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Report

Characteristics of Atmospheric Fine Particulate Matter ($PM_{2.5}$) and Polycyclic Aromatic Hydrocarbon Concentrations in Taichung, Taiwan - Comparison with Metropolitan Areas in Japan

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To investigate the characteristics of fine particulate matter ($PM_{2.5}$) pollution in Taichung, Taiwan, atmospheric concentrations of $PM_{2.5}$ and polycyclic aromatic hydrocarbons (PAHs) were measured weekly from 2016 to 2017 in Taichung and Saitama in the Tokyo metropolitan area of Japan. The following conclusions were drawn: (1) the annual mean concentration of $PM_{2.5}$ in Taichung was 27.7 μg/m³ (2016) and 31.1 μg/m³ (2017), which was twice that of Saitama and exceeded the long-term environmental standard of 15 μg/m³ in both years. (2) Two-year mean concentration of the 10 PAHs was 1.42 ng/m³, which was twice that in Saitama. (3) $PM_{2.5}$ and PAH concentrations were higher with the winter monsoon from China being most likely cause. (4) The correlation between $PM_{2.5}$ and the other pollutant concentrations revealed that the primary sources of $PM_{2.5}$, automobiles, thermal power plants, and factories were also significant. Based on the findings, reducing $PM_{2.5}$ concentration in Taichung requires not only reducing emissions from automobiles, but also implementing measures against power plants and factories. Additionally, it is effective in reducing $PM_{2.5}$ in China. We hope that the reduction in air pollutants in Taiwan and China will clean air in Taichung.

Key words fine particulate matter, polycyclic aromatic hydrocarbon, Taichung, Saitama

INTRODUCTION

Taichung is located in the center of Taiwan's main island and is the second-largest city in Taiwan, with a population of 2.8 million.[1] Taichung has developed industries like steel and semiconductor manufacturing.[2] According to local newspapers, Taichung's air pollution is a crisis because people living near thermal power plants, steel manufacturing factories, and semiconductor factories are exposed to carcinogenic pollutants like arsenic, dioxin, cadmium, and nickel. Their concentrations are related to the level of fine particulate known as $PM_{2.5}$.[3] According to statistical data from the Ministry of Health and Welfare of Taiwan, cancer had the highest mortality rate, and the lungs had the highest cancer site.[4] Thus, air pollution caused by $PM_{2.5}$ is a major concern.

$PM_{2.5}$ includes combustion-derived particles emitted from automobiles and factories, naturally occurring yellow sand and volcanic ash, and secondary particles formed by the chemical reactions of gases in the atmosphere.[5] There are concerns about its impact on health, as there is link between $PM_{2.5}$ exposure and mortality rates from respiratory diseases, cardiovascular diseases, and lung cancer.[5] $PM_{2.5}$ contains carcinogenic substances like polycyclic aromatic hydrocarbons (PAHs).[6] In January 2013, an exceptionally high concentration of $PM_{2.5}$ was observed in Beijing, China,[7] and there was concern about transboundary pollution in neighboring countries, including Taiwan and Japan. As a result, particulate matter was collected weekly from January 2016 to December 2017 in Taichung, near China, and Saitama, Japan, which is far from China. Subsequently, we measured and compared the concentrations of $PM_{2.5}$ and PAH, which are required to take measures to prevent air pollution, and clarify their concentration levels and characteristics.

MATERIALS AND METHODS

Sampling of Particulate Matter Particulate matter was collected every Tuesday for 24 h from January 2016 to December 2017 using a SIBATA (Saitama, Japan) HV-500F high-volume air sampler equipped with a $PM_{2.5}$ particle size separator. The Pallflex Products (Putnam, CT, USA) T60A20 PTFE coated composite filter was used for $PM_{2.5}$, while the Toyo (Tokyo, Japan) GB-100R glass fiber filter with slit was used for particulates larger than 2.5 μm. The flow rate was set to 500 L/min.

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Sampling stations (SS) were China Medical University in Taichung City (Taichung SS, 24°17'96"N 120°66'11"E) and Nihon Pharmaceutical University in Saitama Prefecture (Saitama SS, 35°99'06"N, 139°61'84"E).

Analysis of $PM_{2.5}$ and PAHs The filters were weighed before and after sampling using an electric balance. PAH analysis was performed based on previous studies[8-11] with some modifications. A piece of the filter was placed in a glass test tube and 2 mL of acetonitrile was added. The test tube was sonicated for 10 min, and the extracted solution was centrifuged at 3000 rpm for 5 min. The supernatants were filtered and subjected to high performance liquid chromatography (HPLC). The HPLC system consisted of Shimadzu (Kyoto, Japan) LC-20AD pump, SIL-20A auto sample injector, CTO-20AC column oven, and two RF-10A$_{XL}$ fluorescence detectors. The separation column, Shiseido (Tokyo, Japan) CAPCELLPAK C_{18}MG (4.6 × 250 mm), was stored in a column oven (35°C). The mobile phase was CH_3CN/H_2O (8:2, v/v) with a flow rate of 1 mL/min. Excitation and emission wavelengths were 286/458 nm for fluoranthene (FL), chrysene (CH), benzo[*k*]fluoranthene (BkF), benzo[*a*]pyrene (BaP), dibenz[*a,h*]anthracene (DA), and indeno[1,2,3-*cd*]pyrene (IP), and 334/372 nm for pyrene (PY), benz[*a*]anthracene (BaA), benzo[*b*]fluoranthene (BbF), and benzo[*ghi*]perylene (BgP).

RESULTS AND DISCUSSION

Daily and Annual Mean Concentrations of $PM_{2.5}$ To clarify atmospheric $PM_{2.5}$ pollution in Taichung, Taiwan, $PM_{2.5}$ was collected at China Medical University in the city center from January 2016 to December 2017, and the weight of $PM_{2.5}$ and 10 types of PAHs in were measured. To compare pollution levels in Taichung to those in Japan's Tokyo metropolitan area, sampling was carried out concurrently at Nihon Pharmaceutical University in a Saitama residential area.

Figure 1 shows the daily and annual mean concentrations of $PM_{2.5}$ at Taichung SS. The annual mean concentration was 27.7 μg/m^3 in 2016 and 31.1 μg/m^3 in 2017. Meanwhile, the concentration at Saitama SS was 12.6 μg/m^3 in 2016 and 14.3 μg/m^3 in 2017, which were approximately half that of Taichung SS. We previously reported that the $PM_{2.5}$ concentration at Ueno SS, located in central Tokyo, was 1.4 times higher than that at Saitama SS.[6] Therefore, the $PM_{2.5}$ concentration ratio for Taichung: Ueno: Saitama SS was estimated to be 2:1.4:1.

Taiwan's short-term (daily mean) and long-term (annual mean) environmental standards for $PM_{2.5}$ are 35 and 15 μg/m^3, respectively, which are same as those in Japan. Taichung SS had annual mean concentration that exceeded long-term environmental standard of 15 μg/m^3 in both years, while Saitama SS did not. At Taichung SS, 28 out of 99 days (28%) exceeded the short-term environmental standards of 35 μg/m^3, while Saitama SS only exceeded it for two days. These results indicate that $PM_{2.5}$ pollution in Taichung is significantly more serious than in Saitama.

Monthly Variation in $PM_{2.5}$ Concentration The monthly variation in $PM_{2.5}$ concentrations is shown in Fig. 2A. $PM_{2.5}$ concentration at Taichung SS was higher in winter and spring (December to April, 33–44 μg/m^3) than in summer (June to August, 19–25 μg/m^3). In general, the reasons for heavy air pollution in winter are (1) the inversion layer due to low temperature and low humidity, (2) combustion of fossil fuels by stoves, and (3) the strong northeast monsoon from China. As the seasonal variation at Saitama SS, which has a lower temperature, was smaller than that at Taichung SS, the influence of the inversion layer and stove use was estimated to be small.

PAH Concentration PAHs are produced by the incomplete combustion of fossil fuels such as gasoline and diesel oil and are adsorbed onto particulates. To determine the sources of $PM_{2.5}$, ten PAHs were measured. The range of the calibration curve, limit of detection, reproducibility of HPLC, and recovery rate during the pretreatment process demonstrate that PAHs can be analyzed with high sensitivity and accuracy (Table 1). As the concentrations of each of the 10 PAHs were highly correlated with each other (r>0.9), PAHs were evaluated as the total concentration of the 10 PAHs (ΣPAHs). The monthly mean concentration of ΣPAH is shown in Fig. 2B, and the minimum, maximum and mean value of individual PAH are listed in Table 2. The two-years mean concentration of ΣPAH at Taichung SS (1.42 ng/m^3) was twice that of Saitama SS (0.70 ng/m^3). The ΣPAH concentration in winter at Taichung SS (December to March, 2.08–4.11 ng/m^3) was higher than that in spring to summer (April to September, 0.31–0.79 ng/m^3). The ΣPAH concentration in winter (December to March) at Saitama SS (0.55–1.22 ng/m^3) was lower than that at Taichung SS (2.08–4.11 ng/m^3). These findings raise the possibility of monsoon transport from China. In June and July, Saitama SS had higher ΣPAH concentrations (0.66 and 0.82 ng/m^3, respectively) compared to Taichung (0.38 and 0.31 ng/m^3, respectively). The reason for the high concentration at the

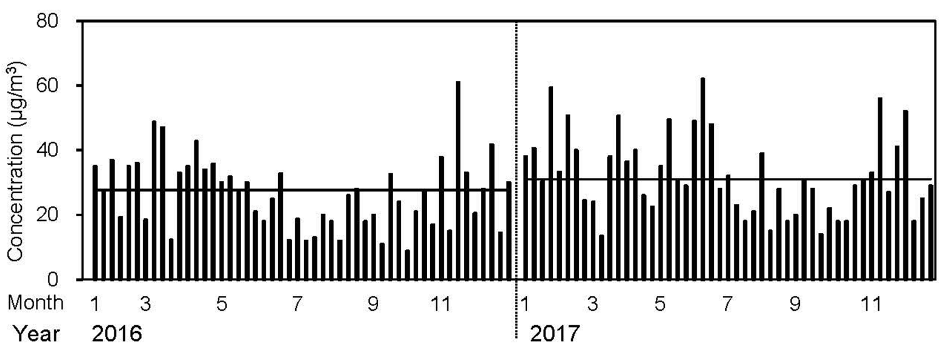

Fig. 1. Daily and Annual Concentrations of $PM_{2.5}$ at Taichung SS

The vertical bars and horizontal line represent daily and annual mean concentrations, respectively.

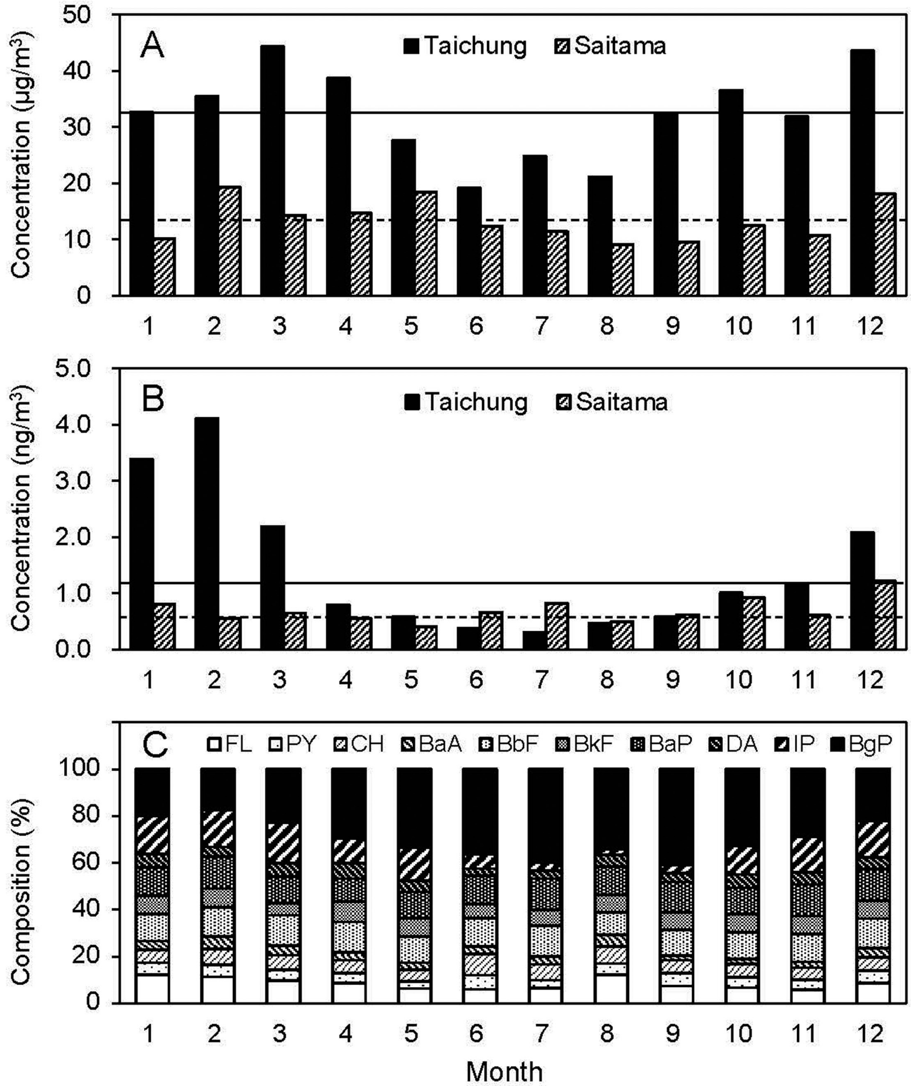

Fig. 2. Monthly Mean Concentrations of $PM_{2.5}$ (A) and ΣPAH (B) at Taichung and Saitama SS, and PAH Composition at Taichung SS (C)

The solid and dashed horizontal lines in graphs A and B represent the two-year mean concentrations at Taichung SS and Saitama SS, respectively.

Table 1. Range of Calibration Curve, Limit of Detection and Reproducibility for HPLC, and Recovery Rate during Pretreatment Process

Chemical	Range of calibration curve (ng/mL)	Limit of detection (pg/injection)	Reproducibility (relative standard deviation, %)	Recovery rate during pretreatment (%)
FL	0.58–140	0.83	0.42	91.8
PY	0.10–24	0.19	0.80	94.6
CH	0.11–27	0.46	0.74	92.0
BaA	0.09–21	0.14	0.95	91.5
BbF	0.32–79	0.59	0.41	99.0
BkF	0.25–62	0.23	0.16	90.5
BaP	0.10–24	0.15	0.35	85.5
DA	0.33–80	0.68	0.94	81.8
IP	1.5–120	5.42	1.2	79.4
BgP	0.50–120	0.58	0.44	103.6

Saitama SS in summer could be the southern monsoon from Tokyo.

Relationship between $PM_{2.5}$ and Other Pollutants To determine the source of $PM_{2.5}$, correlation coefficients between $PM_{2.5}$ concentrations and other pollutants were calculated (Table 3). Environmental Protection Department of Taiwan provided data on NO_2, CO, SO_2 and O_3 levels measured at the Chung Ming Air Monitoring Station, located 2 km south of the Taichung SS, during the same sampling period. The data revealed the following characteristics: (1) The correlation coefficient between NO_2 and CO, which are mainly emitted by automobiles, was high (r=0.911). (2) The correlation coefficients between SO_2, which is mainly emitted from factories, and NO_2 or CO were relatively low (r=0.403 and 0.377,

Table 2. Minimum, Maximum and Mean Concentrations of PAH in the Atmosphere at Taitung SS

Chemical	Minimum concentration (ng/m^3)	Maximum concentration (ng/m^3)	Mean concentration (ng/m^3)
FL	0.01	0.45	0.13
PY	0.01	0.21	0.06
CH	0.02	0.34	0.08
BaA	0.01	0.28	0.05
BbF	0.03	0.53	0.16
BkF	0.02	0.34	0.10
BaP	0.03	0.60	0.16
DA	0.01	0.19	0.07
IP	0.01	0.63	0.19
BgP	0.09	0.67	0.32

Table 3. Correlation Coefficients among Air Pollutants

	$PM_{2.5}$	ΣPAH	NO_2	CO	SO_2	O_3
$PM_{2.5}$	1.000					
ΣPAH	0.594	1.000				
NO_2	0.617	0.830	1.000			
CO	0.647	0.748	0.911	1.000		
SO_2	0.466	0.217	0.403	0.377	1.000	
O_3	0.243	0.095	–0.014	0.019	0.042	1.000

Data for NO_2, CO, SO_2 and O_3 were obtained from the Chung Ming Air Monitoring Station of the Environmental Protection Department of Taiwan. They were automatically and consecutively analyzed by the chemiluminescence, infrared, ultraviolet fluorescence, and ultraviolet absorption methods, respectively.

respectively), owing to the different sources. (3) No correlation was found between O_3, which is formed by sunlight in the atmosphere, and NO_2, CO, or SO_2 (r=–0.014, 0.019, and 0.042, respectively) because the variation in O_3 depends on the intensity of sunlight, whereas the variations in NO_2, CO, and SO_2 depend on the emission of the source.

The $PM_{2.5}$ concentration measured in this study was highly correlated not only with NO_2 and CO (r=0.617 and 0.647, respectively), but also with ΣPAH (r=0.594), which are mainly emitted from combustion sources, indicating that $PM_{2.5}$ concentration was highly influenced by automobile emissions. Moreover, a moderate correlation was observed between $PM_{2.5}$ and SO_2 (0.466) and a low correlation was observed between $PM_{2.5}$ and O_3 (0.243). These results suggest that the atmospheric $PM_{2.5}$ concentration in Taichung is also influenced by factories and photochemical smog.

Taiwan's electricity supply is primarily based on thermal power generation as nuclear power plants have been phased out. Taiwan has also developed the steel and petrochemical industries. Power plants and factories are more prevalent in the central and southern parts of Taiwan than in the northern parts, resulting in serious air pollution. Our correlation results scientifically demonstrated that atmospheric $PM_{2.5}$ concentration in Taichung was influenced by both automobiles and factories.

It is estimated that 70% of $PM_{2.5}$ is generated domestically and 30% comes from China.[12] In 2017, the primary energy consumption in Taiwan was 33% oil, followed by 31% coal[13], while that in China was 60% coal.[14] The PAH composition varies with fuel and combustion conditions, providing information on their sources.[15,16] Monthly variation of PAH composition obtained in this study is shown in Fig. 2C. In this study, the concentration ratio of IP/BgP was higher during heavy pollution (1.07, $[PM_{2.5}]>35$ $\mu g/m^3$) than during light pollution (0.28, $[PM_{2.5}]<35$ $\mu g/m^3$). These results suggest that during periods of heavy air pollution due to $PM_{2.5}$, $PM_{2.5}$ was transported to Taichung from sources other than local sources.

As described above, $PM_{2.5}$ in Taichung is primarily caused by domestic automobile exhaust gas and factories. Taiwan intends to expand its natural renewable energy sources to improve air quality. Although solar and wind power generation had generating capacities of 842 and 467 MW in 2015, respectively, these are expected to be increased to 2000 and 4200 MW, respectively.[17] Monsoon-induced long-distance transport from China is also problematic. In May 2024, the mean $PM_{2.5}$ concentration in major Chinese cities was 22 $\mu g/m^3$, down 4.3% from the previous year.[18] Therefore, $PM_{2.5}$, caused by long-distance transport from China, is expected to decrease in the long term.

Regarding the impact of $PM_{2.5}$ on human health, the one-year mean value of $PM_{2.5}$ in Taichung exceeds the long-term environmental standard, and the daily mean value exceeds the short-term environmental standard on 28% of days, raising concerns about the chronic and acute adverse effects of $PM_{2.5}$ on humans. These findings highlight the urgent need for international cooperation to address air pollution, as it is an international issue that transcends national borders. We hope that China and Taiwan will improve their air quality by promoting measures to prevent air pollution.

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Conflict of interest The authors declare no conflict of interest.

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