Characteristics of Indoor Aerosols in College Laboratories

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ABSTRACT

This study was conducted in National Pingtung University of Science and Technology (NPUST), in Taiwan. The main objective was to provide quantitative information on concentrations of the indoor and outdoor PMs, as well as water-soluble ions, at seven selected locations and the spatial variations in four different types of typical laboratories. They include Type I: General Chemistry Laboratories (GCL); Type II: WCLTP during a semester and a summer vacation in college; Type III: Environmental Research Laboratories; and Type IV: Soil Research Laboratories and Field in NPUST. In addition, this paper also investigates the characteristics of indoor aerosols in college laboratories. Indoor and outdoor particulate matters with aerodynamic diameters of less than 2.5 μm (PM2.5) and 10 μm (PM10) were sampled from June to September in 2002. The acid and base gases in outdoor samples and the amount of eight particle-bound water-soluble ions (NO₃⁻, SO₄²⁻, Cl⁻, NH₄⁺, Na⁺, K⁺, Ca²⁺, and Mg²⁺) were also determined. The results for laboratories Types I and II revealed that the mean PM2.5 concentrations indoors in GCL (during a semester) and WCLTP (during a summer vacation) exceeded the air quality guidelines of the World Health Organization (WHO) of 20 μg/m³ for PM2.5. The results also showed that the indoor concentrations of PM2.5 and PM10 in GCL increased by 4.9 and 1.7 times, respectively, during a semester as compared to the indoor measured data during a summer vacation. Students’ laboratory activities in colleges thus deserve more attention, because these cause significant increases in the PM emissions.

Keywords: PM2.5; Laboratory; Indoor air quality; I/O ratio.

INTRODUCTION

With the increasing human indoor activities, evaluating the impact of these activities on the indoor air quality becomes more important. Numerous papers are found in the literature (Zhu et al., 2010; Masih et al., 2012; Zhu et al., 2012). In general, particles less than 2.5 micrometers in diameter are called "fine particles" or PM2.5 (PM with aerodynamic diameters < 2.5 μm). These particles are so small they can be detected only with an electron microscope. Sources of fine particles include all types of combustion, including motor vehicles, power plants, residential wood burning, forest fires, agricultural burning, and some industrial processes (AIRNow, 2010). Particles between 2.5 and 10 micrometers in diameter are referred to as “coarse particles”. Sources of coarse particles include crushing or grinding operations, and dust stirred up by vehicles travelling on roads (AIRNow, 2010).

Many epidemiological studies have demonstrated the relationships between concentrations of ambient aerosols and adverse health effects (Vedal, 1997; Brunekreef and Holgate, 2002; Pope et al., 2002; Harrison et al., 2004; Migilaretti and Cavallo, 2004; Peden, 2005; Chow et al., 2006; Oftedal et al., 2008; Gan et al., 2011). Particularly, PM2.5, the fraction of fine respirable particulates, is significantly correlated with deaths from cardiopulmonary disease and lung cancer (Bericò et al., 1997). Several studies have also shown the considerable impact of PM2.5 on human health (Dockery et al., 1993; Pope et al., 1995; Samet et al., 2000). Recently, several studies have reported that each 10 μg/m³ increase in fine particulate concentration was associated with an approximate 4%, 6% and 8% increase in risk of all-cause, cardiopulmonary and lung cancer mortality, respectively (Pope et al., 2002; Pope et al., 2004).

Particles can also be generated from interaction and reaction of gas- and liquid- or solid-phase species at the particle surface or in the bulk solution, as well as through coagulation of existing particles (Moore et al., 2007; Sekiguchi et al., 2009). Zhou et al. (2012) have investigated...
carbonaceous and ionic components of atmospheric fine particles in Beijing and their impact on atmospheric visibility. By comparing studies under different synoptic conditions they found that PM$_{2.5}$ pollution was mainly caused by transportation of particulates from remote sources, whereas hazy synoptic conditions are caused by local pollution. Moreover, PM$_{2.5}$ and visibility were negatively correlated, and the relationship between the concentrations of NH$_4^+$, SO$_4^{2-}$, and NO$_3^-$ with PM$_{2.5}$ concentration during winter can be described using power function fitting. Moore et al. (2007) mentioned that atmospheric oxidation of gas-phase primary exhaust species can produce low-vapor-pressure compounds that readily condense onto existing particles and produce secondary mass (Moore et al., 2007; Sekiguchi et al., 2009). Zhu et al. (2012) investigated the indoor and outdoor chemical components of PM$_{2.5}$ in rural area of northern China. They compared the data from indoor and outdoor PM$_{2.5}$ sources and concluded that the dominant primary source (31% for indoor and 44% for outdoor) in summer was biomass burning, whereas in winter coal combustion (21% for indoor and 29% for outdoor) and biomass burning (24% for indoor and 16% for outdoor) were dominant. A study also suggests that inside the museum high concentrations of the suspended acidic particles and their depositions have high risk of erosion on the terra-cotta figures (Gao et al., 2011). Gao et al. (2011) measured indoor particles and microclimate in summer and winter periods inside and outside Emperor Qin's Terra-Cotta Museum in Xi'an, China. They found that the number concentrations of particles were lower (0.3–1.0 μm) in summer, and were higher (1.0–7.0 μm) in winter. The average indoor PM$_{2.5}$ and TSP concentrations were 108.4 ± 30.3 μg/m$^3$ and 242.3 ± 189.0 μg/m$^3$ in summer and were 242.3 ± 189.0 μg/m$^3$ and 312.5 ± 112.8 μg/m$^3$ in winter, respectively. Moreover, sulfate, organic matter, and geological material dominated indoor PM$_{2.5}$, followed by ammonium, nitrate, and elemental carbon. Several milligram of sulfate particles can deposit in the museum per square meter each year based on the dry deposition estimate (Gao et al., 2011). Of course, emissions from small scale industries and workshops and soil derived aerosols are considered as other important contributing sources (Sharma et al., 2003).

In general, the size and distribution of indoor air pollution differs considerably from those of outdoor air pollution. Several factors influence indoor air quality. Outdoor infiltration, human activities, and ventilation types can influence indoor particulate levels in hospitals (Wang et al., 2006). Airborne pollutants originating from indoor sources such as smoking, cooking and cleaning predominately could contribute to poor indoor air quality (Wallace, 1996). Variation of human activity in indoor aerosols has led to considerable difficulty in identifying the determinants in particulate pollutants that are responsible for adverse health effects. Moreover, little research has been published on characteristics of acidic aerosols in college laboratories (Hsieh et al., 2012). A number of PM studies have been conducted in the world. However, few studies were performed on campuses in Taiwan; especially on fine particles in Pingtung City, Southern Taiwan. Also, no specific research on simultaneous indoor and outdoor PM characteristics on college campuses have been reported. Hence, it is crucial to investigate the nature of the sources that contribute to high-level PM emissions in college laboratories, and to develop effective control strategies in order to effectively reduce these emissions.

This study provides quantitative information on indoor and outdoor mass concentrations of PMs and water-soluble ions at seven selected locations for four types of laboratories (Type I: general chemistry laboratories (GCL); Type II: waste chemical liquid treatment plant (WCLTP) during a semester and a summer vacation in college; Type III: environmental research laboratories (ERL); and Type IV: soil research laboratories (SRL)) at the National Pingtung University of Science and Technology (NPUST) and investigated the spatial variations in the studied areas. In addition, this study determined the characteristics of indoor aerosols in college laboratories.

**MATERIALS AND METHODS**

**Sampling Strategy**

This study was conducted at NPUST, in Taiwan. The NPUST campus is situated near the Lao-Pi village in Ping-Tung County, which has minimal anthropogenic pollution and adverse environmental effects. In this study, four representative laboratories (GCL, WCLTP, ERL, and SRL) at NPUST were selected as the indoor environments. At each laboratory two distinct sampling locations (indoor ground and outdoor roof) were investigated for levels of various particulate contaminants. Based on the possible emission sources of aerosols in these representative laboratories, seven locations were chosen and grouped into four types: Type I: GCL; Type II: WCLTP during a semester and a summer vacation in college; Type III: ERL; and Type IV: SRL. Thus, this study provides quantitative information on indoor and outdoor mass concentrations of PMs and water-soluble ions for these types of locations. Table 1 shows detailed information of these four types of locations.

Indoor and outdoor particulate matters with aerodynamic diameters less than 2.5 μm (PM$_{2.5}$) and 10 μm (PM$_{10}$) were sampled from June 2002 to September 2002. Outdoor acid and base gases and eight particle-bound water-soluble ions (NO$_3^-$, SO$_4^{2-}$, Cl$^-$, NH$_4^+$, Na$^+$, K$^+$, Ca$^{2+}$, and Mg$^{2+}$) were also determined. During a semester period, several undergraduate experimental courses were conducted and a large amount of pollutants was released into the atmosphere at the campus. For comparison, indoor PM$_{10}$ samples were collected during two periods (a semester week with human activity and a summer vacation week without activity) from each type of laboratory at sites that represent various spaces (half-open space, roof-open space, enclosed space, and open field). We investigated the characteristics of aerosols at the chemistry laboratories and WCLTP. An annular denuder/filter pack system (ADS) and a PM$_{10}$ high-volume sampler were used to collect gases and particles from laboratories and WCLTP. In addition, PM$_{2.5}$ and PM$_{2.5-10}$ were collected by applying manual dichotomous samplers (GRASEBY ANDERSEN G241) at the first floor ventilation hood, the roof exhaust vent, in the soil research laboratory,
rates were calibrated using a manometer. The principles and specified 50% cut-point of 10 μm cut-point diameter to collect both particulate and gaseous phases (Possanzini et al., 1983; Ye et al., 1991; Baron and Willeke, 2005). In general, fine particles (< 2.5 μm) passing through the denuder in the laminar air stream are unaffected because they have insufficient diffusion coefficients to be deposited to the walls of the denuder (Possanzini et al., 1983; Ye et al., 1991; Baron and Willeke, 2005).

Manual Dichotomous Sampler
A dichotomous sampler (Graseby Andersen G241) was used, and particle concentrations in three ranges (diameter < 2.5 μm, 2.5 μm < diameter <10 μm, and diameter < 10 μm) were determined (Chen et al., 2004). The dichotomous sampler was equipped with an inlet having a cut point of 10 μm. The PM₁₀ particles were divided into two size fractions, a coarse fraction (2.5 μm < diameter < 10 μm, PM₂₅-₁₀) and a fine fraction (diameter < 2.5 μm, PM₂₅) using a virtual impactor with a 2.5 μm cut point when entering the sampler (Chen et al., 2004). The dichotomous sampler was operated at a total flow rate of 16.7 L/min (1.67 and 15 L/min for coarse and fine flows, respectively) (Chen et al., 2004).

Water-Soluble Ions Analysis
Chemical analysis of eight particle-bound water-soluble ions (NO₃⁻, SO₄²⁻, Cl⁻, NH₄⁺, Na⁺, K⁺, Ca²⁺, and Mg²⁺) was conducted using ion chromatography (Dionex DX-120). The following operational parameters were used on ion chromatography (IC) in this study: (i) Three anions, including Cl⁻, NO₃⁻, and SO₄²⁻ are analyzed. (ii) Five cations, including NH₄⁺, Na⁺, K⁺, Mg²⁺, and Ca²⁺ are analyzed. (iii) Both anions and cations samples were shook for 60 minutes during extraction process. (iv) For anions analysis, the AS12A protection column, AS12A separation column, and ASRS-ULTRA II 4-mm suppress column are used. (v) The parameter settings were as follows: flow velocity: 1.5 mL/min; inefficient solvent: 2.7 mM Na₂CO₃/0.3 mM NaHCO₃; elapsed analyzing time: 13 min). (vi) For cations analysis, the CS12A protection column, CS12A separation column, and CSRS-ULTRA 4-mm suppress column are used. (vii) The parameter settings were as follows: flow velocity: 1.0 mL/min; inefficient solvent: 20 mM MSA (Methanesulfonic Acid); elapsed analyzing time: 14 min).

The Quality Assurance/Quality Control (QA/QC) procedures were described in Chen et al. (2004). A detailed

### Table 1. Detailed characteristics of four types in this study (Type I–IV).

| Type   | Type I.                     | Type II.       | Type III.                  | Type IV.       |
|--------|-----------------------------|----------------|---------------------------|----------------|
| Sampling Sites | General Chemistry Laboratories (GCL) | WCLTP         | Environmental Research Laboratories (ERL) | 1. Soil Research Laboratories (SRL) |
| Sampling Conditions | During a semester            | ---            | ground floor (indoor) in ERL | ground floor (indoor) in SRL |
| Activities           | with/without performing organic chemistry Exp. | Performing the treating process of waste liquid | Performing chemical extraction with hood for venting | Performing chemical extraction with fans for venting |

and at the lawn at the Department of Environmental Science and Engineering Building.

The first semester of an academic year in Taiwan generally begins between February and June, while the summer vacation is between July and September. In this study, sampling was performed from June 2002 to September 2002. Each sample collection began at 8:30 a.m. and a high volume sampler was applied continuously for 24 h. The temperature, atmospheric pressure, and wind direction were recorded during the sampling period. Detailed descriptions of all sampling sites are shown in Table 1. The locations of the sites are shown in Fig. 1.

### Sampling and INSTRUMENTS

**PM₁₀ Sampler**

High-volume air samplers of PM₁₀ (Graseby–Andersen GBM-2000H, USA) equipped with Teflon filter papers were used to collect suspended particulate matter at a flow rate of 1.13 CMM. The inlet of the sampler represented the specified 50% cut-point of 10 μm at that flow rate. The flow rates were calibrated using a manometer. The principles and description about the PM₁₀ Sampler are also mentioned in our previous study (Chen et al., 1996, 2004).

Before and after field sampling, all sampling filter papers (used in all samplers in this study) were individually coated to remove selected gas-phase species that diffuse to the walls and react with or adhere to the surface during the passage of a laminar air stream. Theoretically, particles are not trapped on the tube walls but on a filter downstream of the denuder. The use of annular denuders is a good approach for simultaneously sampling gaseous and particulate-phase aerosols. Many studies indicates that the combination of an annular denuder and a filter pack system has been used at flow rates of 10 or 16.7 L/min in a cyclone system with a 2.5 μm cut-point diameter to collect both...
description of the method detection limits (MDLs) and methodology for the analyses can be found elsewhere (Cao et al., 2011). In this study, blank and replicate analyses were also performed for 10% of all samples according to standard operating procedures. Standards were purchased from Merck (Merck KgaA, Darmstadt, Germany) and seven-point calibration curves were prepared for each batch of samples. The r-values of calibration curves were all greater than 0.995. Laboratory blanks were used to assess possible contamination. The blank concentrations of ionic species were less than corresponding MDLs. Concentrations of non-detects were taken as zero.

The paired samples t-test was performed to analyze the differences in PM levels between the indoor measurements and outdoors. The significance level was 0.05 for all statistical tests. The Pearson product moment correlation coefficient was applied to assess any correlation between laboratory PM levels and outdoor ambient PM levels.

RESULTS AND DISCUSSION

A high-volume sampler (PM$_{10}$) and ADS were used to collect gases and particles from laboratories in GCL and WCLTP. In addition, PM$_{2.5}$ and PM$_{2.5-10}$ were collected using manual dichotomous samplers (GRASEBY ANDERSEN G241) at the first floor ventilation hood, the roof exhaust vent, the soil research laboratory, and the lawn at the Department of Environmental Science and Engineering Building.

Meteorological Data

The meteorological data used in the study were obtained using portable meteorological instruments. Table 2 shows general information on meteorological data during the sampling period for Type I: GCL and Type II: WCLTP during a semester and a summer vacation. Table 3 shows general information on meteorological data during the sampling period for Type III: ERL and Type IV: SRL. All four types experienced a hot and humid summer during the sampling periods. In general, Southern Taiwan is located on the lee side of the central mountain range of Taiwan. This region has a stable atmosphere, clear skies, and a distinct pattern of diurnal land-sea breeze circulations (Hsieh et al., 2005). Table 2 shows that, during summer, the difference between the maximal and minimal mean temperatures was 1.8°C in Type I and 1.9°C in Type II. The average indoor temperature ranged from 27.2 to 28.1°C in Type I and 31.2 to 29.5°C in Type II. Table 3 shows that the mean indoor temperature is usually higher than that outdoors.

Particles Mass Concentration

Fig. 2 presents the PM concentrations in sampling locations of Type I (GCL) and Type II (WCLTP) during a semester or/and a summer vacation in college. Moreover,
Table 2. General information on meteorological data during the period of sampling for Type I. (General Chemistry Laboratories, GCL) and Type II. (WCLTP) during a semester and a summer vacation in college.

| Type     | Type I. | Type II. |
|----------|---------|----------|
| Sampling Sites | General Chemistry Laboratories (GCL) | WCLTP |
| Sampling Time | During a semester | During a summer vacation | During a summer vacation |
| Activities | Performing organic chemistry exp. | No | Performing the treating process of waste liquid |
| Internal volume (m³) | 786 | 786 | 750 |
| Weather Condition | sunny | Cloudy/Rainy | Sunny/Cloudy and rainy |
| Mean Temperature (°C) | 27.2 (indoor) | 28.1 (indoor) | 31.4/29.4 (indoor) |
| Mean RH (%) | 72 (indoor) | 93 (outdoor) | 65/76 (indoor) |
| Mean Velocity (m/s) | 0.1 (indoor) | 0.2 (outdoor) | 0.07/0.2 (outdoor) |
| Wind Direction | --- (indoor) | --- (indoor) | ---/N (indoor) |

Table 3. General information on meteorological data during the period of sampling for Type III. (Environmental Research Laboratories) and Type IV. (Soil Research Laboratories and Field in college).

| Type     | Type III. | Type IV. |
|----------|-----------|----------|
| Sampling Sites | Environmental Research Laboratories (ERL) | Soil Research Laboratories (SRL) Field in college |
| Activities | Performing chemical extraction | | Performing chemical extraction |
| Venting Equipments | One hood | Several fans | No |
| Space Type | half open | enclosed | none |
| Weather Condition | sunny/rainy | Cloudy/Rainy | Sunny/Cloudy and rainy |
| Mean Temperature (°C) | 26.6 | 29 | 25.9 |
| Mean RH (%) | 72 | 84 | 56 |
| Mean Velocity (m/s) | 0.1 | 2.7 | 0.07 |
| Wind Direction | --- | S | --- |

Table 4 shows the mean indoor particulate levels in Type I: GCL and Type II: WCLTP during a semester and a summer vacation. Table 5 shows the mean indoor particulate levels in Type III: ERL and Type IV: SRL. The concentrations of PM$_{2.5}$ and PM$_{10}$ aerosols during the entire study period ranged from 5.9 to 88.0 μg/m$^3$ and 22.0 to 124.6 μg/m$^3$, respectively. In general, both PM$_{2.5}$ and PM$_{10}$ increased in Type I (GCL) during a semester or in Type II with the operation of WCLTP, respectively. The mean PM$_{10}$ concentration in Type IV: SRL (124.6 μg/m$^3$) was comparable to the daily-average-limitation of 125 μg/m$^3$ of the National Ambient Air Quality Standards (NAAQS) in Taiwan (NAAAQ, 2012).

In Types I and II, the indoor PM$_{2.5}$ levels were lower than the PM$_{2.5}$ standard (65 μg/m$^3$) recommended by USEPA (1997), and indoor PM$_{2.5}$ constituted a large portion of PM$_{10}$ with a wide range from 23% to 76%, indicating that fine particulate pollution was abundant in GCL and WCLTP. However, the results of Type I and II revealed that the mean PM$_{2.5}$ concentrations indoors in GCL (during a semester) and WCLTP (during a summer vacation) exceeded the air quality guidelines of the World Health Organization (WHO), that is, 20 μg/m$^3$ for PM$_{2.5}$ (WHO, 2006). At the NPUST campus, the major ambient particulate emission sources include the student experimental farms, vehicles, motorcycles, construction activities, and restaurants. The results also show that the indoor concentrations of PM$_{2.5}$ and PM$_{10}$ in GCL increased by 4.9 and 1.7 times, respectively, during a semester period as compared to those measured during the inactive summer vacation.

In Type I, the data provides a comparison between the indoor activities of students and the influence of indoor activities on the outdoor PM level (Table 4). The levels of indoor PM$_{2.5}$ and outdoor PM$_{2.5}$ showed a significant difference between indoor and outdoor concentrations of PM$_{2.5}$ and PM$_{10}$. A paired t-test also indicated a significant difference between indoor and outdoor concentrations of PM$_{2.5}$ and PM$_{10}$. A comparison between indoor PM$_{2.5}$ levels and outdoor PM$_{2.5}$ levels showed that the indoor level of PM$_{2.5}$ (29.1 μg/m$^3$) was approximately 3.1 times higher than that of...
outdoors when the duration of sampling involved laboratorial activities in college, such as general chemistry or other biological laboratories. During a summer vacation, the indoor level of PM$_{2.5}$ (5.9 $\mu$g/m$^3$) was lower than that of outdoors when there was no laboratorial activities duration sampling. Similar to the trend in PM$_{2.5}$, the indoor level of PM$_{10}$ (22.0 $\mu$g/m$^3$) was lower than that of outdoors when there was no laboratorial activities duration sampling. Similar to the trend in PM$_{2.5}$, the indoor level of PM$_{10}$ (22.0 $\mu$g/m$^3$) was lower than that of outdoors when there was no laboratorial activities duration sampling.
μg/m³) was lower than that of outdoors without activities. Thus, there is a distinct difference in indoor levels of both PM$_{2.5}$ and PM$_{10}$ between the periods with laboratorial activities and without.

In WCLTP (Type II), the indoor levels of PM$_{2.5}$ and PM$_{10}$ were higher than those outdoors. The I/O ratio is an indicator for evaluating the difference between indoor concentrations and the corresponding outdoor level (Li and Lin, 2003). The I/O ratios of PM$_{2.5}$ in the Type II site are shown in Table 4. The indoor levels of PM$_{2.5}$ and PM$_{10}$ (24.4 μg/m³ and 31.8 μg/m³, respectively) was 1.6 and 1.2 times higher than those outdoors during sampling. The sampling period was not associated with the laboratorial activities at the college and the sampling site at Type II was an enclosed environment/space for treating waste liquids. Therefore, the ratios of I/O for both PM$_{2.5}$ and PM$_{10}$ exceeded 1.0. Thus, the difference between the laboratorial activities and non-activity for experiments is crucial.

High correlations were observed between PM$_{2.5}$ and PM$_{10}$, indicating that PM$_{2.5}$ and PM$_{10}$ had similar PM emission sources \((R = 0.97, p = 0.036, p < 0.05)\). The indoor particle levels correlated with the corresponding outdoor levels \((R = 0.97\) for PM$_{2.5}$ and 0.95 for PM$_{10}$), indicating that indoor forced venting can lead to direct exit into their adjacent outdoor environments on campus. During our investigation, indoor mass concentrations were generally higher than those outdoors at the chemistry laboratories (Type I) and the WCLTP (Type II) because aerosol pollutants frequently accumulate in higher concentrations indoors than outdoors. These results indicate that high indoor particulate level was associated with human activities in these rooms.

### Size Distribution of Suspended Particle

Figs. 3(a) and 3(b) shows the difference of PM$_{2.5}$ and PM$_{10}$ (indoor and outdoor) between Type I and Type II. As shown in Figs. 3(a) and (b), the I/O ratios indicate that the increase in laboratorial activities indoors resulted in the increase of PM$_{2.5}$ in the laboratories and WCLTP. However, obtained I/O ratio for PM$_{10}$ did not exhibit the same trend.

Particularly, the indoor PM$_{2.5}$ concentration at the laboratory was 3.1 times higher than that outside. However, during the summer vacation without student activities, the indoor PM$_{2.5}$ concentration was 0.6 times that outside. With increased student activities at chemistry laboratories, the mean I/O(PM$_{2.5}$)ratio during mid-term courses (accounted for 3.1) was higher than that during the summer vacation (accounted for 0.6). Moreover, the mean I/O(PM$_{2.5}$) ratio was 1.6 at WCLTP. The mean I/O (PM$_{10}$) ratios exceeded 1.0 at the chemistry laboratories and WCLTP. A number of studies indicated that ultrafine particles (< 0.1 μm in diameter) disproportionately induce oxidative stress in cells and are more toxic than larger particles of similar composition (Li et al., 2003; Nel, 2005; Nel et al., 2006). These results indicate the requirement for improving indoor/classroom ventilation to maintain excellent air quality in colleges in the future.

For Type I and Type II, the average ratio of PM$_{2.5}$ and PM$_{10}$ with 76% during a semester in GCL was higher than that during other periods in GCL (including 26% outdoors during a semester, 27% indoors during a summer vacation, and 23% outdoors during a summer vacation). This result suggested that PM$_{2.5}$ is one of the main contaminations affecting indoor quality in chemistry laboratories and WCLTP (as shown in Fig. 3(a)). The major source of PM$_{2.5}$ or fine aerosols is associated with the emission process of teaching and performing experimental courses in chemistry laboratories. Therefore, safety in chemistry laboratories at colleges deserves more attention.

The ratios of PM$_{2.5}$ and PM$_{10}$ ranged from 23.0% to 76.0% in Type I, 59.0% to 77.0% in Type II, 58% to 72% in Type III, and 39% to 69% in Type IV (as shown in Figs. 3(a) and 3(b)). We also investigated the exhausts or vents in the laboratories. Both PM$_{2.5}$ and PM$_{2.5-10}$ were collected using manual dichotomous samplers. In addition, we compared the mass concentrations of PM$_{2.5}$ and PM$_{10}$ or PM$_{2.5-10}$ and PM$_{10}$ (indoor and outdoor) at a school laboratory.

![Fig. 3(a). PM$_{2.5}$/PM$_{10}$ (%) ratios in sampling locations of Type I (GCL) and Type II (WCLTP).](image-url)
The results show that, among the various sampling sites, the lowest mass concentration of 44.5 μg/m³ for PM2.5 was observed at the SRL. The highest mass concentration of 88.0 μg/m³ for PM2.5 was observed at the roof exhaust vent. The PM2.5 mass concentrations were higher than those of PM2.5–10 at all sampling sites. Moreover, the mass concentrations of PM2.5 accounted for over 58% of particulate matters (PM2.5 + PM2.5–10) in all sampling sites. This result shows that fine particulate is the major contributor of particulate matters at all sampling sites.

The highest PM2.5 mass concentration was observed at the roof exhaust vent because air pollutants are emitted from the roof exhaust vent without air pollution controlling devices. Recent epidemiological studies have revealed that exposure to suspended particles, especially the thoracic fraction and finer particles (PM2.5, respirable particles) causes adverse health effects. Compared to the PM2.5 level of 20 μg/m³, the PM2.5 levels in our sampled indoor environments (such as GCL, WCLTP, ERL, and SRL) are considerably high; therefore, more efforts must be made to control fine particulate pollution and improve the indoor air quality in college laboratories. Besides, Fig. 4 also shows the I/O ratios of PMs in Type I, II, III, and IV for overall view.

Comparison of Acid/Base Gas in Laboratory Indoor and Outdoor

Table 6 shows the average concentrations of indoor and outdoor acid and base gases in in GCL. The indoor and outdoor concentrations of the four species measured in GCL followed the order of NH₃ > HNO₂ > SO₂ > HNO₃ (in ppb, Table 6). In GCL, all I/O ratios exceeded 1.0, and ranged from 1.2 to 3.0. This result suggests that there is a correlation between the concentrations of indoor and outdoor acid and base gases resulted from the emission and ventilation by the hoods or fans from the laboratory to the outdoor ambient.

Particle-Bound Water-Soluble Ions in Laboratory Indoor and Laboratory Outdoor

Table 7 shows the mean concentrations of particle-bound water-soluble ions of PM2.5 and PM10 indoors and outdoors for Types I, II, III, and IV. For PM2.5 of Type I, the indoor concentrations of the eight species measured in PM2.5 followed the order of SO₄²⁻ > NO₃⁻ > Cl⁻ > NH₄⁺ > Ca²⁺ > K⁺ > Na⁺ > Mg²⁺. Such trend may imply that both SO₄²⁻ and NO₃⁻ are abundant and highly associated with the activities during the semester period in the chemistry laboratories. Moreover, for PM10, indoor concentrations of these eight species measured in PM10 followed the order of NO₂⁻ > SO₄²⁻ > Cl⁻ > NH₄⁺ > Ca²⁺ > K⁺ > Na⁺ > Mg²⁺. Such trend may imply that both SO₄²⁻ and NO₃⁻ are abundant and highly associated with the activities during the semester period in the chemistry laboratories.
Table 6. The averaged concentrations of acid and base gases in Indoor and Outdoor in Type I: General Chemistry Laboratories (GCL).

| Species (ppb) | HNO₂ | HNO₃ | SO₂ | NH₃ |
|---------------|------|------|-----|-----|
| Indoor        | 1.97 | 0.05 | 0.12| 6.80|
| Outdoor       | 0.66 | 0.04 | 0.09| 5.62|
| I/O           | 3.0  | 1.3  | 1.3 | 1.2 |
| EPA Monitoring Station | -- | -- | 0.08 | -- |

Fig. 5. Correlation between the concentrations of acid and base gases in outdoor and those in indoor.

Fig. 4. I/O ratios of PMs in Type I, II, III, and IV.

of SO₄^{2-} > NO₃^{−} > Na^{+} > Cl^{−} > Ca^{2+} > NH₄^{+} > K^{+} > Mg^{2+}. For PM_{10} of Type I, the outdoor concentrations of the eight species measured in PM_{10} followed the order of NO₃^{−} > SO₄^{2−} > NH₄^{+} > Na^{+} > Cl^{−} > Ca^{2+} > K^{+} > Mg^{2+}. A comparison of the results of indoor PMs with the results of outdoor PMs indicated that both SO₄^{2−} and NO₃^{−} are abundant and highly associated with emissions from laboratories with indoor activities of chemistry courses during the semester period.

For PM_{2.5} of Type II, the indoor concentrations of these species measured in PM_{2.5} followed the order of Na^{+} > Cl^{−} > Ca^{2+} > SO₄^{2−} > NH₄^{+} > K^{+} > Mg^{2+} > NO₃^{−}. For PM_{10} of
Table 7. The mean concentrations of particle-bound water-soluble ions of both PM$_{2.5}$ and PM$_{10}$ in Type I, II, III, and IV.

| Species (μg/m$^3$) | NO$_3^-$ | SO$_4^{2-}$ | Cl$^-$ | NH$_4^+$ | Na$^+$ | K$^+$ | Ca$^{2+}$ | Mg$^{2+}$ |
|-------------------|----------|-------------|-------|----------|--------|-------|-----------|----------|
| **Type I. General Chemistry Laboratories (GCL)** |          |             |       |          |        |       |           |          |
| PM$_{2.5}$ Indoor | 0.94     | 1.14        | 0.75  | 0.53     | 0.13   | 0.15  | 0.20      | 0.06     |
| PM$_{2.5}$ Outdoor| 1.28     | 2.08        | 0.48  | 0.16     | 0.58   | 0.03  | 0.25      | N.D.     |
| I/O              | 0.7      | 0.5         | 1.6   | 3.3      | 0.2    | 5.0   | 0.8       | ---      |
| PM$_{10}$ Indoor | 2.66     | 2.27        | 1.17  | 0.62     | 0.20   | 0.29  | 0.31      | 0.06     |
| PM$_{10}$ Outdoor| 2.82     | 2.24        | 1.07  | 1.74     | 1.10   | 0.29  | 0.34      | 0.06     |
| I/O              | 0.9      | 1.0         | 1.1   | 0.9      | 1.0    | 0.9   | 1.0       |          |
| **Type II. WCLTP** |         |             |       |          |        |       |           |          |
| PM$_{2.5}$ Indoor | N.D.    | 0.37        | 0.54  | 0.26     | 1.01   | 0.15  | 0.39      | 0.09     |
| PM$_{2.5}$ Outdoor| 0.01     | 0.40        | 0.69  | 0.80     | 1.93   | 0.19  | 0.20      | 0.04     |
| I/O              | ---      | 0.9         | 0.8   | 0.3      | 0.5    | 0.8   | 2.0       | 2.3      |
| PM$_{10}$ Indoor | 3.42     | 6.36        | 6.47  | 0.81     | 5.6    | 0.67  | 0.64      | 0.46     |
| PM$_{10}$ Outdoor| 0.87     | 1.62        | 3.12  | 0.87     | 3.09   | 0.34  | 0.36      | 0.13     |
| I/O              | 3.9      | 3.9         | 2.1   | 0.9      | 1.8    | 2.0   | 1.8       | 3.5      |
| **Type III. Environmental Research Laboratories** |         |             |       |          |        |       |           |          |
| PM$_{2.5}$ Indoor | 4.82     | 5.83        | 10.53 | 5.06     | 7.73   | N.D.  | 2.17      | 0.64     |
| PM$_{2.5}$ Outdoor| 11.89    | 15.26       | 4.70  | 19.38    | 5.65   | 2.05  | 2.41      | 0.52     |
| I/O              | 0.4      | 0.4         | 2.2   | 0.3      | 1.4    | ---   | 0.9       | 1.2      |
| PM$_{10}$ Indoor | 16.81    | 19.04       | 11.69 | 24.50    | 11.57  | 3.14  | 4.59      | 1.26     |
| PM$_{10}$ Outdoor| 0.3      | 0.5         | 2.0   | 0.5      | 1.0    | ---   | 0.8       | 0.9      |
| **Type IV. Soil Research Laboratories and Field in college** |         |             |       |          |        |       |           |          |
| PM$_{2.5}$ Indoor | 5.13     | 6.18        | 9.23  | 8.58     | 5.04   | 1.00  | 2.26      | 0.57     |
| PM$_{2.5}$ Outdoor| 5.05     | 11.42       | 10.30 | 10.70    | 11.50  | 1.10  | 2.76      | 1.18     |
| I/O              | 1.0      | 1.0         | 0.9   | 0.8      | 0.4    | 0.9   | 0.8       | 0.5      |
| PM$_{10}$ Indoor | 5.13     | 6.18        | 14.61 | 13.65    | 11.51  | 1.00  | 4.29      | 1.09     |
| PM$_{10}$ Outdoor| 10.33    | 14.03       | 15.79 | 17.59    | 20.72  | 2.40  | 4.93      | 1.93     |
| I/O              | 0.5      | 0.4         | 0.9   | 0.8      | 0.6    | 0.4   | 0.9       | 0.6      |

Type II, the indoor concentrations of these species measured in PM$_{2.5}$ followed the order of Cl$^-$ > SO$_4^{2-}$ > Na$^+$ > NO$_3^-$ > NH$_4^+$ > K$^+$ > Ca$^{2+}$ > Mg$^{2+}$. Moreover, for PM$_{2.5}$ of Type II, the outdoor concentrations of these species measured in PM$_{2.5}$ followed the order of Na$^+$ > NH$_4^+$ > Cl$^-$ > SO$_4^{2-}$ > Ca$^{2+}$ > K$^+$ > Mg$^{2+}$ > NO$_3^-$ > Cl$^-$ > SO$_4^{2-}$ > NO$_3^-$ > Na$^+$ > K$^+$ > Ca$^{2+}$ > Mg$^{2+}$. For PM$_{10}$ of Type II, the outdoor concentrations of these species measured in PM$_{10}$ followed the order of Cl$^-$ > SO$_4^{2-}$ > NO$_3^-$ > Na$^+$ > K$^+$ > Ca$^{2+}$ > Mg$^{2+}$ > NO$_3^-$ > Na$^+$ > K$^+$ > Ca$^{2+}$ > Mg$^{2+}$.

For PM$_{2.5}$ of Type III, the indoor concentrations of these species measured in PM$_{2.5}$ followed the order of Cl$^-$ > SO$_4^{2-}$ > Na$^+$ > NO$_3^-$ > Ca$^{2+}$ > Mg$^{2+}$ > K$^+$. For PM$_{10}$ of Type III, the indoor concentrations of these species measured in PM$_{10}$ followed the order of Cl$^-$ > SO$_4^{2-}$ > NO$_3^-$ > Na$^+$ > K$^+$ > Ca$^{2+}$ > Mg$^{2+}$ > K$^+$. The outdoor concentrations of these species measured in PM$_{2.5}$ followed the order of Cl$^-$ > SO$_4^{2-}$ > NO$_3^-$ > Na$^+$ > K$^+$ > Ca$^{2+}$ > Mg$^{2+}$ > K$^+$. For PM$_{10}$ of Type IV, the indoor concentrations of the eight species measured in PM$_{2.5}$ followed the order of Na$^+$ > NH$_4^+$ > Cl$^-$ > SO$_4^{2-}$ > NO$_3^-$ > Ca$^{2+}$ > K$^+$ > Mg$^{2+}$.

During the sampling period, the mass concentration of Ca$^{2+}$ outdoors was low (0.03 μg/m$^3$), and is related to high-RH (%) weather, high precipitation, and moderate winds. This occurrence may be associated with local and short-distance transport agricultural activities in Pingtung County. During the sampling period, the Mg$^{2+}$ ion was not detected on approximately 25% of sampling days. The species with N.D. was PM$_{2.5}$ outdoors; the species with the lowest concentration were PM$_{2.5}$ indoors (0.06 μg/m$^3$) and PM$_{10}$ indoors and outdoors (0.06 μg/m$^3$). Watson et al. (1998) indicated that the sources of K$^+$ ion concentration were closely related to biomass and garbage burning. This study also suggests that biomass burning may be a possible source because it is a common traditional agriculture activity in Southern Taiwan during summer.

Fig. 6 also presents the I/O ratios of particle-bound water-soluble ions in Type I, II, III, and IV. The trend in Fig. 6 indicates most I/O ratios of particle-bound water-soluble ions in Type I and IV had I/O ratios lower than 1.0 in this study.
Fig. 6. I/O ratios of particle-bound water-soluble ions in Type I, II, III, and IV.

Regarding the WCLTP, most indoor WSIs concentrations of PM$_{2.5}$ aerosols had I/O ratios higher than one (accounting for K$^+$, NH$_4^+$, and Cl$^-$). Furthermore, most indoor ionic concentrations of PM$_{10}$ aerosols had I/O ratios higher than 1.0 (accounting for Cl$^-$). K$^+$, SO$_4^{2-}$ and Mg$^{2+}$ had I/O ratios equal to 1. However, for PM$_{2.5}$ and PM$_{10}$ in Type IV, all I/O ratios were below 1.0 (except for NO$_3^-$ in PM$_{2.5}$). Compared to the I/O ratio levels in Types I and II, the effect of indoor chemistry/experimental activities on both fine particles and small size aerosols was minor in Type IV.

CONCLUSIONS

The characteristics of indoor and outdoor PM$_{2.5}$, PM$_{10}$, and associated water-soluble ions were evaluated in the four types of laboratories (namely, Type I, II, III, and IV) indoor and outdoor on NPUST campus in Taiwan. The results of Type I and II revealed that the mean PM$_{2.5}$ concentrations indoors in GCL (during a semester) and WCLTP (during a summer vacation) exceeded the air quality guidelines of the World Health Organization (WHO) of 20 $\mu$g/m$^3$ for PM$_{2.5}$. Results also show that the indoor concentrations of PM$_{2.5}$ and PM$_{10}$ in GCL increased by 4.9 and 1.7 times, respectively, during a semester period as compared to the indoor measured data during a summer vacation. It should be noted that the students’ laboratorial activities in colleges deserves more attention because these activities cause significant increase in the PM emissions.

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