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Exposure of Elderly People to Indoor Air Pollutants in Wanxia Nursing Home

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Abstract: The elderly residing in nursing homes are typically more advanced in age, have more health issues, and spend more time indoors than other elderly people. This study explored the indoor air quality in the Wanxia nursing home, the largest private nursing home in Chengdu, China, based on long-term measurement data. Air pollutant sensors measured the level of air pollution in the Wanxia nursing home from March 2021 to February 2022. This study obtained several important results: (1) The indoor air quality index (*IAQI*) of the Wanxia nursing home was at a low pollution level in spring, summer, and autumn, and at a moderate pollution level in winter. PM concentration played the most important role in determining indoor air quality; (2) During winter, the 24 h mean indoor concentrations of PM2.5 and PM10 were close to or even exceeded the standard limits. During winter and summer nights, indoor CO_2 levels were very close to or greater than 1000 ppm. During spring and summer nights, the indoor TVOC concentrations exceeded the limit (0.45 mg/m^3); (3) Apart from HCHO concentrations in autumn, the levels of other indoor air pollutants were significantly influenced by their outdoor levels. In addition, the seasonal indoor/outdoor (I/O) ratios of CO_2 and TVOCs exceeded 1; and (4) Indoor CO_2 levels were closely related to indoor temperature (*Ta*) and relative humidity (*RH*) in each season. PM10 concentration correlated with *Ta* and *RH* in summer, while PM2.5 concentration did not correlate with *Ta* and *RH* in winter. The indoor TVOC level positively correlated with *RH*. Lastly, the indoor HCHO level was minimally influenced by changes in *Ta* and *RH*. Due to the above results, this study proposes targeted strategies for improving indoor air quality in nursing homes.

Keywords: nursing home; air pollutants; indoor exposure; elderly people

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1. Introduction

In the last 20 years, rapid urbanization and economic development have caused significant environmental issues in China, particularly urban air pollution [1]. Epidemiological evidence indicates a relationship between air pollution and people's health. Air pollutants typically include particulate matter (PM) of different sizes, total volatile organic compounds (TVOCs), and gaseous air pollutants, such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), etc. Long-term exposure to air pollution in urban areas is believed to contribute to the degradation of public health [2], causing more than 8.8 million deaths per year, and reducing life expectancy by 2.9 years [3]. Due to their weakened immune system and chronic diseases associated with old age, such as chronic cardiopulmonary disease, influenza, or asthma, elderly people are particularly vulnerable to the adverse effects of air pollutants, even at low concentrations [4,5].

PM usually refers to PM2.5 and PM10, which represent particulate matter with aerodynamic diameters of less than 2.5 μm and 10 μm, respectively [6]. The main sources of PM are traffic and various industrial processes [7]. Previous studies have shown that PM is associated with several medical conditions, including lung cancer, stroke, lower respiratory

infections, chronic obstructive pulmonary disease, ischemic heart disease, acute infections, and sudden infant death syndrome [8,9]. Some studies have found a strong correlation between PM concentration and daily mortality rates among individuals over 75 in Spain [10] and the USA [11]. "Air Pollution and Health: A European Information System" (APHEIS) showed that the improvement in the burden of mortality in European cities brought about by reducing PM2.5 levels to 15 $\mu g/m^3$ was over 30% greater than that brought about by reducing PM2.5 to 20 $\mu g/m^3$ [12]. Moreover, it was found that reducing long-term exposure to PM10 concentrations by 5 mg/m^3 would have "prevented" between 3300 and 7700 early deaths annually in 19 European cities [13]. The PM2.5 increase of 10 $\mu g/m^3$ is associated with a 15~27% increased risk of lung cancer mortality [14]. Since 2010, high PM levels have been identified as the fourth major cause of death in China (WHO 2014). In recent years, the PM2.5 concentration in urban areas of southern China has ranged from 25 $\mu g/m^3$ to more than 60 $\mu g/m^3$, while in northern China, some urban areas witnessed concentrations over 100 $\mu g/m^3$ [15]. In 2016 and 2017, about 40% of cities in China had an annual average concentration of PM2.5 within the range of 35~52.5 $\mu g/m^3$ [16].

TVOCs are total volatile organic compounds. As a precursor to the formation of photochemical smog, outdoor TVOCs play an important role in stratospheric ozone depletion and the greenhouse effect [17]. Indoor TVOCs represent a potential risk to people's health [18], because people are more exposed to them [19]. They are primarily found in construction materials and ambient air [19,20]. Long or recurrent exposure to indoor TVOCs may cause harmful effects on the human nervous, immune, and reproductive systems; cause liver and kidney damage [21]; induce asthma, wheezing, and allergies [22]; and cause cancer [7]. In 2020, TVOCs exhibited a decrease (20~66%) in North China and an increase (13~127%) in the Yangtze River Delta region [23]. While studies on indoor TVOCs are relatively rare compared to outdoor TVOC studies [23], numerous buildings have exceeded TVOC concentrations based on China's "Standards for Indoor Air Quality" (GB/T 18883-2002) [24,25]. In addition, formaldehyde (HCHO) has also been observed indoors due to its relatively high concentration [26,27]. It has been found that construction materials and furniture are the main sources of indoor HCHO [26].

CO_2 in ambient air is primarily a greenhouse gas that causes global warming [28]. Approximately 70% of global CO_2 emissions originate from urban fossil fuel combustion [29]. Nowadays, there is growing interest in monitoring CO_2 in urban areas as an effort to control carbon emissions [30,31]. In residential buildings with natural ventilation, human activities cause significant increases in indoor CO_2 levels [32,33]. Thus, the indoor CO_2 concentration is a crucial factor in assessing indoor air quality (*IAQ*) [34,35]. Previous studies have suggested that the permissible indoor CO_2 concentration is 700~1000 ppm. However, even low CO_2 levels can impact peripheral blood flow, impair the functioning state of the cerebral cortex, and alter respiratory movement [36]. When indoor CO_2 concentration is higher than 1000 ppm and there is inadequate ventilation, it can deteriorate sleep quality, cause headaches, confusion, anxiety, and drowsiness, diminish cognitive decision-making abilities, and reduce psychomotor performance [37–39].

Previous studies have focused on the variability of the indoor-to-outdoor ratio (I/O ratio) of air pollutant concentrations [40]. The large difference in I/O ratios can be attributed to different building types, crack geometry in buildings, construction materials, ventilation, indoor sources of air pollutants, and outdoor wind conditions [40,41]. In addition, the indoor air quality index (*IAQI*) is a nonlinear index that quantitatively describes indoor air quality. It has been used as an indicator to assess the effects of air pollutants on people's health [42,43]. It has been found that a poor *IAQI* can cause poisoning, allergic reactions, and sick building syndrome [44]. Concentration levels of nine common indoor air pollutants, including CO_2, carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), HCHO, PM, TVOCs, radon (Rn), and airborne bacteria count (ABC), were also used as indicators for calculating *IAQI* values [45]. These studies chose the type of indoor air pollutants according to actual indoor conditions. The conditions varied significantly depending on the building type and its characteristics (e.g., ventilation, envelope design, materials, etc.) [46], indoor

emission sources, outdoor environmental conditions, indoor activities (e.g., smoking and cooking) [47], etc. In recent years, *IAQI* data have been observed in many indoor spaces, such as office buildings [42,48], shopping malls [21,49], stations and train cabins [50–52], schools [53–55], hospitals [56], and residential buildings [57,58]. However, *IAQI* data for nursing homes are very scarce.

The World Health Organization defines older persons as those over 60 years of age. In 2018, the total number of elderly aged 65^{+} in China accounted for 12.0% of the total population. There is no doubt that China will soon face particularly tough challenges in regard to the aging population [59,60]. Due to the 4-2-1 family structure in China (four grandparents, two parents, and one child), an increasing number of elderly people have to trade traditional family care for institutional care [61]. Since 2019, nearly 30,000 nursing homes have been established and more than 7.46 million beds have been supplied for the aging population in these homes in China [62]. Due to a weak immune system and a higher chance of chronic diseases [63], the elderly are particularly vulnerable to air pollutants. Moreover, the elderly residing in nursing homes are usually more advanced in age, already have health issues, and spend more time indoors than other elderly people. Assessing indoor air pollution exposure and clarifying the relationship between indoor and outdoor air pollutants is important for understanding the impact of air pollution on the health of elderly people.

The elderly living in nursing homes usually spend more time indoors. Therefore, this study measured the air quality in the Wanxia nursing home. The aims were to (a) use the *IAQI* values of the nursing home with natural ventilation to describe the daily exposure of the elderly to several indoor air pollutants, including PM10, PM2.5, CO_2, HCHO, and TVOCs; (b) analyze the relationship between indoor and outdoor air pollutants and determine the factors influencing indoor air quality; and (c) optimize strategies for natural ventilation to improve the health of the indoor environment. This is the first study to assess exposure to indoor air pollution in nursing home buildings in southwest China. The findings of this study may raise public awareness of indoor air quality in institutional nursing homes in the hopes of protecting the elderly by adopting the most convenient, efficient, and affordable methods to reduce their exposure to indoor air pollutants.

2. Materials and Methods

2.1. Study Area and Sample Selection

As of the end of 2021, the number of elderly people in Chengdu has reached 3.2 million, accounting for 20.61% of the total local population (Chengdu Statistical Yearbook). The elderly care facility in this study was Wanxia Elderly Service Center (Wanxia nursing home in the rest of the paper), the largest private nursing home in Chengdu. It is located in Jinniu District of Chengdu (N30°05′–N31°26′, E102°54′–E104°53′). Established in 2003, the nursing home covers an area of about 46,666.66 m^2 and is equipped with 500 beds. A total of 180 elderly people live in this nursing home. More than 90% of the elderly people are 80 and older, and 2.8% are 90 and older. Of these 180 elderly people, 120 (66.7%) are women and 60 (33.3%) are men.

Within the nursing home, there are nine randomly distributed two-story buildings, covering a total building area of 25,380 m^2. These buildings rely only on natural ventilation, i.e., opening doors and windows. When this study collected data on air quality indicators, the nursing home was divided into four functional spaces: indoor space (bedroom), semi-open pubic corridor space, road space, and garden space. This study selected five random monitoring areas (Figures 1 and 2), i.e., two bedrooms, one public corridor, one main road, and one garden. Each bedroom can house four elderly residents and has a washroom. The bedroom and its indoor washroom are usually cleaned with water every three days. These bedrooms are adjacent to the public corridor. Within the bedrooms and corridors, there is tile flooring. The parameters of the bedrooms and their furniture are shown in Table 1. Within these areas, this study simultaneously monitored air pollutants and microclimate. In addition, there is no kitchen in the bedrooms, and the elderly go to the dining room by

themselves. For the elderly who are unable to take care of themselves, meals are delivered to their bedrooms. At the end of the hallway on each floor is a cleaning room. The parking lot is outside the entrance to the nursing home, away from the accommodation buildings. It is important to note that the elderly residing in the two bedrooms are non-smokers and do not have access to a fresh air system. The bedrooms are naturally ventilated through opening doors and windows. No pets were found in any of the bedrooms.



Figure 1. Spatial layout of measurement sites.



Figure 2. Functional spaces of Wanxia nursing home. (**i**) Bedroom. (**ii**) Public corridor. (**iii**) Road space. (**iv**) Garden space.

Table 1. Bedroom parameters.

	Size (m) (Length × Width × Height)	Number
Bedroom	6.3 × 6.0 × 3.3	1
Door	1.2 × 2.4	1
Window	1.0 × 1.5	3
Beds	2.0 × 1.2	4
Furniture	Tin wardrobe, TV stand and wooden chairs	

2.2. Air Pollutants and Microclimate Measurement

Concentrations of particulate matter (PM10 and PM2.5), gaseous air pollutants (CO_2, HCHO and TVOCs), temperature (*Ta*), and relative humidity (*RH*) within the five areas were monitored simultaneously using direct reading instruments from March 2021 to February 2022, including 15 days in spring, 14 days in summer, 14 days in autumn, and 14 days in winter. These instruments were placed horizontally in the center of the indoor and outdoor spaces, 1.1 m above the ground. To prevent the elderly from tripping, the indoor instruments were placed on the side of the bedroom at a sufficient distance from doors and windows to avoid potential disturbances. During the monitoring period, all monitoring was conducted for 24 h each day. The elderly maintained their everyday activities without changing their typical habits.

Continuous indoor and outdoor CO_2 measurements were conducted using an LI-830 CO_2 analyzer (LI-COR Inc., Lincoln, NE, USA) at 5 min intervals, which is also suitable for monitoring urban CO_2 levels [28]. PM10 and PM2.5 were observed within each area using a SMART 126S monitor (Taylor Inc., Changzhou, China), which is based on the principle of laser scattering. A SMART 128S monitor (Taylor Inc., Changzhou, China) was used to monitor TVOCs and HCHO concentrations using semiconductor and electrochemical sensors, respectively. Finally, *Ta* and *RH* were measured using a Kestrel 5500 portable weather station (Nielsen-Kellerman, Boothwyn, PA, USA). All instruments were configured to perform measurements at 5 min intervals. A detailed explanation of the measuring equipment is shown in Table 2. Overall, the above design of direct detection apparatus is based on the principle of infrared, laser, or electrochemical methods, and the direct detection data are reliable [64].

Table 2. Sensor characteristics and air pollutants exposure limits.

Instrument	Parameter	Operational	Accuracy	Circumstance Demands
Kestrel 5500	*Ta*	−29~70 °C	0.1 °C	−30~80 °C
	RH	0~100%	1%	
SMART126S	PM2.5	0~999 μg/m^3	1 μg/m^3	0–50 °C
	PM10			0~100% *RH*
LI-830	CO_2	0~20,000 ppm	3%	0~45 °C
SMART128S	HCHO	0~3.000 mg/m^3	0.001 mg/m^3	90~100% *RH*
	TVOCs	0~9.999 mg/m^3	0.001 mg/m^3	

2.3. Indoor/Outdoor (I/O) Ratio and IAQI Benchmarks

The I/O ratio represents a direct relationship between indoor and outdoor air pollutant concentrations. The I/O ratio is calculated as follows:

$$\text{I/O ratio} = \frac{C_{in}}{C_{out}} \quad (1)$$

where C_{in} and C_{out} are the indoor and outdoor air pollutant concentration, respectively. Subsequently, the concentrations of PM2.5, PM10, CO_2, HCHO, and TVOCs were chosen to calculate the *IAQI* values. The *IAQI* calculation method takes into account not only the mean concentration of each air pollutant, but also the maximum concentration of the

pollution, enabling an objective assessment of air quality. The following formula was used to calculate *IAQI* values (Equations (2) and (3)) [65,66]:

$$IAQI = \sqrt{I_{max} \times I_{average}} \quad (2)$$

$$I = \frac{1}{n} \sum_{i=1}^{n} \frac{C_i}{S_i} \quad (3)$$

where C_i is the fractional dose of the i^{-th} representative pollutant; n is the number of pollutants, i = 1, 2, ..., n; and S_i denotes the evaluation standard value of the i^{-th} representative pollutant.

The *IAQI* value is divided into 4 levels: good air quality and no pollution (*IAQI* < 0.59), low pollution level (0.5 < *IAQI* < 1), moderate pollution level (1 < *IAQI* < 2), and high pollution level (*IAQI* > 2) [65,66]. The higher the *IAQI* value is, the worse the air quality is. The evaluation of air pollutants was performed by comparing the "Standard for Indoor Environmental Pollution Control of Civil Building Engineering" (GB50325-2020) [67], "Ambient Air Quality Standards" (GB3095-2012) [68], and the "Standard for Indoor Air Quality" (GB/T18883-2022) [69].

2.4. Data Analysis Methods

In this study, all parameters were calculated for each measurement day and mean values were determined for the entire season. Variance and Pearson's correlation analysis in SPSS 11.0 (SPSS Inc., Chicago, IL, USA) were used to assess differences in the concentration of air pollutants between the indoors and the outdoors. Results are expressed as 95% confidence intervals. Origin 8.0 was used to draw charts and perform function fitting.

3. Results

3.1. Seasonal Levels of Indoor and Outdoor Air Pollutants

Given the unique topography of the Sichuan Basin, Chengdu is characterized as a densely populated city with limited air movement, which contributes to the accumulation of air pollutants that are difficult to disperse later. The annual and seasonal mean concentrations of CO_2, HCHO, PM10, PM2.5 and TVOCs in the Wanxia nursing home are shown in Figure 3 and Table 3. The annual mean concentration of indoor CO_2 (594.76 ppm) was clearly higher than that of the outdoor one (479.68 ppm). Moreover, the annual mean CO_2 concentration in all monitored areas did not exceed the standard limit (1000 ppm) and met residential standards.

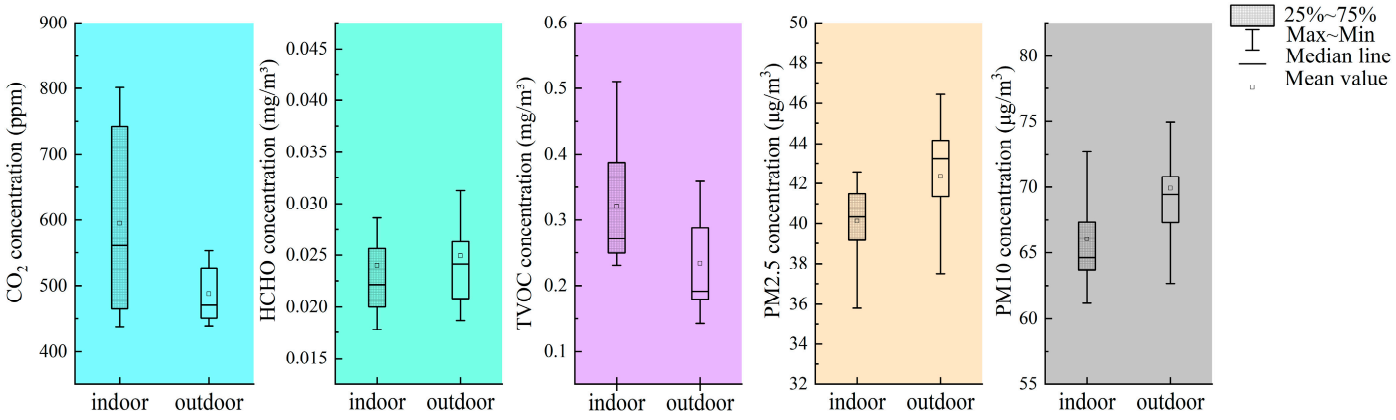


Figure 3. Comparison of annual mean indoor and outdoor air pollutant levels.

Table 3. Seasonal concentrations of indoor and outdoor air pollutants.

Air Pollutants		Spring				Summer				Autumn				Winter			
		Bedroom	**Corridor**	**Road**	**Garden**	**Bedroom**	**Corridor**	**Road**	**Garden**	**Bedroom**	**Corridor**	**Road**	**Garden**	**Bedroom**	**Corridor**	**Road**	**Garden**
CO_2 (ppm)	Mean	526.4 b	468.4 a	451.2 a	453.2 a	623.4 b	497.3 a	484.9 a	487.0 a	563.6 b	475.3 a	463.5 a	466.1 a	665.7 b	536.5 a	504.0 a	475.2 a
	Max	1264.5	855.0	875.5	893.5	1302.1	895.4	872.0	743.2	1016.1	941.8	900.0	919.3	1368.4	900.6	934.6	963.4
	Min	400.0	400.0	400.0	400.0	400.8	400.0	400.0	400.0	400.2	400.0	400.0	400.0	405.3	404.2	403.8	402.4
HCHO (mg/m^3)	Mean	0.030 a	0.037 a	0.037 a	0.037 a	0.034 c	0.030 b	0.025 a	0.023 a	0.013 a	0.017 b	0.018 b	0.018 b	0.019 a	0.017 a	0.026 b	0.024 b
	Max	0.59	0.19	0.09	0.11	0.57	0.08	0.08	0.05	0.46	0.09	0.13	0.066	0.21	0.12	0.16	0.11
	Min	0.012	0.006	0.001	0.001	0.036	0.001	0.001	0.001	0.006	0.001	0.001	0.001	0.005	0.006	0.006	0.002
TVOCs (mg/m^3)	Mean	0.398 b	0.293 ab	0.292 ab	0.279 a	0.401 b	0.231 a	0.202 a	0.275 a	0.191 b	0.157 a	0.147 a	0.147 a	0.295 b	0.305 b	0.286 ab	0.252 a
	Max	2.46	0.51	0.58	0.49	1.835	0.55	0.42	0.57	1.01	0.55	0.56	0.59	1.655	0.60	0.57	0.52
	Min	0.029	0.001	0.005	0.001	0.0085	0.001	0.001	0.001	0.007	0.004	0.007	0.002	0.006	0.001	0.006	0.014
PM10 ($\mu g/m^3$)	Mean	51.1 a	56.4 b	59.8 bc	64.2 d	49.9 a	49.9 a	50.9 a	52.3 a	54.7 a	69.6 b	69. 7 b	69.1 b	108.4 b	100.0 a	99.7 a	97.3 a
	Max	142.1	122.2	132.5	127.5	135.7	145.0	146.4	145.0	248.3	285.2	288.8	283.6	238.9	219.8	226.8	230.0
	Min	5.5	4.0	4.0	4.0	3.5	5.0	5.0	5.0	1.59	2.0	2.0	2.0	25.05	32.6	32.4	34.8
PM2.5 ($\mu g/m^3$)	Mean	29.9 a	30.7 ab	32.7 ab	35.2 b	33.8 a	34.0 a	34.3 a	34.6 a	34.1 a	37.3 b	37.2 b	37.4 b	62.6 a	64.2 b	65.5 b	65.0 b
	Max	118.00	74.35	91.33	57.36	96.24	95.64	95.05	89.22	149.93	144.82	146.88	139.61	137.25	144.6	145.8	141.0
	Min	5.6	3.0	4.0	3.0	3.3	4.8	7.7	4.8	2.3	1.0	1.0	1.0	20.33	24.4	25.4	23.4

Values followed by different letters indicate a statistically significant difference between treatment groups at $p \leq 0.05$ (5%) according to one-way ANOVA test followed by Duncan's post hoc test. The common letters indicate no significant difference between groups.

The annual mean indoor HCHO concentration (0.024 mg/m^3) was below the standard limit (0.07 mg/m^3) (GB50325-2020) and met residential standards (Figure 3). The annual mean outdoor HCHO concentration (0.025 mg/m^3) was higher than the reported outdoor HCHO concentration (0.012 mg/m^3) in Chinese cities [70], exceeding the chronic exposure reference levels (RELs) of 0.009 mg/m^3 set by the Office of Environmental Health Hazard Assessment (OEHHA) [71]. In summer, the indoor HCHO concentration was the highest compared to other seasons. The indoor HCHO concentration was significantly lower than the outdoor concentration in spring, autumn, and winter. However, HCHO concentration was significantly higher indoors than outdoors during summer.

The annual mean concentration of indoor TVOCs (0.32 mg/m^3) in the Wanxia nursing home was significantly higher than that of outdoor TVOCs (0.23 mg/m^3) (Figure 3). Both of the measurements were lower than the standard limit (0.45 mg/m^3) specified for Class I buildings in the "Standard for Indoor Environmental Pollution Control of Civil Building Engineering" (GB50325-2020). The highest indoor TVOCs concentration (0.401 mg/m^3) in the Wanxia nursing home was observed in summer (Table 3), which was very close to the standard limit, followed by spring (0.398 mg/m^3). Moreover, the outdoor TVOCs concentration exhibited a varying decreasing trend across the seasons, with spring (0.288 mg/m^3) having the highest levels, followed by winter (0.281 mg/m^3), summer (0.217 mg/m^3), and autumn (0.150 mg/m^3).

The annual mean concentrations of indoor and outdoor PM 2.5 in the Wanxia nursing home were 40.13 μg/m^3 and 42.34 μg/m^3, respectively, while that of indoor and outdoor PM10 ranged from 66.03 μg/m^3 to 69.91 μg/m^3 (Figure 3), respectively. The concentrations of PM were lower than the upper limit (50 mg/m^3 PM2.5 and 100 mg/m^3 PM10), as proposed in "Standards for Indoor Air Quality" (GB/T18883-2022). This study found that the PM10 concentration was 65% higher than the PM2.5 concentration. In winter, the mean concentrations of PM2.5 and PM10 in all monitored areas almost doubled compared to those in summer (Table 3), and the values exceeded the upper limit. During summer, there were no significant differences ($p \geq 0.05$) between indoor and outdoor PM2.5 and PM10 concentrations in the Wanxia nursing home. This indicates that indoor PM levels were most affected by outdoor levels in summer.

3.2. Diurnal Variation in Indoor and Outdoor Air Pollutant Concentrations

This study used hourly measurements to examine the duration of time during each day when air pollutants exceed the standard limit. Figure 4 shows the 24 h mean concentrations of CO_2, HCHO, PM10, PM2.5, and TVOCs of indoor and outdoor areas in the Wanxia nursing home.

The 24 h mean CO_2 concentration levels in indoor and outdoor areas exhibited a more consistent trend across seasons (Figure 4). The highest 24 h mean indoor and outdoor CO_2 concentrations were observed in winter. Furthermore, the largest differences between indoor and outdoor CO_2 levels also occurred in winter. It is worth noting that there was a peak of CO_2 levels in the late night and early morning hours, specifically from 10:00 pm to 05:00 am. Indoor CO_2 concentration during winter and summer nights was 946.52 ppm and 1004.29 ppm, respectively. These values were close to or exceeded the standard limit (1000 ppm). As the day went by, the CO_2 concentration dropped sharply until 8:00 am and the lowest CO_2 levels appeared in the afternoon. After that, CO_2 levels increased rapidly from 6:00 pm, especially indoors. Changes in indoor concentrations throughout the day were consistent with the daily routines (waking up and sleeping schedules) of the elderly.

The 24 h HCHO concentration levels indoors and outdoors exhibited large differences between seasons (Figure 4). Although the 24 h mean indoor HCHO concentration levels were below the standard limit (0.07 mg/m^3), the maximum value (0.068) was very close to the standard limit in spring. The highest 24 h fluctuations in HCHO concentrations were also observed in spring, with a mean deviation of 0.016 mg/m^3. In contrast, the lowest concentration fluctuations occurred in autumn, with a deviation of only 0.001 mg/m^3. In spring and summer, indoor and outdoor HCHO levels increased rapidly from 6:00 pm, and

their peaks were observed at 9:00 pm (Figure 4). However, in autumn and winter, the peak was delayed until 1:00 am.

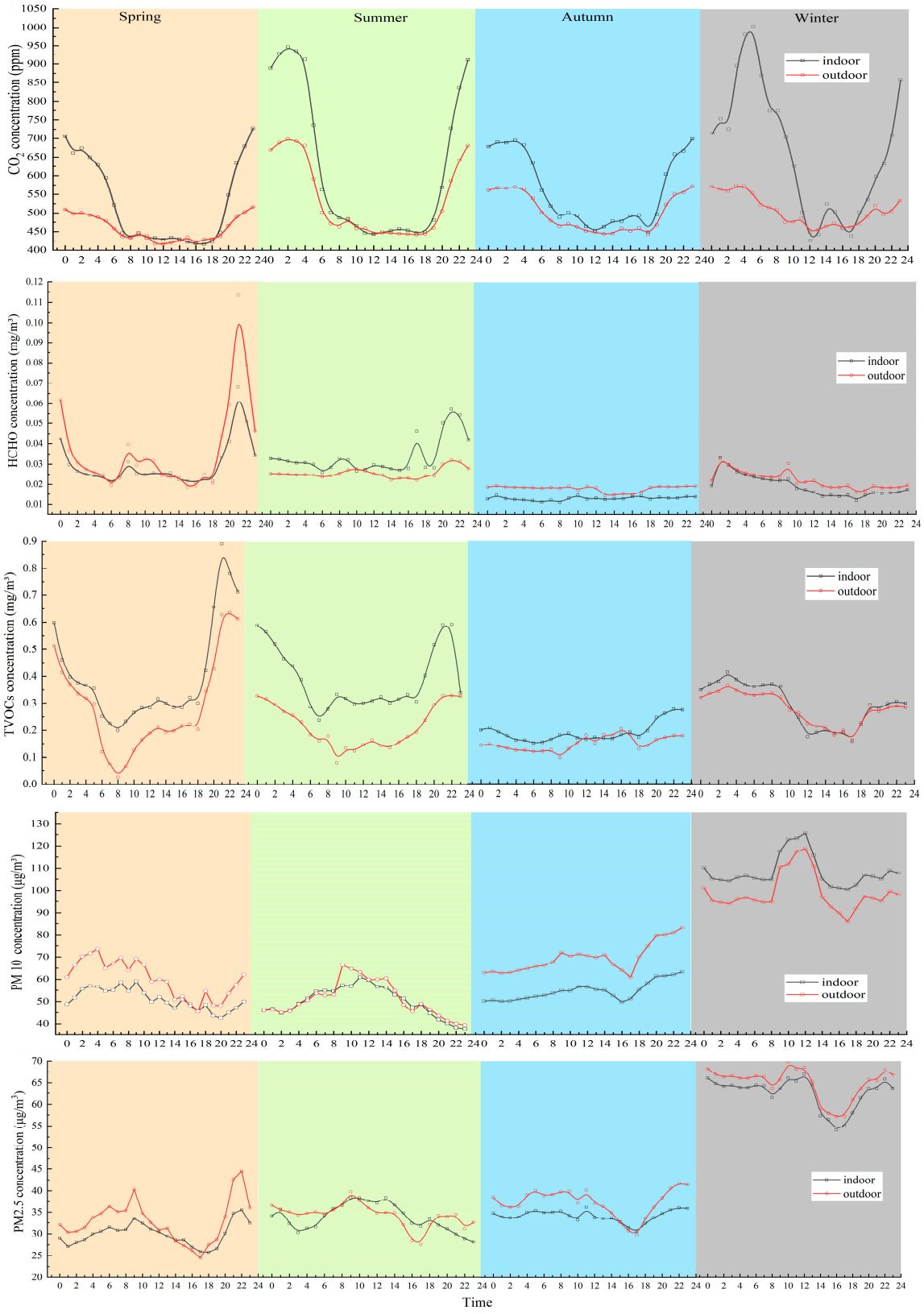


Figure 4. The 24 h variation in indoor and outdoor air pollutant levels.

The 24 h fluctuations in TVOC concentrations were highest in spring (0.19 mg/m^3), followed by summer (0.14 mg/m^3), winter (0.07 mg/m^3), and autumn (0.04 mg/m^3). In spring and summer, the 24 h indoor TVOCs concentration was consistently higher than that outdoors. Moreover, two peak concentrations were observed at 9:00 pm and 12:00 pm (Figure 4). However, in autumn and winter, the outdoor TVOCs concentration was higher than the indoor from 11:00 am to 4:00 pm. It is worth noting that the indoor TVOC concentrations from 8:00 pm to 4:00 am consistently exceeded the standard limit (0.45 mg/m^3) in spring and summer.

The 24 h mean concentrations of indoor PM2.5 ranged from 35.80 mg/m^3 to 42.57 mg/m^3, while the indoor PM10 ranged from 61.18 mg/m^3 to 73.43 mg/m^3 (Figure 4). The trajectories of the indoor and outdoor PM concentrations were more consistent over the 24 h period. The indoor and outdoor concentration of PM2.5 increased sharply around 6:00 pm and remained at its lowest value in the afternoon. The highest (42.57 mg/m^3) and lowest (35.80 mg/m^3) hourly mean indoor PM2.5 concentrations occurred at 11:00 am and 17:00 pm, respectively. The hourly PM10 concentration showed an inconsistent pattern of change throughout the seasons. In summer, autumn, and winter, the peak indoor and outdoor PM10 concentration was observed between 9:00 am and 12:00 am. In spring, however, the highest concentrations of indoor and outdoor PM10 occurred at 4:00 am. Although both indoor and outdoor concentrations were lower than the standard limit (50 mg/m^3 PM2.5 and 100 mg/m^3 PM10) (GB/T18883-2022), they exceeded the recommendations of the World Health Organization (WHO) (AQG2021) of 15 mg/m^3 of PM2.5 and 45 mg/m^3 of PM10 by 2 and 1.55 times.

3.3. Level of Indoor Air Quality and Its Main Influencing Factor

As seen in Table 4, indoor air quality was at a low pollution level ($0.51 < IAQI < 1$) in spring, summer, and autumn. In winter, it rose to a moderate pollution level ($1 < IAQI < 2$). The PM concentration played an important role in the indoor air quality levels. In spring, summer, and winter, the PM10 level had the greatest impact on *IAQI* values, followed by PM2.5 levels. In autumn, however, the impact of PM2.5 concentration on *IAQI* was more prevalent compared to that of PM10. HCHO, on the other hand, had a minimal impact on *IAQI* in all seasons. In addition, in spring and summer, the TVOCs concentration had a greater impact on *IAQI* than CO_2, but in autumn and winter it was the opposite.

Table 4. Individual air quality index of indoor air pollutants and seasonal *IAQI*.

	Indoor Air Pollutants	Spring	Summer	Autumn	Winter	Mean
Individual air Quality Index	CO_2	0.58	0.63	0.57	0.66	0.61
	HCHO	0.39	0.43	0.16	0.24	0.31
	TVOCs	0.66	0.80	0.38	0.61	0.61
	PM10	1.04	1.07	0.91	2.25	1.32
	PM2.5	0.85	0.97	0.98	1.87	1.17
Seasonal *IAQI*		0.87	0.92	0.77	1.59	1.04

The indoor/outdoor (I/O) ratios offered a general understanding of the relationship between indoor and outdoor air pollutants (Table 5). The seasonal I/O ratios of CO_2 and TVOCs exceeded 1. A higher I/O ratio of TVOCs (1.945) was found in summer. There was a considerable seasonal variability in the HCHO I/O ratio. The highest I/O ratio of HCHO was approximately 1.31 in summer. However, the HCHO I/O ratio ranged from 0.728 to 0.882 in other seasons. The I/O ratios of PM2.5 and PM10 ranged from 0.919 to 0.988 and from 0.788 to 1.097, respectively. Most of them were <1 in this study.

Table 5. Pearson correlation analysis between indoor and outdoor air pollutant concentrations.

Air Pollutants	Spring	I/O Ratio	Summer	I/O ratio	Autumn	I/O Ratio	Winter	I/O Ratio
CO_2 concentration	0.985 **	1.139 ab	0.989 **	1.245 bc	0.997 **	1.118 a	0.834 **	1.303 c
HCHO concentration	0.996 **	0.882 b	0.725 **	1.303 c	−0.022	0.728 a	0.941 **	0.860 b
TVOCs concentration	0.953 **	1.812 b	0.929 **	1.945 b	0.434 *	1.294 a	0.983 **	1.039 a
PM10 concentration	0.894 **	0.856 c	0.936 **	0.982 b	0.985 **	0.788 d	0.985 **	1.097 a
PM2.5 concentration	0.942 **	0.919 a	0.560 **	0.988 a	0.960 **	0.918 a	0.986 **	0.965 a

Values followed by different letters indicate a statistically significant difference between treatment groups at $p \leq 0.05$ (5%) according to one-way ANOVA test followed by Duncan's post hoc test. The common letters indicate no significant difference between groups. All values followed by * show a significant correlation; by ** shows an extremely significant correlation.

Table 5 also shows the Pearson correlation between indoor and outdoor air pollutant levels across seasons. There was no correlation between indoor and outdoor HCHO levels in autumn only. Setting this aspect aside, indoor air pollutant levels were significantly influenced by outdoor air pollutant levels in all seasons. The ingress of PM from the outdoor to the indoor environment is evident in the high correlations between indoor and outdoor PM2.5 (r from 0.56 to 0.986) and PM10 (r from 0.894 to 0.985) in all seasons. These high correlations suggest that outdoor PM, including emissions from construction and vehicles, predominantly contributed to indoor PM exposure. Figure 5 and the fitted equations within it describe the significant linear correlations between indoor and outdoor air pollutant levels. These results are similar to studies in a primary school in Nakhon Si Thammarat, Thailand [72] and urban buildings in Guangzhou, China [73], which indicated a strong linear correlation between outdoor and indoor PM and TVOCs, respectively. Indoor air pollutant levels can be calculated from outdoor air pollutant levels using high-fit linear equations.

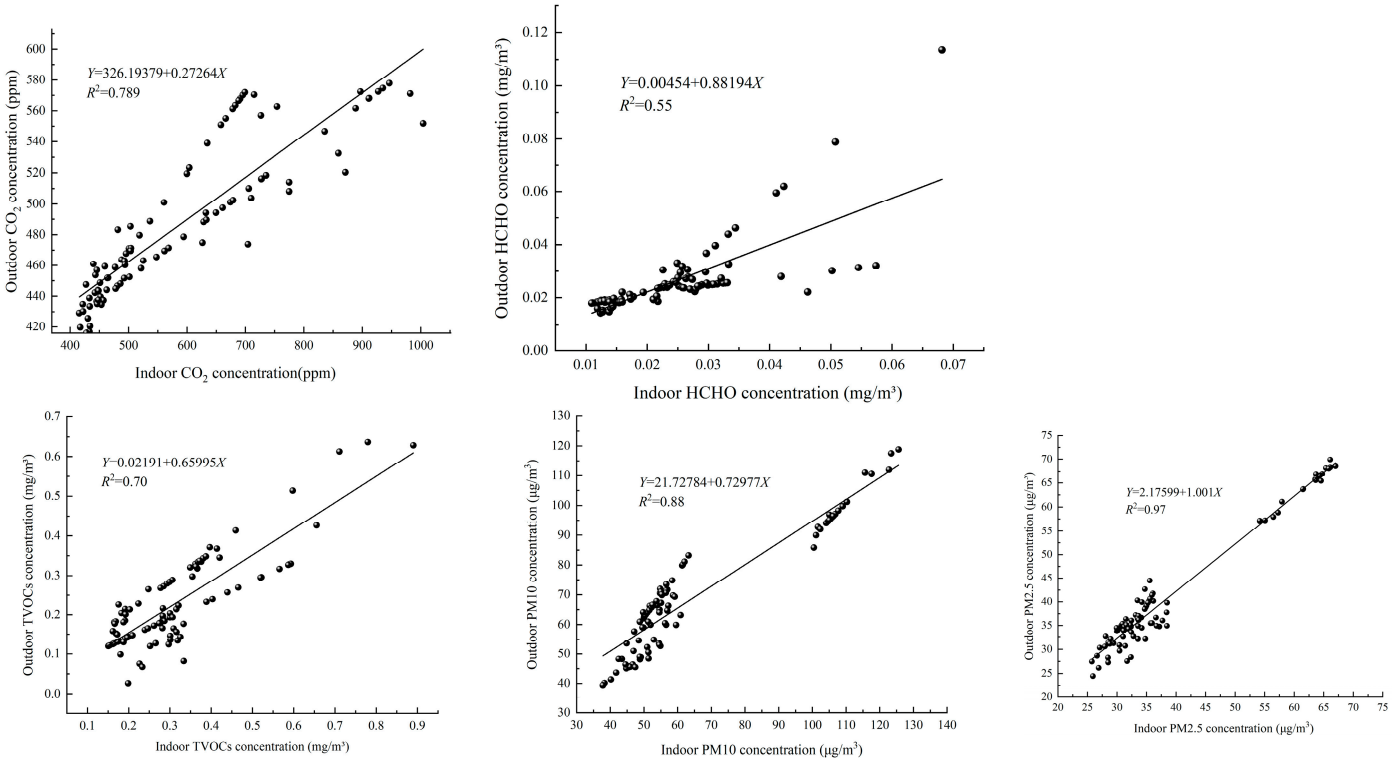


Figure 5. Linear correlations between indoor and outdoor air pollutant levels.

Table 6 shows a comparison of seasonal indoor air pollutant concentrations affected by *Ta* and *RH*. Indoor CO_2 levels were closely related to indoor *Ta* and *RH*. It was found that the higher the indoor *RH* in all seasons, the higher the concentration of CO_2 ($p < 0.01$). In winter, CO_2 levels increased as *Ta* decreased, but in other seasons it was the opposite. Trends in PM10 and PM2.5 levels varied considerably with *Ta* and *RH*. In particular, PM10 concentration was correlated with *Ta* and *RH* only in summer, while PM2.5 concentration did not correlate with *Ta* and *RH* in winter (Table 6). Indoor HCHO levels were positively correlated with *Ta* in winter and *RH* in summer, but negatively correlated with *Ta* in spring and summer. TVOCs concentration was also positively correlated with *RH*.

Table 6. Pearson correlation between indoor air pollutant concentrations and microclimate parameters.

Indoor Air Pollutant Levels	Spring		Summer		Autumn		Winter	
	Ta	*RH*	*Ta*	*RH*	*Ta*	*RH*	*Ta*	*RH*
CO_2	−0.796 **	0.741 **	−0.602 **	0.666 **	−0.540 **	0.781 **	0.370 *	0.466 *
HCHO	−0.370	0.391	−0.220	0.455 *	0.167	−0.114	0.633 **	0.361
TVOCs	−0.445 *	0.416 *	−0.423 *	0.657 **	−0.179	0.345	0.454 *	0.525 **
PM10	0.353	0.334	0.410 *	−0.628 **	−0.012	0.020	−0.270	−0.012
PM2.5	−0.231	−0.295	−0.341 *	−0.487 *	−0.417 *	0.502 *	0.599 **	0.504 *

All values followed by * are significantly different at $p \leq 0.05$ and followed by ** are significantly different at $p \leq 0.01$ according to one-way ANOVA test followed by Duncan's post hoc test.

4. Discussion

In many cities, the highest outdoor CO_2 levels are observed in winter [74], due to heating emissions from private households and businesses [75]. In this study, indoor and outdoor CO_2 concentrations were slightly higher in winter than in other seasons. The reason for this may be related to natural ventilation in the cold season [76]. In many urban areas, such as Baltimore [77], London [78], Tokyo [74], and Melbourne [79], increased outdoor CO_2 levels also occur during the nighttime or early morning throughout the seasons. In these areas, atmospheric stability and increased CO_2 emissions during the nighttime were the main reasons for increased outdoor CO_2 concentration [74]. Similarly, in this study, the 24 h mean indoor and outdoor CO_2 concentration levels showed a more consistent trend across seasons. Indoor CO_2 concentrations during winter and summer nights were close to or exceeded the standard limit (1000 ppm). More importantly, one study found that the indoor CO_2 concentration of 945 ppm corresponded to a 15% decline in cognitive functions [80]. High indoor CO_2 concentration is usually caused by inadequate ventilation and airflow [81]. Therefore, the high indoor CO_2 concentration during the night in this study was possibly also the result of inadequate ventilation. Closing windows and door at night, small rooms, and residents' breathing during sleep cause a sharp increase in indoor CO_2 concentration because residents cannot control ventilation at all times [38]. A similar pattern of changes in CO_2 levels was observed in elderly care centers in Lisbon and Loures in the District of Lisbon [82]. In contrast, the lowest CO_2 levels occurred in the afternoon. At that time, plants in urban areas photosynthesize the most, absorbing and converting large amounts of CO_2 [83]. In addition, seasonal I/O ratios of CO_2 exceeded 1. This result is consistent with previous studies on naturally ventilated urban buildings [84,85], where the I/O ratio of CO_2 was higher than 1. The metabolic rate and respiration of the elderly can contribute to higher CO_2 levels indoors.

In this study, indoor HCHO concentration was significantly higher than that outdoor only in summer. Similar results of indoor HCHO seasonal variations have also been reported in other studies [86–88]. This can be attributed to higher indoor *Ta* and *RH* during summer that causes the highest indoor HCHO release. A previous study reported that indoor HCHO concentrations were higher in southern than in northern China in summer, which can be partially explained by higher indoor *Ta* and *RH* in the south [26]. In spring and summer, 24 h indoor and outdoor HCHO levels increased rapidly from 04:00 pm, and their peaks occurred at 9:00 pm. However, in autumn and winter, the peak is delayed

until 1:00 am. This finding is contrary to the results of previous studies, which indicated that indoor HCHO was highest at noon and lowest at night [87]. These differences may be attributed to the dependence of indoor HCHO levels on outdoor HCHO levels. This study showed that outdoor HCHO may contribute more than three-quarters to the indoor concentration in all seasons except summer, implying that outdoor HCHO contributes substantially to the indoor concentrations in the Wanxia nursing home during most of the year. It is totally different from the results of campus buildings (I/O ratio ranged from 3.70 to 5.55) [87], public buildings (1.75), and residential buildings (2.13) in developing countries [89]. In these studies, although outdoor HCHO concentrations still had some degree of influence indoors, the degree of influence was much less than that in the Wanxia nursing home. This could be attributed to the fact that the interior furniture in the Wanxia nursing home was mostly made of metal rather than wood. Moreover, there were almost no interior decorations. Generally speaking, HCHO is primarily emitted by wood-based products due to the widespread use of formaldehyde-related adhesives [90]. In addition, the variation in outdoor HCHO levels has a strong dependence on meteorological and dispersive conditions, especially on *Ta* [91]. Chengdu is located at the bottom of the Sichuan Basin, with a high frequency of static winds and more foggy days in autumn and winter. There is also an inversion layer throughout the year, with higher nighttime *Ta*, which is not conducive to horizontal and vertical dispersion of air pollutants [92]. At 6:00 pm, increased traffic begins during the evening rush hour. Higher *Ta* due to the inversion layer and the burning of large amounts of fuels such as oil, coal, and natural gas in the evening could produce profiles with the highest concentrations of outdoor HCHO.

A high concentration of TVOC was observed in a recently conducted study in Chengdu [93]. In the Wanxia nursing home, the highest indoor TVOCs concentration (0.401 mg/m^3) was observed in summer, which was very close to the standard limit. This was mainly attributed to paint, glue, or panel furniture, which are known sources of TVOCs [24]. Here, the TVOC levels were lower than in residential buildings in the Terai region of northern India, where the indoor TVOC level was 0.90 mg/m^3 [94]. Outdoor TVOCs concentration showed higher levels in spring and winter. It was noticed that the seasonal variation trend of outdoor TVOCs in northern India and northern China was conducive to the results of this study, where high TVOCs generally occur in winter and are usually more than double those in summer [94]. This can be attributed to relatively lower photochemical degradation in winter caused by OH radicals, infrequent rain showers, and increased biomass burning and fuel consumption [95–97]. Seasonal I/O ratios of TVOCs exceeded 1. Similarly, the I/O ratios of TVOCs in eighteen naturally ventilated dormitories at a certain university in China were higher than 1 [98]. A higher I/O ratio of TVOCs (1.945) was found in summer, which can be attributed to elevated *Ta* and *RH* in this season [99]. These phenomena were considered as a potential indication of insufficient ventilation, indicating the significant presence of indoor air pollution sources [85,100].

The annual mean indoor and outdoor PM concentrations were lower than the upper limit. Nevertheless, these values exceeded the recommendations of the World Health Organization (WHO) (AQG2021) of 15 mg/m^3 of PM2.5 and 45 mg/m^3 of PM10 by 2 to 1.55 times. This concentration of indoor PM has been found to pose a threat even at low doses, leading to chronic exposure and illness [81]. This suggests that, during a significant part of the day, elderly people are exposed to an environment that poses potential health risks. The side effects of PM should not only be viewed only as a result of its concentration, but also as a result of biological constituents, biological activity, and chemical characteristics [101]. However, current research almost always ignores these elements. In winter, the mean concentrations of both PM2.5 and PM10 in all monitored areas were almost doubled compared to those in summer, and the values exceeded the upper limit (1000 ppm). This can be attributed to elevated concentrations of PM in winter. In northern China, the use of combustion sources indoors or within urban areas, such as heating, cooking, and industrial emissions, was considered the most likely contributor to

PM in the winter months [102]. In Chengdu, industrial and vehicle pollution were the main sources of PM [103]. During winter, the prevailing westerly or north-westerly winds and the complex and enclosed terrain hinder the formation of precipitation and wind, creating static meteorological conditions. This stagnant weather promotes the PM accumulation and the formation of secondary PM pollutants and reduces the scavenging efficiency of PM [104,105]. The I/O ratios of PM in residential buildings in China usually vary in the range of 0~5 [41]. The PM2.5 I/O ratio in the Wanxia nursing home ranges from 0.919 to 0.988 and is similar to Chen's report [106], which indicated that natural ventilation can reduce indoor air pollution generated by outdoor sources by 5 to 20%. This also indicates that the buildings in the Wanxia nursing home are only able to minimally reduce infiltrating PM due to their building envelopes and natural ventilation. The PM2.5 I/O ratio here was much higher than the previously reported ratio ranging from 0.197 to 0.876 in residential buildings in the Yangtze River Delta [107] and Beijing [15], but was close to the ratio in six office buildings in Chengdu (0.97) [81]. It varies between cities depending on climate conditions, pollutant concentrations, and building envelopes and ventilation. In addition, the levels of PM infiltration from the outside were highest in summer compared to other seasons. In addition, considering that PM is the most important parameter in determining indoor air quality, this further implies that the *IAQI* in the nursing home was influenced by outdoor PM. In their hospital-based study, Chamseddine et al. [85] found that PM2.5 and PM10 have the most significant impact on *IAQI*.

Indoor CO_2 levels were closely related to indoor *Ta* and *RH*. A study on residential and private daycare centers in Korea also observed the same variation trend in indoor CO_2 levels affected by *RH* [88]. Indoor HCHO levels are positively correlated with *Ta* in winter and *RH* in summer. This result is slightly different from a previous report that stated that the emission rate of indoor HCHO was positively correlated with *Ta* and *RH* [26,108]. In addition, Jarnstrom et al. [86] reported a higher indoor HCHO concentration when *RH* was higher than 50%. In addition, indoor TVOCs concentration was negatively correlated with *Ta* in spring and summer and positively correlated with *Ta* in winter. TVOCs concentration was also positively correlated with *RH*. This finding differs from a previous study in which indoor TVOC emission rates increased with increasing *Ta* and *RH* [99].

The current study has some limitations that should be addressed in the future. One limitation is the small sample size wherein only one nursing home was monitored, although it is the largest private nursing home in Chengdu. Limited sampling sites do not allow for more general conclusions to be drawn. Another limitation is the performance of air monitoring during only one year. It was not possible to obtain a multi-year pattern of indoor air pollutants variation in nursing homes. More detailed research is needed in the future in order to investigate the spatial and temporal variations in indoor air quality in other types of nursing homes with multi-year follow-up, such as those with mechanical ventilation or en-suites.

5. Conclusions

Overall, the indoor air quality of the Wanxia nursing home is poor, showing low pollution levels in spring, summer, and autumn, and a moderate pollution level in winter. Sources of outdoor air pollutants play an important role in the indoor air quality of the analyzed nursing home. It was found that PM concentration played the most important part in determining *IAQI* values. Although the annual and 24h mean levels of indoor PM2.5 and PM10 were lower than the upper limit, the mean levels in winter were very close to or exceeded this limit. The ingress of PM from outdoor to indoor spaces was made evident in the extremely high correlation between indoor and outdoor PM levels in all seasons. This situation suggests that the elderly should adopt effective mitigation strategies to avoid exposure to indoor PM by reducing outdoor PM levels. It was found that the location of the nursing home is also very important. In terms of the annual mean PM values in Chengdu, PM levels in areas outside the third Ring Road were lower than those inside it [109]. Likewise, PM levels near large parks were also lower than in other places.

Therefore, to control the exposure to PM, the focus needs to be on local sources of PM, such as traffic and various industrial processes. Due to this, the location of future nursing homes should be outside the third Ring Road or near large parks. Similarly, nursing homes should be located away from major traffic and industrial enterprises. Between 8:00 am and 10:00 am and 6:00 pm and 8:00 pm, windows or doors should be closed due to rush hours.

During winter and summer nights, the CO_2 concentration was very close to or exceeded the standard limit (1000 ppm). From 8:00 pm to 4:00 am in spring and summer, the indoor TVOCs concentration was above the standard limit (0.45 mg/m^3). Moreover, indoor levels of CO_2 and TVOCs exceeded outdoor levels in all seasons. This can be attributed to poor ventilation and small bedrooms in the nursing home. Although indoor HCHO levels had a minimal impact on *IAQI* values in all seasons, prolonged exposure to HCHO and inadequate ventilation could adversely affect the health of the elderly. Therefore, natural ventilation in the Wanxia nursing home proved to be ineffective, especially after 8:00 pm. It is recommended to increase natural ventilation (with filtration) by opening windows and doors, optimize the ventilation systems in periods with less traffic (afternoon and night), and use mechanical ventilation instead of natural ventilation.

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