Predictive Meteorological Factors for Elevated $PM_{2.5}$ Levels at an Air Monitoring Station Near a Petrochemical Complex in Yunlin County, Taiwan

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Abstract

Since 1991, air pollution has gained special attention in Taiwan after a petrochemical complex was constructed in Mailiao Township, Yunlin County. We explored the association between the magnitude of $PM_{2.5}$ and meteorological factors during 2012-2016. Our findings revealed that 1) mean $PM_{2.5}$ levels gradually decreased from 30.70 μg/m^3 in 2013 to 25.36 μg/m^3 in 2016; 2) wind speed is the main determinant of air quality—air quality significantly improved when it was faster than 4 m/sec; and 3) wind direction is another determinant of air quality—when the wind direction was southerly, air quality improved. Elevated $PM_{2.5}$ levels were defined as those hourly levels higher than the third quartile (36 μg/m^3). The significantly negative predictive factors for elevated $PM_{2.5}$ levels were the summer or autumn seasons, rainfall, increased wind speed, and wind direction from 150˚ to 230˚ from the north. The significantly positive predictive factors for elevated $PM_{2.5}$ levels were working hours from 6 a.m. to 2 p.m., a temperature between 11˚C and 25˚C, relative humidity between 40% and 68%, and wind direction (e.g., northerly wind, northeasterly wind, and easterly wind). The predictive formula is attached in the **Appendix**. Therefore, people should protect themselves on these high-risk days.

*Contributed equally.

Keywords

Fine Particulate Matter ($PM_{2.5}$), Petrochemical Complex, Meteorological Factors

1. Introduction

Air pollution is a major health concern and has been extensively studied. Exposure to pollutants such as fine particulate matter ($PM_{2.5}$) and ozone has been associated with an increase in mortality and hospital admissions due to respiratory and cardiovascular diseases [1] [2] [3] [4]. A study reported that $PM_{2.5}$ causes approximately 3% of mortality due to respiratory cancer (cancer of the trachea, bronchus, and lung) and approximately 1% of mortality due to respiratory infection in children aged under 5 years; this amounts to approximately 0.8 million deaths and 6.4 million years of life lost; furthermore, this burden occurs predominantly in Asia (65%) [5]. The global burden of disease attributable to outdoor air pollution uses the annual average concentration of $PM_{2.5}$ as the indicator of air pollution [6]. Only 1% of global $PM_{2.5}$ exposure occurs in outdoor environments in the developed world, whereas a staggering 14% occurs in outdoor environments in the developing world [7].

Located in Yunlin County in western Taiwan, Mailiao Township has a world-class petrochemical industry zone and a coal-fired power plant. Within the township, the complex (area around 26 square kilometers) is located in the north-western coastal area, and an air monitoring station is located 6 km away from the complex in the populated south-east area of Mailiao. This chief industry includes oyster oil plants, ethylene light oil pyrolysis plants and their related petrochemical plants, heavy machinery plants, steam power plants, Mailiao Industrial Port, and the third largest coal-fired power plant in Taiwan. Furthermore, there are many small industrial areas in Yunlin County.

Another study reported that ambient $PM_{2.5}$ pollution is a major mortality risk factor in Taiwan. The same study also reported that substantial geographic variations in $PM_{2.5}$ attributable to the mortality fraction were found, and Yunlin County had the highest percentage (21.8%) of deaths attributable to $PM_{2.5}$ [8]. According, the $PM_{2.5}$ pollution was an important issue for the citizens of Yunlin County. It is the motivation of this study. According to the statistics of the Environmental Protection Administration, Executive Yuan (Taiwan), of the $PM_{2.5}$ emissions from various sources, motor vehicles emissions accounted for 36%, overseas imports accounted for 27%, industry (coal-fired power generation, petrochemical, and steel-making) accounted for 25%, and other sources accounted for 12% [9].

Air quality is severely influenced by weather conditions. A 19-year observational study reported that 14,700 excess deaths from $PM_{2.5}$ were attributable to weather-related increases in air quality in the United States [10]. Studies have reported that temperature, relative humidity (RH), and air pressure have significant effects on air pollution [11]. The orography is played a pivotal role over the variations of PM [12]. Taiwan is located in an area affected by the monsoon climate. During summer, it is affected by the moist and warm air flow brought by the southwest monsoon, and the average temperature reaches 28˚C in July. Because Mailiao Township is located near the coast, the usual wind direction is westerly (from sea to land) during the daytime and easterly (from land to sea) during the nighttime.

In this study, we explored the effects of meteorological variables, such as temperature, wind speed and direction, RH, and daily rainfall on elevated $PM_{2.5}$ levels (higher than the third quartile) of all hourly records at the air monitoring station in Mailiao during 2012-2016. The novelty and contributions of this study were meteorological factors such as wind speed and direction, and daily rainfall on the effect of elevated $PM_{2.5}$ levels near the huge petrochemical complex.

2. Materials and Methods

2.1. Meteorological Records

First, the hourly mean data for temperature, wind speed and direction, RH, rainfall, and $PM_{2.5}$ from the air quality monitoring station were downloaded from the website of the Environmental Protection Administration; these data were open for public use. Second, we downloaded data from the nine air quality monitoring stations within 50 km for hourly spatial changes [13].

2.2. Data Were Recorded by Hour

Concentration of $PM_{2.5}$ (μg/m^3): Since 2012, hourly mean concentrations have been continually measured at the monitoring station using a β-ray attenuation method for $PM_{2.5}$. The instrument used for $PM_{2.5}$ analysis was VEREWA F701 [13]. The standard "satisfactory rate" for $PM_{2.5}$ results was 99% in 2012. An accuracy difference between the hand-standard results and automatic monitoring method results of less than 9% is considered "satisfactory" [13].

Wind speed and direction: The hourly mean wind speed was measured using cup anemometers (Model 014A; Met One Instruments, Inc., Grants Pass, USA), and the mean wind direction was measured using a wind vane (Model 024A; Met One Instruments, Inc., Grants Pass, USA) [14]. The means of wind speed and direction for day, month, and seasons were calculated using a vector method.

Seasons: We defined seasons as spring (February to April), summer (May to July), autumn (August to October), and winter (November to January).

The study protocol was reviewed and approved by the Research Ethics Committee of Buddhist Dalin Tzu Chi Hospital, Taiwan (No. B10601004).

2.3. Statistical Analysis

All statistical operations were performed using the R 3.0.2 software (R Foundation for Statistical Computing, Vienna, Austria). The openair, sp, and gstat packages of R were applied to analyze the data.

Continuous variables were examined using analysis of variance and are expressed as mean ± standard deviation. Categorical variables were examined using a trend test and are presented as the frequency and percentage. The mean wind speed and direction were calculated using a vector method for days, weeks, and months.

The multiple logistic regression model with a stepwise variable selection procedure was conducted to determine the vital predictors of $PM_{2.5}$ level above the third quartile (36 μg/m^3). The quartile method was used in other study (Rumchev *et al*., 2018). Furthermore, generalized additive models were fitted to detect the potential nonlinear effects of continuous covariates and determine the appropriate cutoff points for discretizing the covariates, if necessary, during stepwise variable selection.

We assessed the goodness of fit of the final logistic regression model according to the estimated area under the receiver operating characteristic curve (AUC). Statistical tools of regression diagnostics were applied to discover any problems associated with the regression model or data. Two-sided $p \le 0.05$ was considered statistically significant. Hourly mean data of the nine air monitoring stations within 50 km were downloaded and stratified by seasons. The Kriging method was applied to estimate the spatial data to explore changes by hour.

3. Results

In total, 43,847 hourly records from 2012 to 2016 from the air quality monitoring station in Mailiao were used; 42,499 (96.9%) records were enrolled for analysis after excluding the records with missing data. The third quartile for $PM_{2.5}$ was set at 36 μg/m^3, which was defined as elevated $PM_{2.5}$ levels in this study. The mean $PM_{2.5}$ levels at this station had a lower trend according to Theil–Sen analysis ($p < 0.001$) (**Table 1**).

The daily means of $PM_{2.5}$ were higher at the end of the year and beginning of the following year and lower during the summer (**Figure 1**). Moreover, the data stratified by months showed lower levels during summer (**Figure 2**).

Table 1. The level of $PM_{2.5}$ (μg/m^3) at the monitoring station in Mailiao, Yunlin County, from 2012 to 2016.

Year	$PM_{2.5}$ (μg/m^3)				
	Mean	Standard deviation (SD)	Minimum	Maximum	Median
2012	25.47	17.39	0	132	22
2013	30.70	20.25	0	179	27
2014	27.75	20.54	1	145	24
2015	24.44	19.83	0	145	20
2016	25.36	16.73	3	153	21

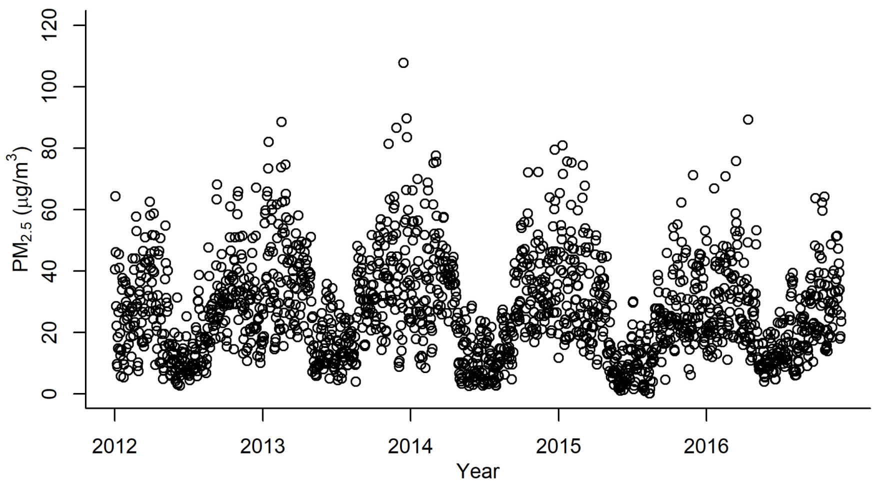

Figure 1. Scatter plot of hourly records for $PM_{2.5}$ levels from 2012 to 2016.

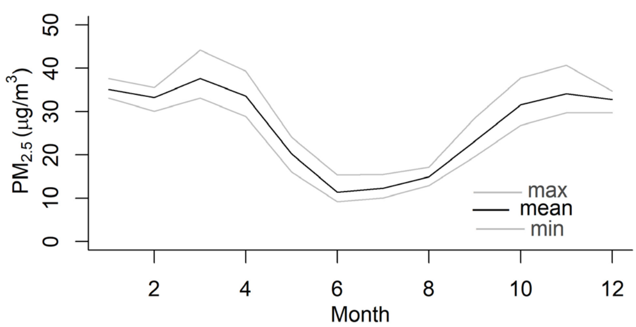

Figure 2. Mean, minimum, and maximum $PM_{2.5}$ levels stratified by months.

The data were stratified and compared by season and daytime or nighttime. The means of $PM_{2.5}$ were significantly lower during summer as well as daytime and nighttime ($p < 0.001$) than during other seasons. Spring and summer are the rainy seasons in Taiwan (from 7.0% to 8.6%) ($p < 0.001$). The hottest season is summer (28.7˚C ± 2.1˚C), followed by autumn (25.7˚C ± 3.1˚C) and the coldest season is winter (18.0˚C ± 3.0˚C) ($p < 0.001$). The percentage of higher $PM_{2.5}$ levels was lowest in the summer. The mean RH (77% - 87%) is the highest during summer. Regarding wind direction, the mean wind directions were southerly or southeasterly during summer. During autumn and winter, the mean wind directions were easterly to northeasterly during both daytime and nighttime. During spring, the mean wind direction was southerly during the daytime and easterly during the nighttime. The highest mean wind speed was noted at nighttime during winter (1.81 m/s), and the lowest mean wind speed was noted in the daytime during spring (0.37 m/s) (**Table 2**). The hourly analysis showed elevated $PM_{2.5}$ during the daytime (**Figure 3**).

The significant factors associated with elevated $PM_{2.5}$ levels included work hours from 6 a.m. to 2 p.m. [6 a.m.: odds ratio (OR): 1.20, 95% confidence interval (CI): 1.06 - 1.35; 7 - 9 a.m., OR: 1.66, 95% CI: 1.56 - 1.78; 11 a.m. to 2 p.m.:

Table 2. Distributional properties stratified by seasons and daytime or nighttime.

Variables	Total	Spring	Summer	Autumn	Winter	*p* value
$PM_{2.5}$, mean ± SD (μg/m³)						
whole day (24 hours)	26.7 ± 19.2	30.7 ± 19.3	12.7 ± 10.0	29.7 ± 17.5	33.7 ± 20.5	<0.001
Daytime	27.5 ± 19.4	30.6 ± 19.5	13.0 ± 10.0	31.8 ± 17.4	34.6 ± 20.7	<0.001
Nighttime	25.9 ± 18.9	30.8 ± 19.2	12.5 ± 10.0	27.5 ± 17.2	32.8 ± 20.3	<0.001
$PM_{2.5}$, hourly records > Q3						
whole day (24 hours)	10,580 (24.9%)	3598 (33.7%)	318 (3.0%)	2903 (27.3%)	3761 (35.2%)	<0.001
Daytime	5586 (13.1%)	1739 (16.3%)	166 (1.6%)	1705 (16.0%)	1976 (18.5%)	<0.001
Nighttime	4994 (11.8%)	1859 (17.4%)	152 (1.4%)	1198 (11.3%)	1785 (16.7%)	<0.001
Rainfall (per hour records), n (%)						
whole day (24 hours)	2205/42,499 (5.2)	763/10,665 (7.2)	833/10,514 (7.9)	257/10,633 (2.4)	352/10,687 (3.3)	<0.001
Daytime	1145/21,028 (5.4)	384/5272 (7.3)	449/5204 (8.6)	136/5262 (2.6)	176/5290 (3.3)	<0.001
Nighttime	1060/21,471 (4.9)	379/5393 (7.0)	384/5310 (7.2)	121/5371 (2.3)	176/5397 (3.3)	<0.001
Temperature, mean ± SD (degree C)						
whole day (24 hours)	23.9 ± 5.0	23.2 ± 4.0	28.7 ± 2.1	25.7 ± 3.1	18.0 ± 3.0	<0.001
Daytime	24.8 ± 5.2	24.1 ± 4.2	29.7 ± 2.2	26.7 ± 3.1	18.8 ± 3.1	<0.001
Nighttime	23.0 ± 4.7	22.3 ± 3.7	27.7 ± 1.5	24.8 ± 2.8	17.4 ± 2.8	<0.001
Relative humidity, mean ± SD (%)						
whole day (24 hours)	81.4 ± 10.1	82.0 ± 10.6	82.8 ± 8.7	80.5 ± 10.0	80.2 ± 10.6	<0.001
Daytime	77.2 ± 10.3	77.4 ± 11.3	78.0 ± 9.0	76.6 ± 9.9	77.0 ± 10.9	<0.001
Nighttime	85.4 ± 7.9	86.5 ± 7.5	87.4 ± 5.3	84.4 ± 8.5	83.3 ± 9.2	<0.001
Wind direction, mean (degree)						
Whole day	100.2	126.8	203.7	71.4	67.8	<0.001
Daytime	122.5	184.3	220.4	76.4	72.4	<0.001
Nighttime	88.9	94.6	178.6	67.5	63.4	<0.001
Wind speed, mean (m/second)						
Whole day	0.58	0.34	1.30	0.92	1.79	<0.001
Daytime	0.42	0.37	1.68	0.83	1.77	<0.001
Nighttime	0.79	0.57	1.11	1.02	1.81	<0.001

Daytime: 6 am to 5 pm; nighttime: 6 pm to next day 5 am. Q3: the third quartile of $PM_{2.5}$ (36 μg/m³).

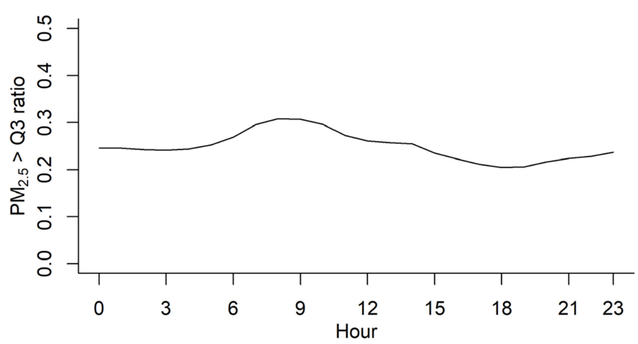

Figure 3. Portions of $PM_{2.5}$ higher than the third quartile (36 μg/m³) stratified by time.

OR: 1.32, 95% CI: 1.22 - 1.42], a temperature between 11˚C - 25˚C (OR: 2.22, 95% CI: 2.07 - 2.38), and RH between 40% - 68% (OR: 0.42, 95% CI: 0.36 - 0.49). Regarding wind direction, northerly winds (<30˚ and > 330˚ from north, OR: 1.57, 95% CI: 1.43 - 1.74) and northeasterly winds (30˚ - 60˚ from the north, OR: 1.23, 95% CI: 1.16 - 1.30) were associated with higher probabilities of elevated $PM_{2.5}$ levels. Easterly winds (60˚ - 90˚ from the north) with a wind speed between 4 and 6 m/s (OR: 4.57, 95% CI: 2.50 - 8.24) and easterly to southeasterly winds (90˚ - 120˚ from the north) with a wind speed between 2 and 4 m/s (OR: 1.45, 95% CI: 1.22 - 1.73) were associated with higher probabilities of elevated $PM_{2.5}$ levels (**Table 3**). Regarding easterly winds, the hourly spatial data of the surrounding nine monitoring stations within 50 km were stratified by seasons and analyzed using the Kriging method (**Figure 4**). During the daytime, air pollution was blown inland by westerly winds or diffusion. During the nighttime, easterly land winds blew the pollution into the area of the studied monitoring station.

The relationships between the air quality monitoring stations are shown in **Figure 4**. The key monitor in Mailiao (m) was located 6 km away from the complex (chief industrial area, c), and south-east direction to the complex. The polar wind figure can elucidate the results (**Figure 5**). It can be depicted that lower wind speeds (breeze), northerly and eastly wind brought the most pollutants to

Table 3. Significant factors associated with hourly mean $PM_{2.5}$ levels higher than the third quartile (36 μg/m^3).

Variable	Estimate	O.R. (95% C.I.)	*p* value
Summer	−2.02	0.13 (0.12 - 0.15)	<0.001
Autumn	−0.21	0.81 (0.76 - 0.86)	<0.001
Hour on 6 o'clock	0.18	1.20(1.06 - 1.35)	0.003
Hour on 7, 8, 9, 10 o'clock	0.51	1.66 (1.56 - 1.78)	<0.001
Hour on 11, 12, 13, 14 o'clock	0.27	1.32 (1.22 - 1.42)	<0.001
Temperature (11 - 25 degrees C)	0.80	2.22 (2.07 - 2.38)	<0.001
Relative humidity between 40% - 68% (yes vs. no)	0.90	2.46 (2.28 - 2.65)	<0.001
Rainfall (yes vs. no)	−0.86	0.42 (0.36 - 0.49)	<0.001
Wind speed (per m/s)	−0.46	0.63 (0.61 - 0.65)	<0.001
North wind (<30, >330 degree)	0.45	1.57 (1.43 - 1.74)	<0.001
North-east wind (30 - 60 degree)	0.21	1.23 (1.16 - 1.30)	<0.001
East wind (60 - 90 degree) × wind speed (4 - 6 m/s)	1.52	4.57 (2.50 - 8.24)	<0.001
East wind (90 - 120 degree) × wind speed (2 - 4 m/s)	0.37	1.45 (1.22 - 1.73)	<0.001
South west wind (150 - 230 degree) × wind speed (per m/s)	−0.20	0.82 (0.78 - 0.86)	<0.001
Intercept	−0.82		

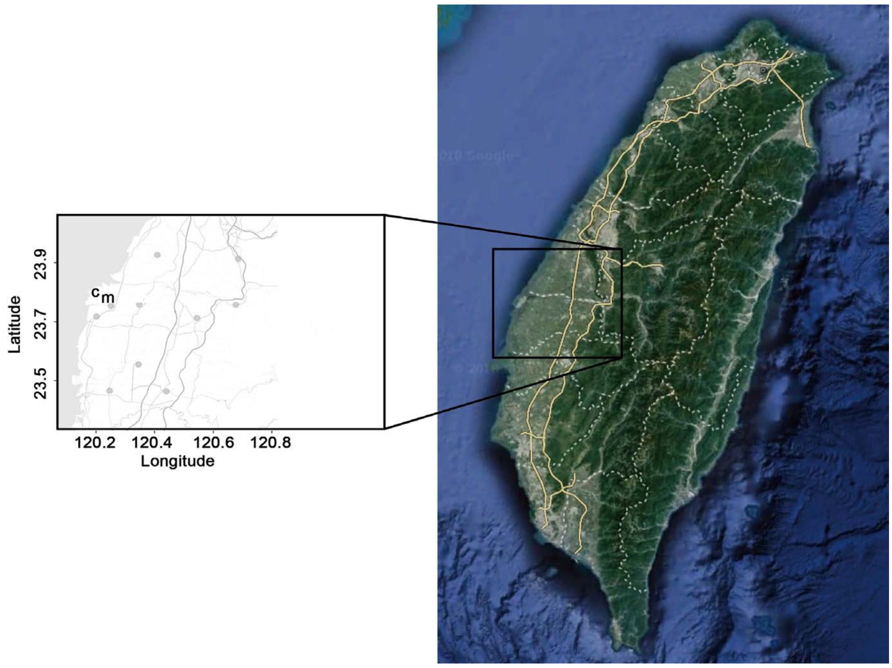

Figure 4. Locations of the 10 air monitoring stations in this study (c, the chief industrial area; m, the key monitor in Mailiao; the other nine monitors, black circles).

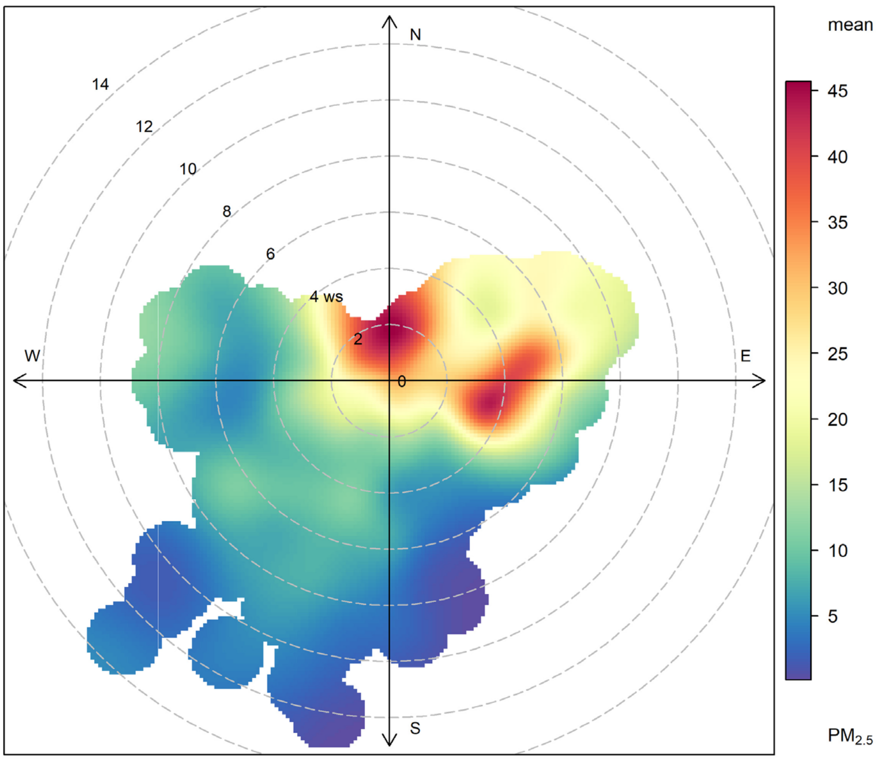

Figure 5. Polar wind diagram showing the wind direction and wind speed with $PM_{2.5}$ levels.

Yunlin county, and higher wind speeds and southerly wind brought the lower levels of $PM_{2.5}$ to Yunlin county. The adjusted generalized R squared (Nagelkerke's R squared) value of this final model was 0.272, and the AUC (78.3%) was acceptable (**Figure 6**). The programming code for calculating the probability of elevated $PM_{2.5}$ levels at this key monitoring station based on the final model is provided in **Appendix**.

4. Discussion

The novel finding of this study was that the annual mean $PM_{2.5}$ concentration had significantly negative trend from 30.70 μg/m³ in 2013 to 25.36 μg/m³ in 2016. The contributions of this study were wind speed and direction, and daily rainfall on the effect of elevated $PM_{2.5}$ levels near the huge petrochemical complex. Daytime (from 6 a.m. to 2 p.m.) was the significant factor associated with hourly $PM_{2.5}$ concentrations higher than the third quartile (36 μg/m³). Another key proposed approach was the hourly spatial data of the surrounding nine monitoring stations within 50 km were stratified by seasons and analyzed using the Kriging method. Another key finding was that the significantly positive meteorological factors associated with hourly levels of $PM_{2.5}$ higher than the third quartile (36 μg/m³) were cool weather (temperature between 11˚C - 25˚C or 51.8˚F - 77˚F), RH of 40% - 68%, northerly winds (330˚ - 360˚ and 0˚ - 30˚ from the north), northeasterly winds (30˚ - 60˚ from the north), easterly winds (60˚ - 90˚ from the north) with a wind speed of 4 - 6 m/s, and easterly winds (90˚ - 120˚ from the north) with a wind speed of 2 - 4 m/s. Furthermore, the significantly negative meteorological factors associated with higher $PM_{2.5}$ levels were summer and autumn, daily rainfall, wind speed, and southerly winds (150˚ - 230˚ from the north) with a wind speed of m/s. These findings were further discussed in the below sections.

After decades of industrialization, air pollution has become a major environmental problem in Taiwan. Poor air quality has both acute and chronic effects on human health. In 2012, the Air Pollution Control Act (APCA) was formulated to control air pollution, maintain public health and living environments,

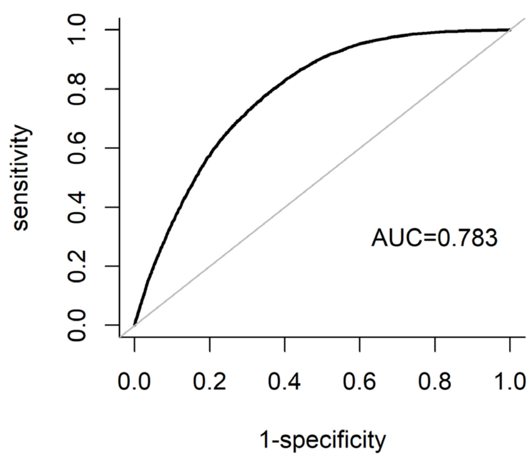

Figure 6. Area under the receiver operating characteristic curve was 0.783 for predicting elevated $PM_{2.5}$ levels in our study.

and improve the quality of life in Taiwan [15]. The improvement in annual $PM_{2.5}$ concentration might contribute to the APCA's formulation. In Taiwan, when $PM_{2.5}$ levels are higher than 36 μg/m^3, the air quality indicator is yellow; people with a history of heart, respiratory, and cardiovascular disease are vulnerable to elevated $PM_{2.5}$ levels and should decrease their outdoor activities 90 [13]. In this study, the third quartile for $PM_{2.5}$ was set at 36 μg/m^3, which was defined as elevated $PM_{2.5}$ levels. In this study, the daily average level of $PM_{2.5}$ was 26.69 ± 15.88 μg/m^3. Although this data was slightly higher than the World Health Organization (WHO) ambient air quality guidelines (25 μg/m^3 for the 24-hourly mean) [16], it was lower than the standard level (35 μg/m^3) in Taiwan.

4.1. Diurnal Variation: Daytime Had Elevated $PM_{2.5}$ Levels

In this study, we observed a diurnal variation in $PM_{2.5}$ with elevated levels during the daytime. This result differs from another study that reported that $PM_{2.5}$ levels were higher in concentration during the nighttime and lower during the daytime in Beijing [17]. The reasons for this might be work-related, such as working in a petrochemical complex and high human activities, and the usual wind direction is westerly (from sea to land) during the daytime. In this study, daytime was defined from 6 a.m. to 5 p.m. However, working hours defined as 8 a.m. to 5 p.m. The phenomena of $PM_{2.5}$ concentrations start to rise from 6:00 a.m. until 2:00 p.m. that cannot be easily explained by atmospheric condition or emission, mobile-source influence. It is one of limitations in this study.

4.2. Wind Direction (Northerly or Northeasterly; 330˚ - 360˚, 0˚ - 30˚, or 30˚ - 120˚)

A relevant study reported that wind direction is a critical parameter affecting $PM_{2.5}$ levels [18]. The current study reported that wind speed was independently and negatively correlated with elevated $PM_{2.5}$ levels, but that different wind directions had different effects associated with elevated $PM_{2.5}$ levels, as shown in another study [19]. In this study, we found that northerly or northeasterly winds (0˚ - 120˚ and 330˚ - 360˚ from the north) were positively correlated with elevated $PM_{2.5}$ levels (OR: 1.57, 95% CI: 1.43 - 1.74). This might be because the monitoring station is located to the southeast of the petrochemical complex, and also because of the monsoon climate in Taiwan (northeast in winter and southeast in summer). When the wind blew from the south or southwest (150˚ - 230˚ from the north), higher wind speed correlated negatively with $PM_{2.5}$ levels. These wind directions might be caused by atmospheric influences such as the monsoon climate. When the wind blew from the east (60˚ - 90˚ from the north) with a wind speed between 4 - 6 m/s as well as from the east to southeast (90˚ - 120˚ from the north) with a wind speed between 2 - 4 m/s, this was positively associated with elevated $PM_{2.5}$ levels (OR: 1.45, 95% CI: 1.22 - 1.73). The spatial hourly data of the surrounding nine stations were analyzed using the Kriging method [20]. A possible explanation might be that $PM_{2.5}$ air pollution could be diffused from higher concentrations to lower areas as well as by westerly winds during the daytime (from sea to land). The usual land wind blew the air pollution during the nighttime.

4.3. Season (Summer and Autumn)

A study reported that elevated $PM_{2.5}$ levels occurred during the winter and spring [21]. In the current study, we found that summer and autumn were correlated negatively with $PM_{2.5}$ levels. Although higher temperatures, more rainfall, higher wind speeds, and lower RH occurred during the summer and autumn, this finding may be explained by the climate in Yunlin being affected by the northeast monsoon during the winter and spring (November to April); furthermore, the wind direction is mainly north-northeasterly, followed by northeasterly or northerly. The average wind speed is between 8.6 - 10.8 m/s during these seasons. During the summer and autumn (May to October), the climate is affected by the southwest monsoon, and the wind direction is mainly south-southeasterly with an average wind speed of 4.9 - 7.3 m/s, as well as north-northeasterly with an average wind speed of 7.0 - 8.1 m/s.

4.4. Cool Weather (11˚C - 25˚C or 51.8˚F - 77˚F)

In the current study, we found that cool weather (11˚C - 25˚C) was associated with higher $PM_{2.5}$ levels, compared with temperatures lower than 11˚C and higher than 25˚C, an inverted U-shaped effect. One study reported that temperature was positively correlated with $PM_{2.5}$ concentration in four seasons in Nagasaki, Japan (Wang and Ogawa, 2015) [18]. Another study reported that temperature has a negative relationship with $PM_{2.5}$ in summer and autumn and then turned to positive in spring and winter in Nanjing, China [22]. In Chen's study, the relation between $PM_{2.5}$ and temperature was not linear, likely an inverted V-shaped effect [22], which was similar our result. However, the different phenomena cannot be easily explained by atmospheric condition, photochemical activity, or emission influence. Therefore, the mechanism between temperature and $PM_{2.5}$ concentrations warrant in the future study.

4.5. RH (40% - 68%)

In the current study, we found that RH between 40% and 68% was a positive factor for $PM_{2.5}$ levels above the third quartile. A similar finding was reported in that RH had an inverted U-shaped relationship with $PM_{2.5}$ concentration (peaking at an RH of 45% - 70%) [23]. In Lou's study reported that the dry (RH = 45% - 60%) and low-humidity (RH = 60% - 70%) conditions are positively affected $PM_{2.5}$ and exerted an accumulation effect (Lou *et al*., 2017). Previous study also reported that positive correlations between RH and $PM_{2.5}$ were identified [24]. The explanation might be strong evaporation and transpiration in the presence of water or wetlands could form a microclimate with lower temperature and higher RH compared with the surrounding environment, which may decrease the gas-to-particle conversion rate and favor particle deposition [25].

4.6. Rainfall

A study reported that rainfall had washout effects on atmospheric particulate pollution and was recognized as one of the main mechanisms for reducing $PM_{2.5}$ pollution [26]. Rainfall possesses a threshold and also the lag effect for reducing $PM_{2.5}$ [26]. In the current study, we found that rain was the independently negative factor for $PM_{2.5}$ levels above the third quartile.

4.7. Limitation

Our study has some limitations. First, the data about the original sources of $PM_{2.5}$ included atmospheric condition, emission, or mobile-source influence with multi-resources data such as pollution source information, real-time population grid data, meteorological data, and traffic data were not available in this study, and that is a limitation. Second, we find some phenomena that cannot be easily explained by atmospheric condition, emission, or mobile-source influence. For example, $PM_{2.5}$ concentrations start to rise from 6:00 a.m. until 2:00 p.m. Therefore, further studies should be carried out with multi-resources data, such as pollution source information, real-time population grid data, meteorological data and traffic data, to provide reasonable interpretations for these unexplainable phenomena. Third, the result cannot apply to other places, however we provided a formula based on the final multiple logistic regression model in the **Appendix** to calculate the probability of elevated $PM_{2.5}$ level.

Furthermore, we found that meteorological factors were associated with elevated $PM_{2.5}$ levels, and provided a formula for calculating the probability of elevated $PM_{2.5}$ (>36 μg/m^3) levels at this key monitoring station. Similar functions based on our method could be established to calculate the probability of elevated $PM_{2.5}$ levels in other cities. Further studies should investigate multi-resources data, such as $PM_{2.5}$ source information, real-time population data, and traffic data, which may provide deeper interpretations for air pollution prediction.

5. Conclusion

The annual $PM_{2.5}$ concentration gradually decreased from 30.70 μg/m^3 in 2013 to 25.36 μg/m^3 in 2016. The meteorological conditions have important effect on $PM_{2.5}$ mass concentration. We found that the factors associated with elevated $PM_{2.5}$ levels were daytime, cool weather (11˚C - 25˚C), winter and spring, RH between 40% - 68%, lower wind speeds, wind direction, and days with no rain. Furthermore, by the relationship with meteorological conditions, it can be depicted that daytime with cool weather, no rain, relatively dry (RH = 40% - 68%), lower wind speeds (breeze), northerly wind, and in winter and spring brought the most pollutants to Yunlin county; and daytime in summer, with rain, relatively humidity (RH > 68%), higher wind speeds, and southerly wind brought the lower probabilities of pollution to Yunlin county. If people want to know the more accurate probability of elevated $PM_{2.5}$ level (>36 μg/m^3), the predictive formula is attached in the **Appendix**. Therefore, people should protect themselves on these high-risk days.

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Author Contributions

JKC and YHK designed, conducted and drafted the manuscript. JKC and CWL analyzed the data. All authors contributed to the manuscript, revised drafts critically for important intellectual content, and read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix

Programming code in OpenOfficeCalc, Microsoft Excel, and R environment for calculating the probability of elevated $PM_{2.5}$ (>36 μg/m^3) based on our multiple logistic regression model.

1) In OpenOfficeCalc or Microsoft Excel:

Key in the values for summer (yes = 1, no = 0) in the A1 cell, autumn (yes = 1, no = 0) in the A2 cell, 6 o'clock (yes = 1, no = 0) in the A3 cell, 7 - 10 o'clock (yes = 1, no = 0) in the A4 cell, 11 - 14 o'clock (yes = 1, no = 0) in the A5 cell, temperature 11 - 25 degree C (yes = 1, no = 0) in the A6 cell, relative humidity 40% - 68% (yes = 1, no = 0) in the A7 cell, rainfall (yes = 1, no = 0) in the A8 cell, wind speed (m/s) in the A9 cell, wind direction, <30 degree, >330 degree from north, (yes = 1, no = 0) in the A10 cell, wind direction, 30 - 60 degree from north, (yes = 1, no = 0) in the A11 cell, wind direction, 60 - 90 degree from north, (yes = 1, no = 0) in the A12 cell, wind speed 4 - 6 m/s, (yes = 1, no = 0) in the A13 cell, wind direction, 90 - 120 degree from north, (yes = 1, no = 0) in the A14 cell, wind speed 2 - 4 m/s, (yes = 1, no = 0) in the A15 cell, wind direction 150 - 230 degree from north, (yes = 1, no = 0) in the A16 cell, and wind speed, m/s in the A17 cell.

Key in the following formula in any empty cell on the same spreadsheet to obtain the estimated probability of elevated $PM_{2.5}$ (>36 μg/m^3):

= 1/(EXP(−(−0.82 + (−2.02)*A1 + (−0.21)*A2 + 0.18*A3 + 0.51*A4 + 0.27*A5 + 0.80*A6 + 0.90*A7 + (−0.86)*A8 +(−0.46)*A9 + 0.45*A10 + 0.21*A11 + 1.52*A12*A13 + 0.37*A14*A15 + (−0.20)*A16*A17))+1)

2) In an R environment:

To calculate the probability of elevated $PM_{2.5}$ (>36 μg/m^3), substitute the values for the variables X1 to X17 in the following regression equation and execute in the R console:

```
yhat<- (-0.82      # constant
+ (-2.02)*X1    # X1= summer (yes=1, no=0)
+ (-0.21)*X2       # X2 = autumn, (yes=1, no=0)
+ 0.18*X3          # X3 = 6 o'clock, (yes=1, no=0)
+ 0.51*X4         # X4 = 7-10 o'clock, (yes=1, no=0)
+ 0.27*X5        # X5 = 11-14 o'clock, (yes=1, no=0)
+ 0.80*X6      # X6 = temperature 11-25 degree C, (yes=1, no=0)
+ 0.90*X7        # X7 = relative humidity 40-68%, (yes=1, no=0)
+ (-0.86)*X8       # X8 = rainfall, (yes=1, no=0)
+ (-0.46)*X9       # X9 = wind speed, m/s
+ 0.45*X10      # X10 = wind direction, <30 degree, >330 degree from north,
(yes=1, no=0)
+ 0.21*X11      # X11 = wind direction, 30-60 degree from north, (yes=1,
no=0)
+ 1.52*X12 *X13
# X12 = wind direction, 60-90 degree from north, (yes=1, no=0)
```

```
# X13= wind speed 4-6 m/s, (yes=1, no=0)
+ 0.37*X14 *X15
# X14 = wind direction, 90-120 degree from north, (yes=1, no=0)
# X15= wind speed 2-4 m/s, (yes=1, no=0)
+ (-0.20)*X16*X17
# X16 = wind direction 150-230 degree from north, (yes=1, no=0)
# X17 = wind speed, m/s)
phat <- 1/(1 + exp(-(yhat)))
phat
```