

Article

# Risk Assessment for People Exposed to PM<sub>2.5</sub> and Constituents at Different Vertical Heights in an Urban Area of Taiwan

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Abstract: Environmental epidemiological studies have consistently reported associations between ambient particulate matter (PM) concentrations and everyday mortality/morbidity. Many urban dwellers in Asia live in high-rise apartment buildings; thus, the pollutant concentrations of their immediate outdoor environments are affected by the vertical distribution of pollutants in the atmosphere. The vertical distributions of pollutants provide unique information about their sources and dynamic transport in urban areas, as well as their relationship to people's exposure at ground level, while the vertical distributions of pollutants have rarely been considered in exposure assessment. In the current study, PM concentrations (with aerodynamic diameters less than 1.0  $\mu$ m (PM<sub>1</sub>), 2.5  $\mu$ m (PM<sub>2.5</sub>), and 10 µm (PM<sub>10</sub>)), nanoparticles, black carbon (BC), and particle-bound polycyclic aromatic hydrocarbons (p-PAHs) were measured at different residential heights-6 m, 16 m, and 27 m-at Feng Chia University near a popular night market in Western Taiwan. PM<sub>2.5</sub> data were further adopted for health risk estimations. In winter, the magnitude of  $PM_1$ ,  $PM_{2.5}$ , and  $PM_{10}$  concentrations were 16 m > 6 m > 27 m; nanoparticle concentrations were 6 m > 27 m > 16 m; and BC and p-PAHs concentrations were 27 m > 16 m > 6 m. In summer,  $PM_{1}$ ,  $PM_{2.5}$ , and  $PM_{10}$  concentrations ranged from 6 m > 16 m > 27 m; nanoparticle concentrations were 6 m > 16 m; and BC and p-PAHs concentrations were from 27 m > 16 m. PM and constituents concentrations during winter were significantly higher in the nighttime than those in daytime, and levels of PM<sub>1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> increased rapidly on 6 m and 16 m heights (but did not increase at 27 m) after 5 pm, whereas these trends became less significant in summer. Health risk analysis for PM2.5 concentrations showed a decrease in lung cancer mortality rate and an extended lifespan for residents living at 27 m. Overall, the current study investigated the vertical profile of particulate matters and analyzed health impacts of PM<sub>2.5</sub> at different residential heights in urban area of Taiwan. As the distributions of PM and the constituents varied at different residential heights, exposure and risk assessment of particle concentrations with multiple sizes and various components at broader vertical heights should be further investigated.



**Keywords:** fine particulate matter; particle-bound polycyclic aromatic hydrocarbons; black carbon; nanoparticle; vertical height; risk assessment

#### 1. Introduction

As economic development increases, urban air quality decreases because of the increasing air pollution produced by industries, automobiles, and other human activity-based emission sources. In 2013, outdoor air pollution, especially outdoor particulate matter (PM), was classified as carcinogenic to humans (Group 1) by the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO). Global air pollution reports showed that over 95% of the world's population lived in areas that exceeded the air quality guideline of PM with aerodynamic diameter less than 2.5  $\mu$ m (PM<sub>2.5</sub>; fine particulate matter), and that nearly 60% lived in areas that did not meet even the least stringent air quality target from WHO [1]. Air pollution from PM, ozone (O<sub>3</sub>), and household burning of solid fuels might have contributed to 6.1 million deaths (11% of the global total) in 2016 [1].

In addition to the attention to the health hazards of particles with different sizes, the composition of PM varies; it is formed through complex chemical reactions by different pollutants emitted from fossil fuel power plants, industries, and automobiles. Black carbon (BC), polycyclic aromatic hydrocarbons (PAHs), and heavy metals are also constituents of PM, which are mainly derived from traffic emissions, activities of combustion, and anthropogenic as well as biomass burning emissions [2–4].

The health effects of exposure to PM have been getting great attention. A time-series analysis showed that, in China, a 10  $\mu$ g/m<sup>3</sup> increase in PM<sub>2.5</sub> levels was associated with 0.65%, 0.63%, and 1.38% increases in non-accidental mortality, respiratory mortality, and circulatory mortality, respectively, during 2005–2009 [5]. In Spain, the relative risks (RR) for an increase level of 25  $\mu$ g/m<sup>3</sup> in PM<sub>2.5</sub> were 1.057 for all-cause mortality, 1.088 for circulatory mortality, and 1.122 for respiratory mortality [6]. Pope et al. reported that a 10  $\mu$ g/m<sup>3</sup> elevation of fine particulate in the United States was associated with approximately 4%, 6%, and 8% increases in the risk of all-cause, cardiopulmonary, and lung cancer mortality, respectively [7]. The toxicity potential of PM on respiratory health are in fact based on their residence time in the different regions of the airway [8]. Pan et al. reported that long-term exposure to PM<sub>2.5</sub> and low-grade inflammation might lead to hepatic tumorigenesis and increase the risk of liver cancer [9]. Moreover, exposure to PAHs would cause different impacts on human health [10]. With long-term exposure, effects included skin, lung, bladder and gastrointestinal cancers, DNA damage, cataracts, kidney and liver damage, gene mutation cell damaging, and cardiopulmonary mortality [11–19]. As a result, the risks of exposure to PM<sub>2.5</sub> and PAHs should be of great concern.

On the other hand, the vertical comparison of  $PM_{2.5}$  and  $PM_{10}$  (particulate matter with an aerodynamic diameter less than 10 µm) concentrations were evaluated in previously reports [20–22]. Kalaiarasan et al. measured PM<sub>2.5</sub> levels at various heights of two typical types of buildings, point block configuration and slab block configuration, near a busy expressway in Singapore. For both buildings, the highest concentration of  $PM_{2.5}$  was at the mid-floors, and the lowest was at upper floors, which might be due to interception by tree leaves or the mixing effect by the inflow of clean air from higher altitude. For point block and slab block, the health risk values at the mid and lower floors suggested that occupants living in these floors experienced 1.62–1.81 and 1.28–1.34 times of risk, respectively, compared to those living at the upper floors [21]. The vertical comparison of PM<sub>2.5</sub> and PM<sub>10</sub> concentrations was also studied in Osaka, Japan [22]. The concentrations of samples collected at 200 m were lower than those collected on the ground. In summer, the high concentration on the ground might be because particles absorbed water when relative humidity (RH) was high. In winter, the accumulation of particles might be due to stable meteorological conditions and vehicle exhaust on the ground. Despite these findings, the previous studies were conducted in relatively high-rise buildings, while most people in Taiwan lived at the height of life circumstances relatively lower than the heights in the aforementioned studies. In fact, more than 52% of the buildings in Taiwan were

less than 30 m height [23]. Therefore, it can be suspected that PM concentrations at different vertical heights might vary in different seasons. The objectives of this study are to investigate the particle distribution at different residential heights in different seasons, where the results will be further taken into consideration for health risk assessment at different residential heights.

### 2. Materials and Methods

#### 2.1. Field Measurement

Taichung is a special municipality located in central-western Taiwan. Metropolitan Taichung covers an area of 2215 km<sup>2</sup> and hosts a population of over 2.8 million people, making it the second largest city on the island [24]. In recent years, the city ran into further climatic anomalies, reducing the number of rainy days and increasing temperatures, providing the appropriate conditions for a chain reaction to occur that contributes to a worsening of the air quality [25]. The field sampling (including instrument collocation) was carried out during the summer and winter of 2014. Outdoor air pollutant concentrations were measured on different floors in a building at Feng Chia University in Taichung. There was a big night market about 100 m west of the building. Vertical sampling at different residential heights was done simultaneously for 10 days from 23 February to 6 March, as well as from 18 to 28 July 2014. Sampling was conducted from the balconies of 2nd floor (6 m), the 5th floor (16 m), and the 8th floor (27 m). Before the vertical sampling began, three sets of identical instruments were set up on the top floor for simultaneous measurement in order to compare and adjust the data collected from the three identical instruments. Instrument collocation was performed for three days in winter and in summer separately.

PM concentrations with aerodynamic diameters less than  $1.0 \ \mu m (PM_1)$ ,  $PM_{2.5}$ , and  $PM_{10}$  were measured using three portable aerosol monitors (model 1.108/1.109, Grimm, Ainring, Germany). Nanoparticle (20–700 nm) levels were measured using three miniature diffusion size classifiers (DiSCmini, Matter Aerosol, Wohlen, Switzerland). BC and particle-bound PAHs (p-PAHs) were measured using three micro-aethalometers (model AE51, AethLabs, San Francisco, CA, USA) and three photoelectric aerosol sensors (PAS 2200 CE and PAS 2000 CE, EcoChem Analytics, League City, TX, USA). Temperature and RH were also collected simultaneously using three data loggers (HOBO UX100-011A, Onset, MA, USA). All of the monitoring data were set to output data in 1 min.

#### 2.2. Quality Control

Quality control procedures were performed each sampling day. In addition to the routine calibration and maintenance of the instruments used in this study, the research staff performed essential calibration for the instrument readings and flows before and after each monitoring. To ensure the quality of data processing, Microsoft Excel (2010) was used for data management, descriptive analysis, and to calculate health risks of pollutant exposures. Zero, negative, missing, and unreasonably high and low values were excluded, as were continuous values in a range more than ten folds.

#### 2.3. Data Analysis

Simple linear regression analysis was performed to compare concentrations obtained in field collocation and vertical sampling. For a given pollutant, the coefficient of determination ( $\mathbb{R}^2$ ) of the identical instruments was determined. The ratio of means between collocating instruments was applied as an adjustment factor to correct for the measured levels. After corrections were made for the testing methods, intraclass correlation coefficients (ICC) were computed to verify the agreement between the collocating measurements. The value of ICC > 0.75 indicates excellent reliability, 0.4 < ICC < 0.75 indicates good reliability, and ICC < 0.4 indicates poor reliability for the comparison among different instruments [26]. Additionally, paired t-tests were also used to investigate the concentration differences between different residential heights during different seasons. Statistical analyses were performed using JMP (version 5.0) and STATISTICA (version 7.1) software.

In the current study, the elevated risks suggested by previous studies were adopted for estimating the excess risk of lung cancer mortality rate for residents living on different floors with different  $PM_{2.5}$  exposures [7,27–31]. The  $PM_{2.5}$  levels measured at the height of 6 m were set as the baseline to calculate the deviation of the mortality rate of lung cancer caused by  $PM_{2.5}$  exposures at different residential heights. Excess lung cancer mortality rate and life expectancy change were calculated by Equations (1) and (2), respectively:

Excess lung cancer mortality rate = Vertical deviation of  $PM_{2.5}$  concentration \* 0.1 \* Elevated lung cancer risk per 10  $\mu$ g/m<sup>3</sup> increase of  $PM_{2.5}$  \* Lung cancer mortality rate, (1)

where the vertical deviation of  $PM_{2.5}$  concentrations (16 m, 27 m) was compared with the levels measured at 6 m, the elevating lung cancer risk of 12% per 10 µg/m<sup>3</sup> increase of  $PM_{2.5}$  was adopted from Huang et al., and the lung cancer mortality rate in Taiwan was 60.59 per 100,000 in 2017 [30,32].

Life expectancy change = Vertical deviation of  $PM_{2.5}$  concentration \* 0.1 \* Loss of life year per 10  $\mu$ g/m<sup>3</sup> increase of  $PM_{2.5}$  \* 365, (2)

where the vertical deviation of  $PM_{2.5}$  concentrations (16 m, 27 m) was compared with the levels measured at 6 m, the loss of 0.61 life year per 10  $\mu$ g/m<sup>3</sup> increase of  $PM_{2.5}$  was adopted from Pope et al. [7,33].

As the excess mortality rate of lung cancer was estimated mainly by two factors—vertical  $PM_{2.5}$  concentrations and the RRs of lung cancer mortality in different studies—the software @Risk (version 7.6) was applied for evaluating the sensitivity of the risk estimation.  $PM_{2.5}$  concentrations in different seasons (winter and summer) were combined together for annual analysis at different residential heights, and the extreme high or low values out of 1% (±2.576 standard deviation) were excluded for truncating the reliable results of PM data [34].

# 3. Results and Discussion

#### 3.1. Collocation Comparison

Results of the collocation comparison were summarized in Table 1. For PM<sub>1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> measurements, R-squared and ICC values were all greater than 0.9 and 0.85, respectively, indicating the measurement agreement between the identical sampling instruments were in high reliability. The concentrations of nanoparticle, temperature, and RH also showed high ICCs in both winter and summer. Meanwhile, for BC, one of the instruments presented poor reliability in summer (ICC less than 0.4 for serial No. 580), as well as one p-PAHs instrument showed a poor ICC (serial No. 210 in summer), as a result, the corresponding sampling data were excluded from further analyses.

Season	Pollutant	Instrument Serial No.	<b>R</b> <sup>2</sup>	Adjustment Factor	ICC <sup>4</sup>
Winter	PM <sub>10</sub>	086 vs. 098	0.96	1.33	0.97
		050 vs. 098	0.93	1.53	0.94
	PM <sub>2.5</sub>	086 vs. 098	0.98	1.29	0.99
		050 vs. 098	0.93	1.83	0.91
	$PM_1$	086 vs. 098	0.99	1.31	0.99
		050 vs. 098	0.99	2.17	0.85
	Nanoparticle	485 vs. 444	0.86	1.70	0.91
	*	443 vs. 444	0.94	0.85	0.96
	BC <sup>1</sup>	580 vs. 365	0.67	0.94	0.81
		314 vs. 365	0.83	0.95	0.91
	p-PAHs <sup>2</sup>	234 vs. 102	0.58	1.77	0.76
	1	210 vs. 102	0.56	1.64	0.75
	Temperature	642 vs. 644	0.97	1.02	0.98

Table 1. Results of collocation comparison.

Season	Pollutant	Instrument Serial No.	<b>R</b> <sup>2</sup>	Adjustment Factor	ICC <sup>4</sup>
		643 vs. 644	0.98	1.02	0.98
	Relative humidity	642 vs. 644	0.99	0.99	1.00
		643 vs. 644	0.99	1.00	1.00
Summer	PM <sub>10</sub>	086 vs. 098	0.93	1.18	0.96
		056 vs. 098	0.90	1.27	0.94
	PM <sub>2.5</sub>	086 vs. 098	0.99	1.15	0.99
		056 vs. 098	0.98	1.14	0.99
	$PM_1$	086 vs. 098	0.99	1.13	0.99
		056 vs. 098	0.99	1.11	0.99
	Nanoparticle	485 vs. 444	N.A. <sup>3</sup>	N.A. <sup>3</sup>	N.A. <sup>3</sup>
		443 vs. 444	0.99	0.71	0.98
	BC <sup>1</sup>	580 vs. 365	0.09	0.86	0.28
		315 vs. 365	1.00	0.97	0.99
	p-PAHs <sup>2</sup>	234 vs. 102	0.37	1.52	0.61
	1	210 vs. 102	0.11	1.16	0.25
	Temperature	642 vs. 644	0.98	1.00	0.99
	-	643 vs. 644	0.99	1.00	0.99
	Relative humidity	642 vs. 644	0.99	0.99	0.99
	,	643 vs. 644	0.98	1.00	0.99

Table 1. Cont.

<sup>1</sup> BC: black carbon. <sup>2</sup> p-PAHs: particle-bound polycyclic aromatic hydrocarbons. <sup>3</sup> N.A.: not available due to instrumental malfunction. <sup>4</sup> ICC: intraclass correlation coefficient.

# 3.2. PM Concentrations at Different Residential Heights in Different Seasons

The vertical concentrations of PM pollutants at different residential heights in winter and summer are shown in Table 2 and Figure A1 in Appendix A. According to the Taiwan Environmental Protection Administration's (Taiwan EPA) Ambient Air Quality Standards, the 24 h standard value of  $PM_{10}$  is 100 µg/m<sup>3</sup> and the 24 h standard value of  $PM_{2.5}$  is 35 µg/m<sup>3</sup> [35]. Given this, the average concentrations of PM<sub>2.5</sub> at 6 m and 16 m in the winter exceeded the standard value in the current study for administrative purposes. Current results of PM<sub>2.5</sub> concentrations were comparable to the findings of previous research in Taichung [36]. Comparing the monitoring data in different seasons, the levels of PM<sub>1</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, nanoparticle, and BC were significantly higher in winter than those in summer. In winter, the vertical concentrations of PM<sub>1</sub>, PM<sub>2.5</sub> and PM<sub>10</sub> were 16 m > 6 m> 27 m, and nanoparticle concentrations were 6 m > 27 m > 16 m. For BC and p-PAHs concentrations, both were in range as 27 m > 16 m > 6 m, results of which were consistent as the finding in Beijing, China where the concentrations of BC significantly correlated with those of PAHs [37]. In summer, the concentrations of PM<sub>1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> were in range as 6 m > 16 m > 27 m, where the result of a decreasing trend with increasing height was consistent with the concentration distribution of PM<sub>2.5</sub> and its chemical compositions in Tianjin, China [38]. Finally, BC and p-PAHs concentrations ranged from 27 m > 16 m.

The proportion of  $PM_1$  (or  $PM_{2.5}$ ) in  $PM_{10}$  at different heights were presented in Figure 1. The similar ranges were found in both seasons for  $PM_1/PM_{10}$  (between 45% to 65%) and  $PM_{2.5}/PM_{10}$  (66% to 77%), the results of which were comparable with the daytime averaged  $PM_1$  and  $PM_{2.5}$  contributing 51–60% and 66–67%, respectively, of  $PM_{10}$  at the roadside in Macao, China [39]. Furthermore, current results indicated that the proportions of different size PM did not vary so much at different residential heights, therefore the components of PM should play a critical role for health risk estimation.

Pollutant

(Unit) PM<sub>10</sub>

 $(\mu g/m^3)$ 

PM<sub>2.5</sub>

 $(\mu g/m^3)$ 

 $PM_1$ 

 $(\mu g/m^3)$ 

Nanoparticle

 $(ng/m^3)$ 

BC<sup>1</sup>

 $(\mu g/m^3)$ 

p-PAHs<sup>2</sup>

 $(ng/m^3)$ 

nt residential heights in both seasons.			
16 m (5F) <sup>4</sup>	27 m (8F) <sup>4</sup>	Significant Difference <sup>6</sup>	
59.0 (37.1)	48.8 (21.9)	6 m vs. 16 m	
		6 m vs. 27 m	
		16 m vs. 27 m	
28.7 (16.6)	24.9 (14.8)	6 m vs. 16 m	

32.0 (15.2)

19.3 (13.7)

22.1 (10.4)

16.1 (13.1)

24.0 (22.4)

N.A.<sup>5</sup>

2.2 (1.8)

2.4 (2.2)

7.7 (11.5)

6 m vs. 27 m 16 m vs. 27 m

6 m vs. 16 m 6 m vs. 27 m

16 m vs. 27 m

6 m vs. 16 m

6 m vs. 27 m 16 m vs. 27 m

6 m vs. 16 m

6 m vs. 27 m 16 m vs. 27 m

6 m vs. 16 m 6 m vs. 27 m 16 m vs. 27 m

6 m vs. 16 m

6 m vs. 27 m 16 m vs. 27 m

6 m vs. 16 m

6 m vs. 16 m

6 m vs. 27 m 16 m vs. 27 m

16 m vs. 27 m

6 m vs. 27 m

16 m vs. 27 m

Table 2. Vertical PM concentrations at different residential heights in both seasons.

42.8 (30.2)

20.9 (14.4)

31.5 (23.5)

16.8 (13.0)

23.5 (24.1)

11.0 (8.4)

2.1 (1.6)

1.6 (1.1)

7.2 (9.8)

6 m (2F)<sup>4</sup>

57.2 (36.5)

31.4 (114.4)

42.1 (29.9)

21.1 (16.0)

29.5 (21.9)

17.0 (15.0)

26.6 (32.5)

13.1 (10.0)

2.0 (1.8)

N.A.<sup>5</sup>

7.1 (9.6)

N <sup>3</sup>

9522

13028

9522

13028

9522

13028

9522

12658

9278

525

9522

Season

Winter

Summer

Winter

Summer

Winter

Summer

Winter

Summer

Winter

Summer

Winter

 $\frac{1}{1} \text{ BC: black carbon. } {}^{2} \text{ p-PAHs: particle-bound polycyclic aromatic hydrocarbons. } {}^{3} \text{ N: sample size. } {}^{4} \text{ mean (standard deviation). } {}^{5} \text{ N.A.: not available due to instrumental malfunction. } {}^{6} p < 0.05.$ 

#### 3.3. Temporal Patterns of PM Concentrations at Different Residential Heights

In order to investigate the temporal variation of PM concentrations, the hourly averaged concentrations within a day in winter and summer were calculated (as shown in Figures 2 and 3, respectively). In winter, the levels of PM<sub>1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> at 27 m height were apparently lower than those of the other floors, and the PM<sub>2.5</sub> concentrations in the nighttime were higher than those measured at daytime. Furthermore, after 5 pm, levels of PM<sub>1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> increased rapidly on 6 m and 16 m heights, but did not increase at 27 m. These results indicated that people living above 27 m might be exposed to less PM from local emission sources. Likewise, the concentrations of nanoparticle presented a similar temporal distribution at different heights, suggesting a well-mixed finer particle size distribution in vertical diffusion [40,41]. For p-PAHs, the concentrations rose at 8 am, but did not considerably increase after 5 pm, results of which showed that emissions from vehicles might be the major source for p-PAHs while the night market activities might be minor in this study. Quang et al. have reported that particle number (PN) and PM<sub>2.5</sub> concentrations of PN in size range of < 30 nm and total PN increased (7–65% and 5–46%, respectively), while PM<sub>2.5</sub> concentration decreased (36–52%) with height.







**Figure 2.** Hourly averaged concentrations of particulate air pollutants at different residential heights in winter. Vertical sampling at different residential heights was done simultaneously for 10 days from 23 February to 6 March 2014. (Nano PM: nanoparticle; BC: black carbon; PAH: particle-bound polycyclic aromatic hydrocarbons.)



**Figure 3.** Hourly averaged concentrations of particulate air pollutants at different residential heights in summer. Vertical sampling at different residential heights was done simultaneously for 10 days from 18 to 28 July 2014. (Nano PM: nanoparticle; BC: black carbon; PAH: particle-bound polycyclic aromatic hydrocarbons.)

In summer,  $PM_{2.5}$  concentrations in the daytime were more variable and higher than those at night, which might be due to intense human activities, like vehicle emission, and suitable meteorological condition in the daytime [38]. The concentrations of  $PM_{2.5}$  and  $PM_{10}$  were relatively high at 6 pm and 10 pm on the 6 m height, while the pattern did not hold at the higher floors, which implied that some coarser PM sources might exist near the ground. In addition, the temporal trend and levels of nanoparticle were similar at different heights, except for those at 27 m in the night. BC and p-PAHs concentrations showed varying fluctuations at different heights, especially for those at 27 m, which in part might be attributed to the semivolatile characteristic of p-PAHs.

Figure 4 presented diurnal averaged concentrations of PM at different heights. In winter, PM<sub>1</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, nanoparticle, BC, and p-PAHs were significantly higher in the nighttime than those in daytime, whereas these trends became less apparent or even opposite in summer. As wintertime temperature was lower than that in summer, especially at night, the height of atmospheric mixing layer was closer to the ground surface, which resulted in a poor diffusion vertically and accompanied with the accumulation of air pollutants in the night [43–45]. In contrast, the temperature variation was less noticeable in summer; hence the diurnal differences of PM pollutants did not show statistical significance. Using an unmanned aerial vehicle, Lu et al. showed that the PM<sub>2.5</sub> concentrations at 300–1000 m altitude in morning flights were generally lower than those in afternoon ones, while the

variations of  $PM_{2.5}$  in morning flights were much higher than those in afternoon ones [46]. Besides, in a study of 31 Chinese provincial capital cities, the correlation coefficients between  $PM_{2.5}$  and nitrogen dioxide (NO<sub>2</sub>) (or sulfur dioxide (SO<sub>2</sub>)) were either high or moderate based on data from 286 monitoring sites [47]. Previous studies have also reported that  $PM_{2.5}$  was associated with PAHs, heavy metals, and other gaseous pollutants, which implied that if the residents were exposed to high levels of  $PM_{2.5}$ , they might be exposed to other pollutants, such as NO<sub>2</sub> and SO<sub>2</sub>, at the same time [1,20,48].







**Figure 4.** Diurnal averaged concentrations of particulate air pollutants at different residential heights in winter and summer. (Nano PM: nanoparticle; BC: black carbon; PAH: particle-bound polycyclic aromatic hydrocarbons.)

#### 3.4. Excess Lung Cancer Risk and Loss of Life by PM<sub>2.5</sub> Exposure

As of today, the impact of season on the associations between air pollution and mortality were found to vary in different researches [49,50]. We therefore combined all of the winter and summer data for excess risk estimation. In the current study, the elevated risks reported by Pope et al. were first adopted for estimating the excess risk, with the PM<sub>2.5</sub> level at 6 m height serving as the baseline to estimate life expectancy changes due to PM<sub>2.5</sub> exposure at different heights [7,33]. As shown in Table 3, people living at 16 m height might lose 4.5 days of their life as comparing with the life expectancy of the residents living at 6 m height, and might also increase 0.15 per 100,000 for mortality rate of lung cancer. Additionally, the residents living at 27 m might extend 86.8 days of their life and decrease 2.84 per 100,000 in mortality rate of lung cancer due to less PM<sub>2.5</sub> exposures. Even though people in Taiwan have relatively long lifespan, with a life expectancy of 80.39 years of age and the standardized mortality rate of lung cancer 60.59 per 100,000 in 2017, the potential health risk from air pollution still could not be neglected [32,51].

Table 3. Estimation of PM<sub>2.5</sub>-associated excess lung cancer mortality rate and life expectancy change.

Height	PM <sub>2.5</sub> Concentration (µg/m <sup>3</sup> ) <sup>1</sup>	Excess Lung Cancer Mortality Rate (per 1,000,000) <sup>2</sup>	Life Expectancy Change (Day) <sup>2</sup>
6 m	27.9	-	-
16 m	28.1	0.15	-4.5
27 m	24.0	-2.84	86.8
1			

<sup>1</sup> Averaged concentrations for summer and winter data. <sup>2</sup> Data at 6 m serving as the baseline.

The relationship between exposure to  $PM_{2.5}$  and lung cancer mortality had been documented worldwide. For qualitative sensitivity analysis in discussing whether the quantitative relative risk or  $PM_{2.5}$  levels is the more important factor in influencing  $PM_{2.5}$  exposure on lung cancer risk at different

vertical heights, various associations between PM<sub>2.5</sub> and lung cancer mortality were adopted from results of previous studies [7,27–31]. In the United States (U.S.), Pope et al. have shown that the elevation of 10 µg/m<sup>3</sup> in PM<sub>2.5</sub> concentration was associated with approximately an 8% increase for lung cancer mortality, and a decrease of  $10 \,\mu\text{g/m}^3$  of fine particulate matter was associated with an estimated increase life expectancy of  $0.61 \pm 0.20$  year [7,33]. Besides, the RRs of lung cancer mortality with a 10  $\mu$ g/m<sup>3</sup> increase in PM<sub>2.5</sub> concentrations were 1.20 (95% confidence interval (CI): 0.79, 1.82) in Los Angeles, U.S. and 1.08 (95% CI: 1.07, 1.09) in China [29,52] A meta-analysis of 17 studies showed that the RR of lung cancer per 10  $\mu$ g/m<sup>3</sup> increase in PM<sub>2.5</sub> exposure was 1.09 (95% CI: 1.03, 1.15) in Asia; in subgroup analyses for country, the mortality meta-estimate for developed countries was 1.14 (95% CI: 1.06, 1.23), and for developing countries was 1.03 (95% CI: 1.00, 1.07) [30]. Other meta-analysis studies also demonstrated comparable RRs of 1.09 (95% CI: 1.04, 1.14), 1.09 (95% CI: 1.06, 1.11), and 1.14 (95% CI: 1.07, 1.21) for lung cancer associated with PM<sub>2.5</sub> [27,28,31]. Lately, the higher risk of lung cancer with increased PM<sub>2.5</sub> exposure was found to be more significant for female, and the carcinogenic effects of PM<sub>2.5</sub> have urban/rural differences as well as sex differences [53,54].

Results of qualitative sensitivity analysis showed that variations of vertical PM<sub>2.5</sub> concentrations were dominant for excess lung cancer risk estimation in different scenarios, which might be attributed to the wide seasonal variation of vertical PM<sub>2.5</sub> levels. Variation of PM<sub>2.5</sub> at 16 m height as compared to those at 6 m drove the final distribution of excess lung cancer risk at 16 m, accounting for 74.5% of the variance, while the RRs of lung cancer from different studies accounted for 25.5% (Figure 5a). At 27 m height, deviation of  $PM_{2.5}$  concentrations and the lung cancer RRs from different studies explained 88.6% and 12.8% of the variance, respectively (Figure 5b). Findings of the current study demonstrated that the representativeness of  $PM_{2,5}$  monitoring was crucial for estimating the relative risk in alternative heights, and the lung cancer slope factor only had a relatively small influence on the results. Therefore, how to acquire more detailed and representative concentrations at different residential heights warrants further studies.



Figure 5. Cont.



**Figure 5.** Sensitivity analysis of the parameters to increasing lung cancer risk in 16 m and 27 m. (RR: relative risk).

As there is no known level of pollution exposure that is harmless, strategies to minimize daily exposure are often impactful across a good range of settings. In Toronto, Canada, Zuraimi and Tan reported that tighter building envelope, use of mechanical ventilation systems, and improved filtration are key factors that reduce  $PM_{2.5}$  exposure and its impacts on population health [55]. In fact, the indoor/outdoor ratios of PM concentration vary considerably due to the different-sized particles with different emission rates, the cracks and leaks in the building envelope, and the air exchange rates [56]. A study in Durbin, Ireland suggested that increasing air exchange between the outdoors and indoors during nighttime periods could flush out air pollutants [57]. Meanwhile, in the current study, as the levels of PM pollutants were higher at night than in the day, the proposal might not be applicable in Taiwan. Some qualified evidence supports individual actions to reduce cardiopulmonary health risks from exposures to ambient air pollutants by staying indoors and limiting physical exertion when air pollutant concentrations exceed levels associated with increased risk of acute and chronic health problems [58,59]. Overall, based on the results of the current study, to minimize PM exposures, personal strategies for people residing in urban areas below 16 m are to keep the windows closed and stay indoors during the traffic rush hour of 8 am as well as the business hour of night market after 5 pm. Besides, keeping away from mobile sources during the traffic jam is advised in avoiding exposure to p-PAHs.

#### 4. Conclusions

The present study analyzed vertical distribution and health impacts of PM in urban residential area of Taiwan. For vertical  $PM_{2.5}$  concentrations, the lowest levels were found at the height of 27 m as compared to those at 6 m and 16 m. In winter, PM and the constituents concentrations were significantly higher in the nighttime than those in daytime, and levels of  $PM_1$ ,  $PM_{2.5}$ , and  $PM_{10}$  increased rapidly on 6 m and 16 m heights (but did not increase at 27 m) after 5 pm, whereas these trends became less significant in summer. Health risk analysis for  $PM_{2.5}$  concentrations showed a decrease in lung cancer mortality rate and an extended lifespan for residents living at 27 m. Findings in the current study highlight the needs to integrate more measurement data at broader residential heights, exposure scenarios, and the behaviors of deploying window/door for future investigation.

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writing—original draft preparation, H.-L.C, C.-P.L., and L.-T.C.; writing—review and editing, C.-S.T., S.-C.C.L., and H.-C.C.; supervision, L.-T.C. All authors have read and agreed to the published version of the manuscript.

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## Appendix A



**Figure A1.** Bar chart of vertical PM mean concentrations at different residential heights in both seasons. Error bars represent the standard deviations of the measurement data. (BC: black carbon; p-PAHs: particle-bound polycyclic aromatic hydrocarbons.)

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