hair salons were the sites with the highest pollution. This is because the customers' fallen hair trimmings and dandruff were not cleaned up in a timely manner, causing them to flow in the air and contribute to the relatively high concentration of particulate matter. In addition, the frequent flow of personnel in hair salons accelerates the secondary suspension of fine particulate matter from the ground, resulting in an overall high concentration of fine particulate matter. This result is consistent with the conclusions in the literature [27], verifying the correctness of our results. The overall order observed with regard to the pollutant concentrations was hair salons > driving schools > milk tea shops > outdoors > supermarkets > stationery stores. The relatively high outdoor concentration is due to the influence of the external environment [28], which leads to a sharp increase in vehicles and fluctuations in the particle concentration when sand transport vehicles pass by. Similarly, the concentrations of HCHO and/or TVOCs in milk tea shops and hair salons reached or surpassed the standard limits. This is because the heating equipment, food packaging, and plastic products in milk tea shops contain a large amount of HCHO and TVOCs [29]. Meanwhile, due to the use of various adhesives for perms, curling, and other hair treatments, hair salons emit large amounts of HCHO under heating and hair-drying equipment [26,30], resulting in higher pollution concentrations. Due to the low emissions of pollution sources and low flow rates, there was no phenomenon of concentrations exceeding the standard in other functional areas, which once again proves the good ventilation effect of semi-underground buildings. This provides a reference for pollution prevention and control and ventilation optimization in subsequent semi-underground buildings.

Overall, the concentration of $PM_{2.5}$ exceeded the standard by the most, followed by HCHO and TVOCs. The hair salons had the highest concentration, exceeding the standard, followed by the milk tea shops. This also indicates that there are still differences in ventilation between different functional areas in this semi-underground building. In future semi-underground buildings, the ventilation systems in different functional areas should be optimized.

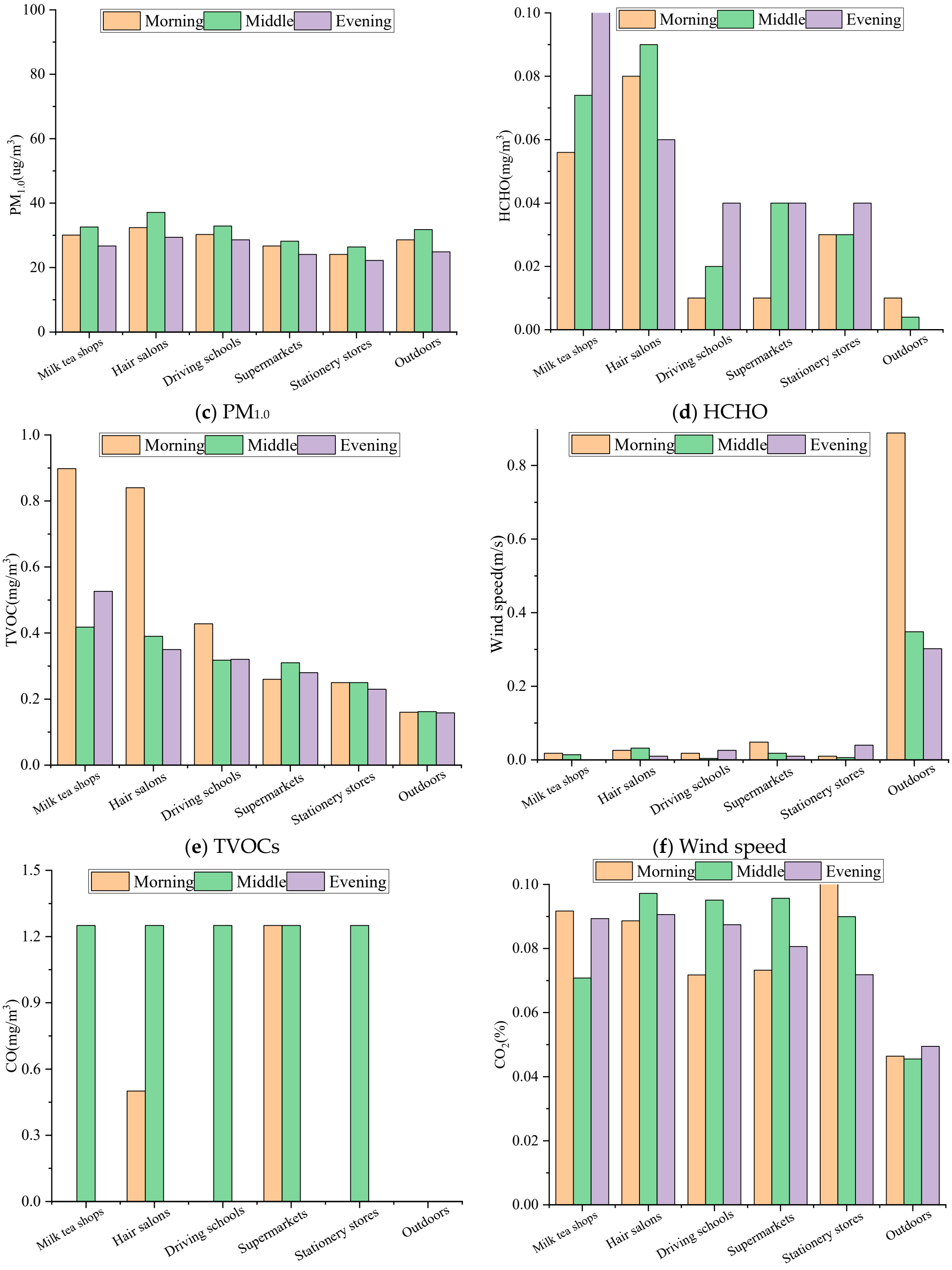
### *3.2. Distributions of Pollutant Concentrations at Different Times*

The concentration distributions of major indoor pollutants in different locations at different times are shown in Figure 2.




(**a**) $PM_{10}$ (**b**) $PM_{2.5}$

**Figure 2.** *Cont.*




(**c**) $PM_{1.0}$ (**d**) HCHO (**e**) TVOCs (**f**) Wind speed (**g**) CO (**h**) $CO_2$

**Figure 2.** Concentration distributions at different times.

As shown in Figure 2, the pollutants exhibited different trends at different times. The mass concentrations of $PM_{10}$, $PM_{2.5}$, and $PM_{1.0}$ reached their maximum at noon when the concentrations in the hair salons were highest. The corresponding mass concentrations of $PM_{10}$, $PM_{2.5}$, and $PM_{1.0}$ were 91.8 $\mu g/m^3$, 78.8 $\mu g/m^3$, and 37.1 $\mu g/m^3$, respectively. This is because, in semi-underground buildings, there is relatively less movement of people in the morning and evening, with more people present at noon, resulting in a relatively high concentration of indoor particulate matter [31]. In addition, outdoor particulate matter levels are relatively high in the morning due to the lower temperature and the presence of an inversion layer [32], which is not conducive to the diffusion of particulate matter. At noon, the inversion layer is destroyed, and the concentration is relatively low. At night, due to factors such as reduced personnel and relatively calm surroundings, the concentration is relatively lower. This result is consistent with conclusions in the literature [33], which also proves that the particulate matter concentration is greatly influenced by personnel. TVOCs showed the highest concentration in the morning, mainly in milk tea shops and hair salons. This is because of poor ventilation at night, resulting in the highest concentration occurring in the morning. The HCHO concentration was the highest in milk tea shops, followed by hair salons, but the highest concentrations occurred in the evening. This is because business is relatively good in the evening and there are more customers buying hot drinks. Therefore, milk tea shops generate a large amount of HCHO at this time due to the extensive use of heating equipment, food packaging, and plastic products. The indoor wind speed, CO, and $CO_2$ were all within the normal range without significant fluctuations. Fluctuations in the $CO_2$ concentration were mainly related to personnel flow, but they met the requirements of regulatory restrictions during the testing period.

*3.3. The Impact of Outdoor Air on Indoor Pollutant Concentrations*

The impact of outdoor air on the concentration distributions of major indoor pollutants is shown in Figure 3.

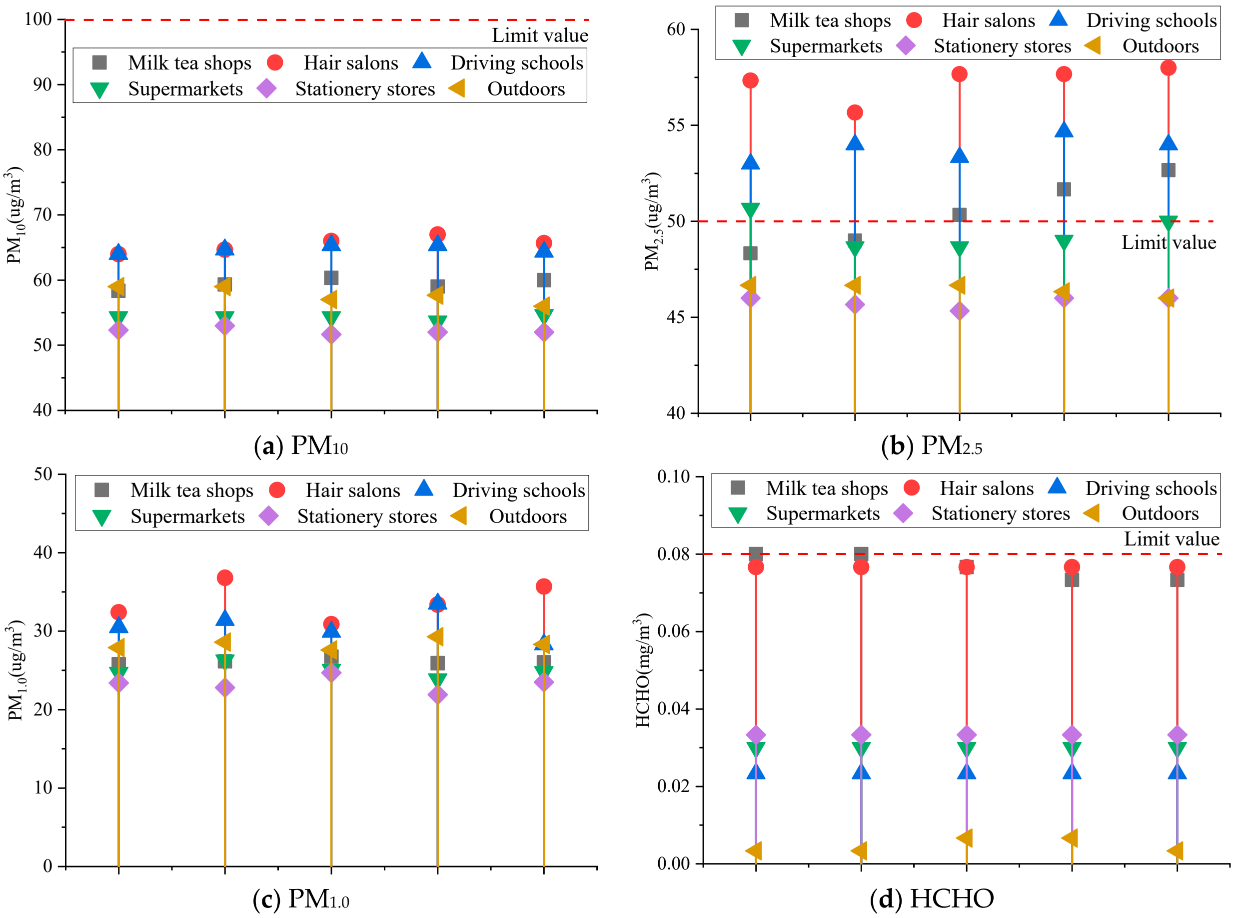



**Figure 3.** *Cont.*

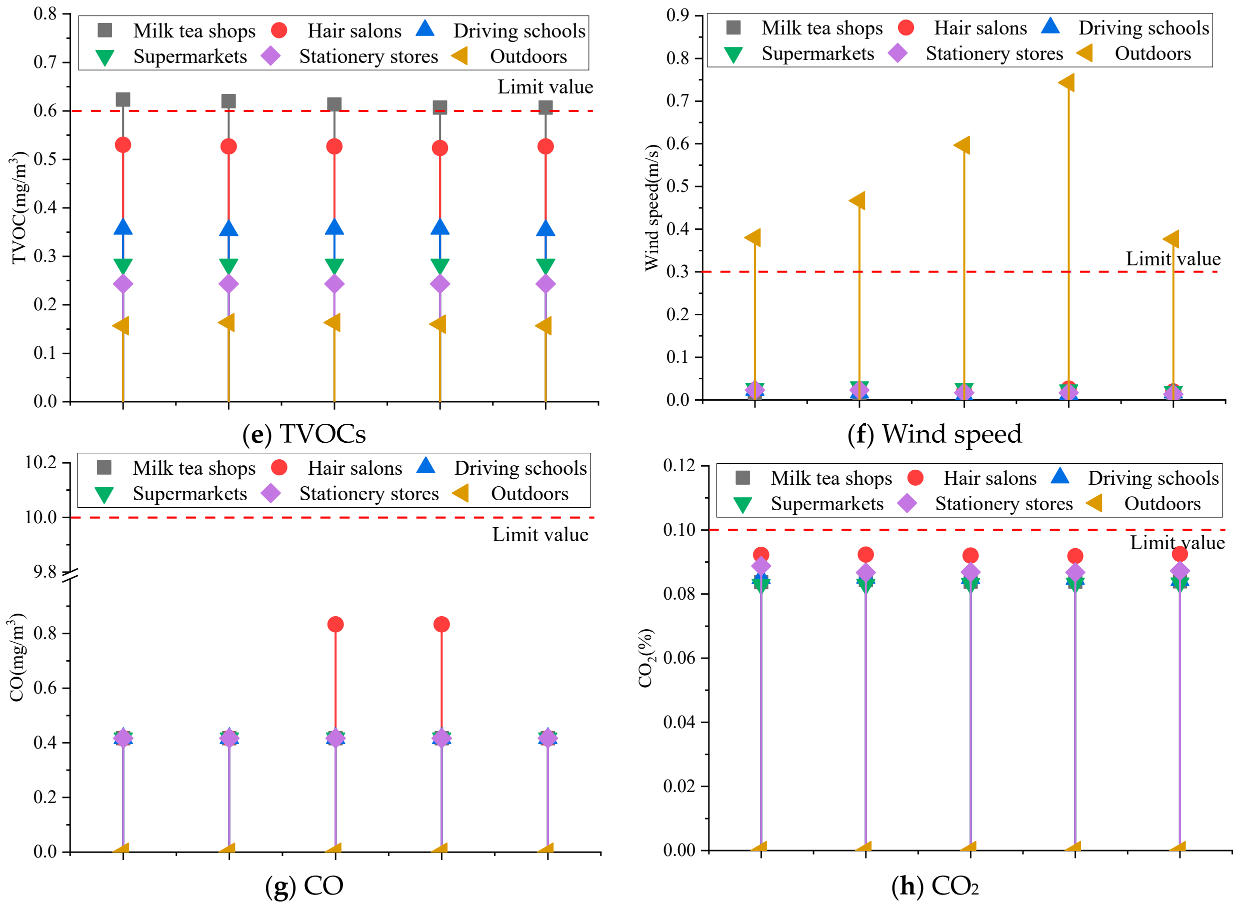



**Figure 3.** The impact of outdoor air on indoor pollutant concentrations.

Figure 3 shows that, excluding those for wind speed, all the outdoor measurement points were below the standard limit [24], and the indoor concentrations of pollutants were higher than those outside. The mass concentrations of $PM_{10}$, $PM_{2.5}$, and $PM_{1.0}$ in the milk tea shops, hair salons, and driving schools were higher than those outdoors. Indoor activities were the source of this pollution. The difference in mass concentration between indoors and outdoors was between 0.33 and 9.67 $\mu g/m^3$ for $PM_{10}$, between 0.00 and 12.00 $\mu g/m^3$ for $PM_{2.5}$, and between 0.00 and 8.20 $\mu g/m^3$ for $PM_{1.0}$. The indoor concentrations in different functional areas for TVOCs, HCHO, CO, and $CO_2$ were higher than the outdoor concentrations. Again, indoor activities were the source of this pollution. The difference in mass concentration between indoors and outdoors was 0.02–0.077 $mg/m^3$ for HCHO, 0.08–0.47 $mg/m^3$ for TVOCs, 0.42–0.83 $mg/m^3$ for CO, and 0.036–0.045% for $CO_2$. The wind speed outdoors was higher than that indoors, with a difference of 0.36–0.73 m/s. Therefore, it is still necessary to strengthen the construction of the indoor environment, especially regarding the form and equipment selection for indoor ventilation [34].

### *3.4. The Relationship between Human Satisfaction and the Concentrations of Various Pollutants*

A total of 378 valid questionnaires were obtained in this survey, and the distribution of the 378 subjects by gender is shown in Table 4.

**Table 4.** Gender distribution in different functional areas during the research period.

| Functional Areas | Males | Females | Total |
|---|---|---|---|
| Milk tea shops | 34 | 87 | 73 |
| Hair salons | 45 | 41 | 82 |
| Driving schools | 17 | 24 | 69 |
| Supermarkets | 23 | 58 | 76 |
| Stationery stores | 11 | 38 | 78 |
| Total | 130 | 248 | 378 |

From Table 4, it can be seen that the male-to-female ratio was nearly 1:2. Among the respondents, there was one person aged less than 16 years old and one person aged over 55 years old, accounting for 0.3% and 0.3% of the total, respectively. There were 40 people aged between 16 and 25 years old, accounting for 10.6%; 301 people aged between 26 and 35 years old, accounting for 79.6%; 29 people aged between 36 and 45 years old, accounting for 7.7%; and 6 people aged between 46 and 55 years old, accounting for 1.6%. Figure 4 shows the frequency distribution of the indoor personnel's voting values in different areas of the semi-underground building.

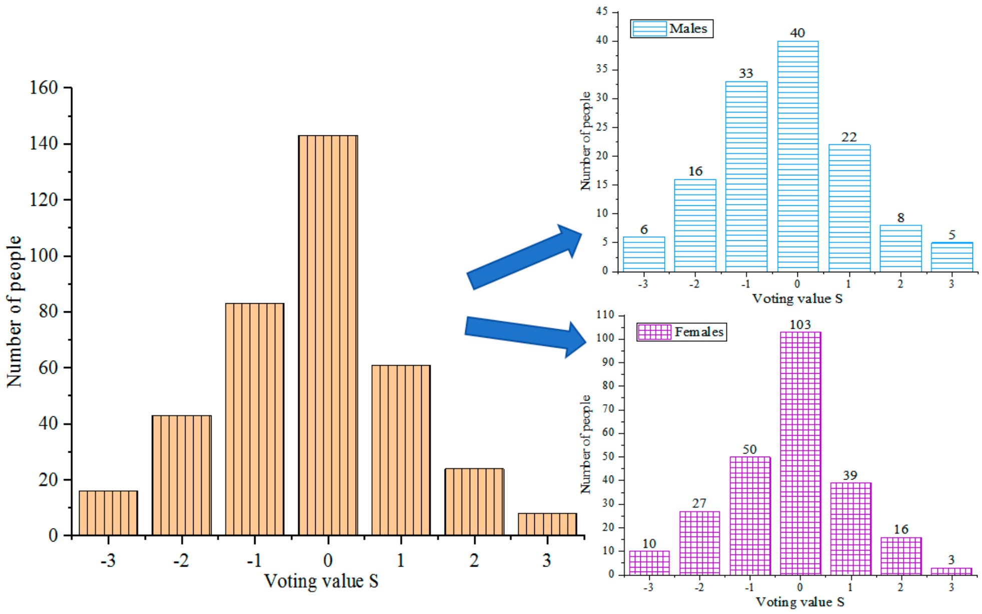


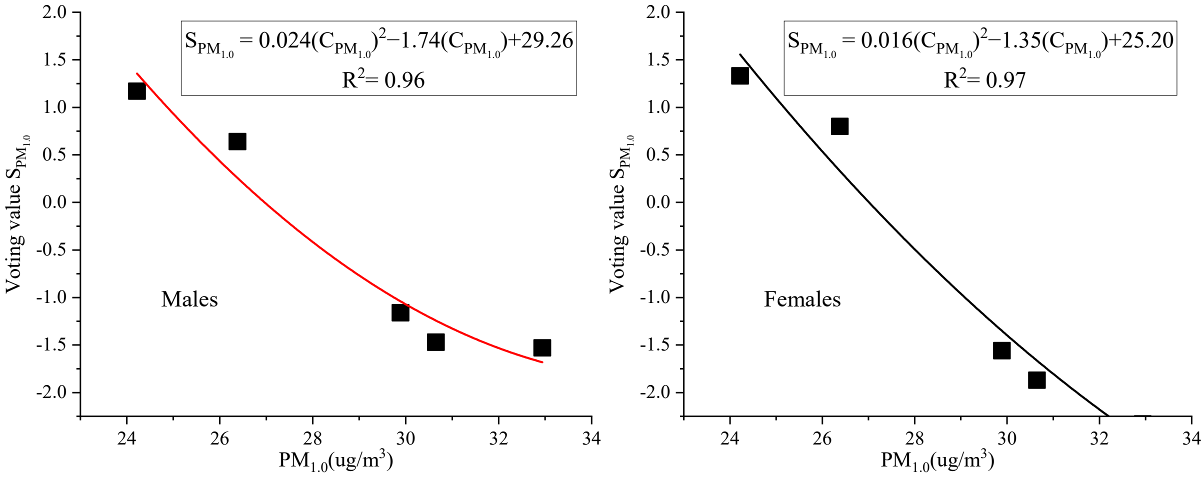

**Figure 4.** Subjective voting on indoor air quality in a semi-underground building.

From Figure 4, it can be seen that the proportion of respondents who rated the indoor air quality as "moderate" was the highest, at 37.83%. However, the proportion of people who were dissatisfied with the indoor air quality, i.e., $S < 0$, was 37.57%. The proportion of people who were satisfied with the indoor air quality, i.e., $S > 0$, was 24.60%. Among them, males to the indoor air quality as "moderate" was 10.58%. The proportion of people who were dissatisfied with the indoor air quality was 14.55%. The proportion of people who were satisfied with the indoor air quality was 9.26%, while females who categorized their satisfaction with indoor air quality as "moderate" was 27.25%. The proportion of people who were dissatisfied with the indoor air quality was 23.02%. The proportion of people who were satisfied with the indoor air quality was 15.34%. It can be seen that there is a significant difference in the satisfaction level of indoor air quality between males and females. Females have a higher proportion of evaluations, with a moderate difference of 16.67%, dissatisfaction difference of 8.47%, and satisfaction difference of 6.08%. This is mainly due to the physiological and psychological differences between males and females.

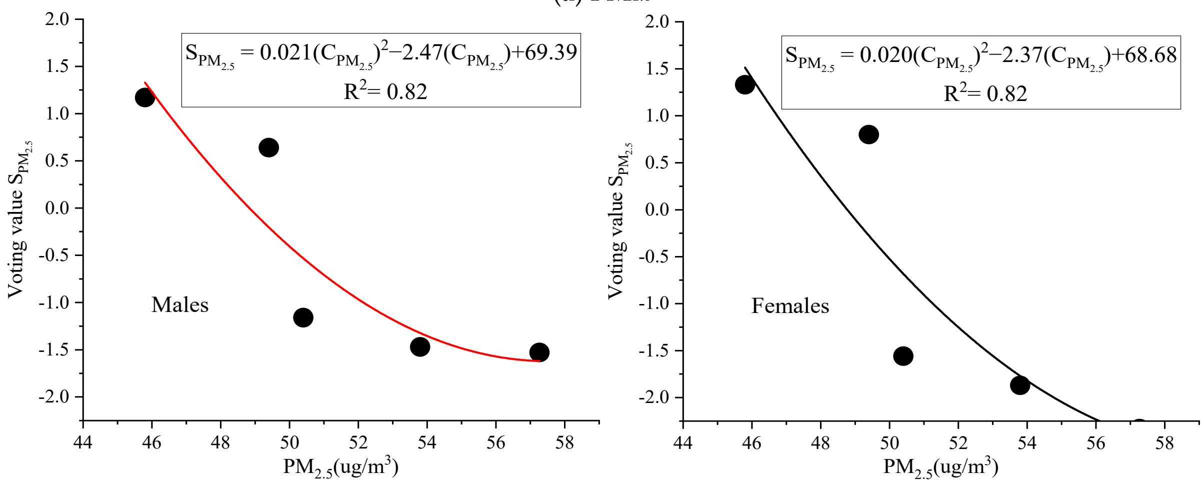
Therefore, the evaluation of males and females should be studied separately in subsequent research, which is more practical.

This indicates that the proportion of dissatisfied personnel in this semi-underground building is still high. This is mainly due to the relatively poor ventilation conditions in the semi-underground building, with some ventilation doors and windows located near the surface, causing surface pollutants to pollute the indoor environment. In addition, due to design differences, its natural ventilation is influenced by surface doors and windows, which also results in a greater ventilation effect [14]. There is also cross-contamination of the environment between different functional areas because of the limited space inside the semi-underground building, which can sometimes become relatively crowded. Therefore, although the overall evaluation was moderate, the proportion of dissatisfaction is still the main factor to consider.

To further provide upper-limit concentration values associated with human satisfaction for various pollutants in the semi-underground building, the measured average concentration of each pollutant in the semi-underground building was plotted as the horizontal axis, and the average voting value S from the personnel was plotted as the vertical axis. For each harmful substance X, the relationship between the indoor personnel's satisfaction with the air quality, $S_X$, and the concentration of the pollutant, $C_X$, was then obtained via fitting, as shown in Figure 5.

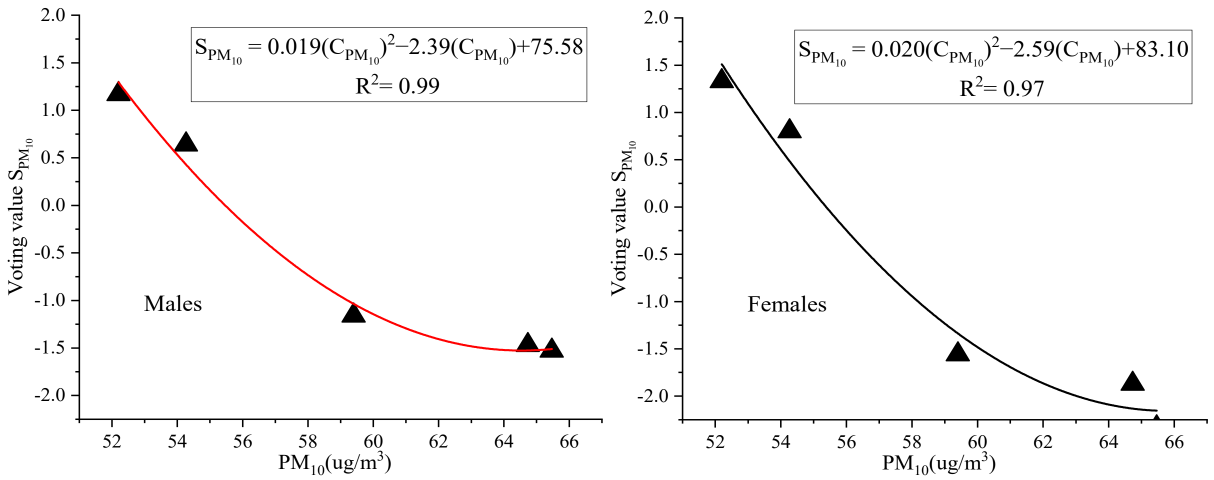



(**a**) $PM_{1.0}$

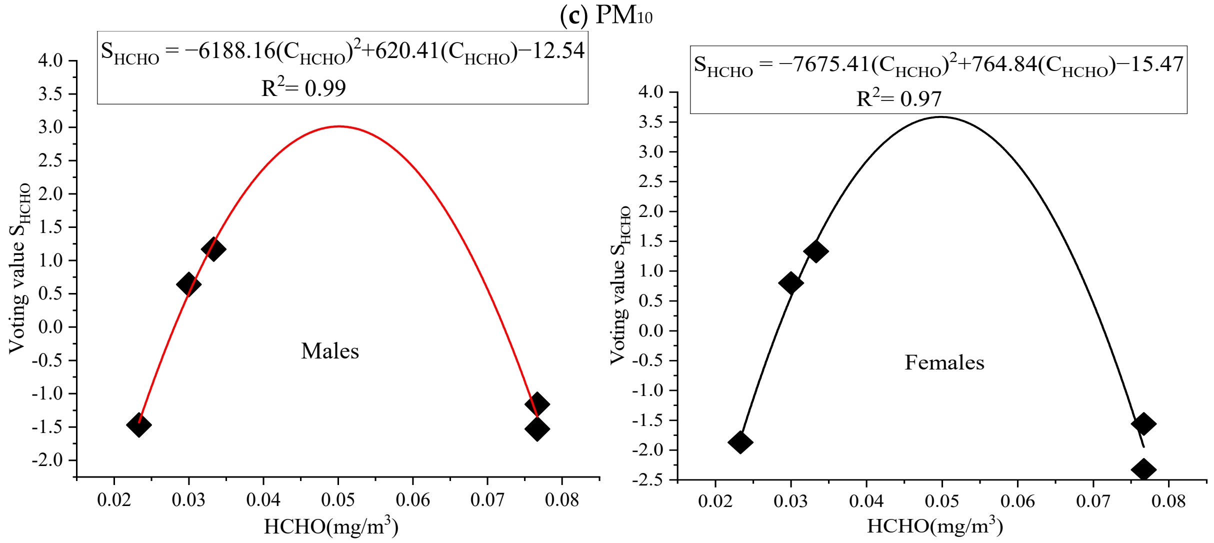



(**b**) $PM_{2.5}$

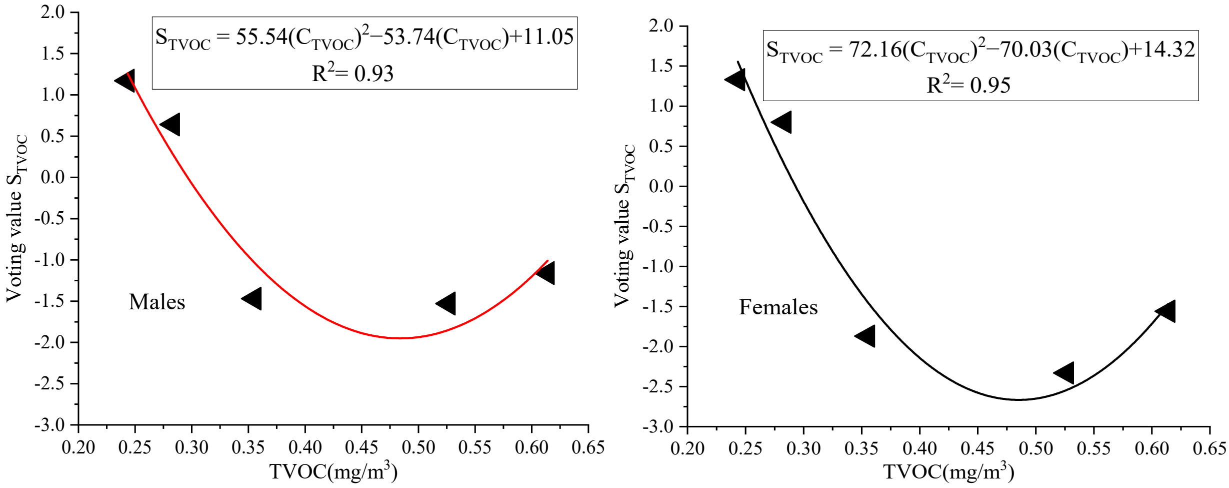
**Figure 5.** *Cont.*




(**c**) $PM_{10}$

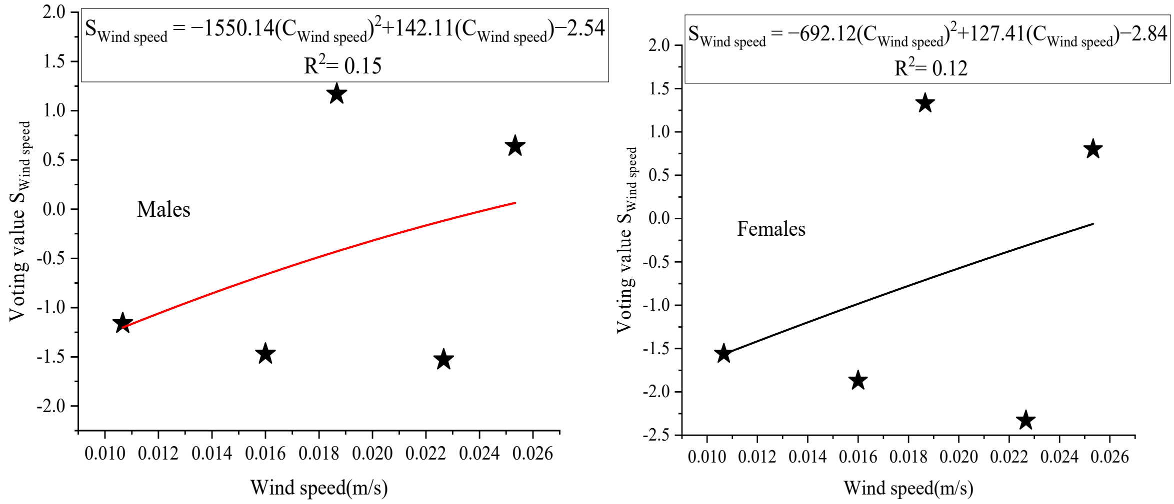



(**d**) HCHO

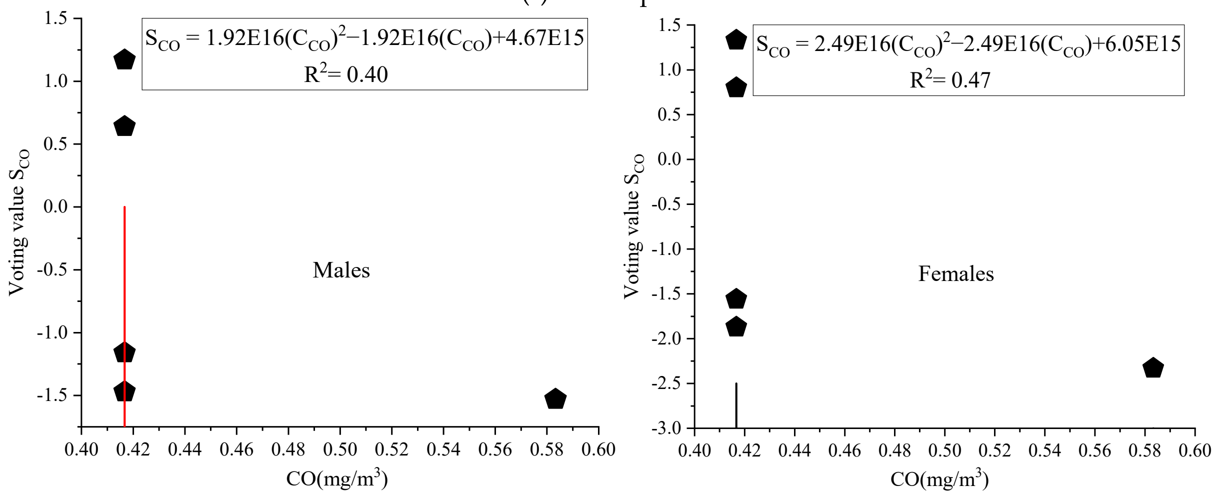



(**e**) TVOCs

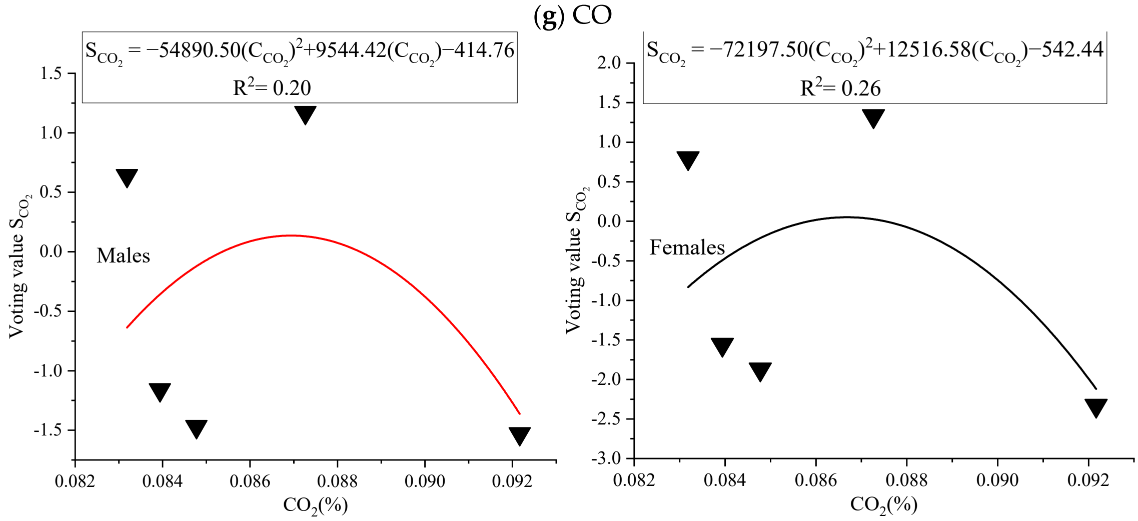
**Figure 5.** *Cont.*




(**f**) Wind speed




(**g**) CO




(**h**) $CO_2$

**Figure 5.** Relationships between air quality satisfaction and the concentrations of various pollutants.

In Figure 5, the quadratic regression fitting results for the relationships between human satisfaction and the concentrations of various pollutants show a weak correlation for wind speed, CO, and $CO_2$ (with correlation coefficients ($R^2$) of 0.14, 0.44, and 0.23, respectively). $PM_{1.0}$, $PM_{2.5}$, $PM_{10}$, HCHO, and TVOCs all showed strong correlations (correlation coefficients ($R^2$) of 0.96, 0.82, 0.98, 0.98, and 0.94, respectively). Therefore, human satisfaction can be used to evaluate indoor pollutant concentration values. The pollutant concentration value corresponding to $S_X = 0$ can then be taken as the upper-limit concentration value of human satisfaction for that particular pollutant.

When $SPM_{1.0} = 0$, the upper limit of satisfaction with the indoor $PM_{1.0}$ concentration for males and females is about 45.99 μg/m$^3$, 56.50 μg/m$^3$. However, there is currently no concentration limit for $PM_{1.0}$ indoors. Therefore, based on the relevant literature and indoor environmental testing results, the concentration limit results are significantly high. When $SPM_{2.5} = 0$, the upper limit of satisfaction with the indoor $PM_{2.5}$ concentration for males and females is about 71.23 μg/m$^3$, 68.00 μg/m$^3$, which is slightly higher than the standard requirement of 0.50 mg/m$^3$. When $SPM_{10} = 0$, the upper limit of satisfaction with the indoor $PM_{10}$ concentration for males and females is about 65.97 μg/m$^3$, 70.88 μg/m$^3$, which is slightly lower than the standard requirement of 0.1 mg/m$^3$. The reason for this may be that such particles are colorless and odorless [28] and cannot be recognized with the naked eye, resulting in differences in the upper limit of human satisfaction with particle concentrations. When SHCHO = 0, the upper-limit concentration of satisfaction with indoor HCHO for males and females is about 0.03 mg/m$^3$, 0.03 mg/m$^3$, which is slightly lower than the standard requirement of 0.08 mg/m$^3$. When STVOC = 0, the upper limit of satisfaction with the indoor TVOC concentration for males and females is about 0.95 mg/m$^3$, 0.68 mg/m$^3$, which is slightly higher than the standard requirement of 0.60 mg/m$^3$. When $S_{\text{wind speed}}$ is 0, the upper limit of satisfaction with the indoor wind speed for males and females is about 0.02 m/s, 0.03 m/s, which is consistent with the standard requirement of $\leq$0.03 m/s. When SCO = 0, the upper-limit concentration of satisfaction with indoor CO for males and females is about 0.63 mg/m$^3$, 0.58 mg/m$^3$, which is far below the standard requirement of 10 mg/m$^3$. When $SCO_2 = 0$, the upper limit of human satisfaction with the indoor $CO_2$ concentration for males and females is about 0.09%, 0.09%, which is slightly lower than the standard requirement of 0.1%. This is because the personnel are in a semi-underground building, and due to the differences in the building itself and the personnel's subjective evaluations, they have higher requirements for indoor air quality. This indirectly indicates that more attention should be paid to indoor air quality in semi-underground buildings due to their unique location.

In addition, it was found through the human satisfaction survey that the upper-limit concentration values of $PM_{1.0}$, $PM_{2.5}$, and TVOCs are all higher than the indoor hygiene standard concentration limits. The human satisfaction upper-limit concentrations of $PM_{10}$, HCHO, wind speed, CO, and $CO_2$ are all below the standard limits. Therefore, indoor pollutant hygiene standards should take into account two factors—personnel health and human satisfaction—to establish stricter standards.

## 4. Conclusions

This study examined indoor air quality and personnel satisfaction in different functional areas of a semi-underground building in Xi'an City. Preliminary conclusions were drawn as follows:

1. The places where the concentration of $PM_{2.5}$ exceeded the standard limit were the milk tea shops, hair salons, and driving schools, presenting 1.01 times, 1.15 times, and 1.08 times the standard limit, respectively. Overall, the concentration of fine particulate matter showed the following trend: hair salons > driving schools > milk tea shops > outdoors > supermarkets > stationery stores. The next most prominent pollutants were HCHO and TVOCs.
2. Pollutants exhibited different trends at different times of the day. The mass concentrations of $PM_{10}$, $PM_{2.5}$, and $PM_{1.0}$ reached their maximum at noon, while TVOCs showed their maximum concentration in the morning. The maximum concentration of HCHO occurred in the evening. The indoor wind speed, CO, and $CO_2$ were all within the normal range.

3. Excluding those for wind speed, all the outdoor measurement points were below the standard limit, and the indoor concentrations of pollutants were higher than those outside.
4. The upper-limit concentration values of human satisfaction for $PM_{1.0}$, $PM_{2.5}$, and TVOCs were all higher than the standard limit values. The human satisfaction upper-limit values for $PM_{10}$, HCHO, wind speed, CO, and $CO_2$ were all below the standard limits. The results of this study, which examined the indoor air quality and personnel satisfaction in different functional areas of a semi-underground building, can contribute to the widespread development and application of such buildings.

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