Air quality investigation and research for various types of student-oriented indoor environments on a university campus

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Abstract. This study investigated suspended particles (PM2.5 and PM10), formaldehyde, TVOC, ozone, carbon dioxide, and carbon monoxide in seven student-oriented indoor environments, which are inclusive of the library study room (A), computer classroom (B), teacher and student compound office (C), classroom-1 (D), classroom-2 (E), student cafeteria (F), and underground motorcycle parking lot (G) on a university campus. We monitored each indoor environment during the open hours for at least three weekdays. The averaged concentrations of CO2 in environments A, B, C, and D all exceeded the standard (1000 ppm) with values of 2,628±375, 1,908±613, 1,752±495, and 1,076±280 ppm. The corresponding minimum and maximum CO2 concentrations were 1,101 and 3,314, 836 and 3,272, 672 and 2,667, and 752 and 2,040 ppm, respectively. Sites A, B, C, D, F, and G are the environments where the concentrations of TVOC exceeded the standard (560 ppb) with the averaged values of 829±21, 920±192, 582±8, 607±15, 640±102 and 815±205 ppb, respectively. Both concentrations of PM2.5 and PM10 in site F exceeded the standards (i.e., 35 μg/m3 and 75 μg/m3) with averaged values of 39±13 μg/m3 and 103±51 μg/m3, respectively. Three target compounds, CO, O3, and HCHO, were below their respective standards.

1 Introduction

People spend about 90% of their time indoors. The indoor air quality may affect work/study performance and occupants’ health. There are 149 colleges and universities in Taiwan, with a total of about 1.26 million faculties, staff, and students [1]. There are many possible sources of air pollution on campus, such as CO2 produced by various activities; PM2.5 and PM10 caused by cleaning activities and construction dust; VOCs emitted by multiple activities, equipment, and furniture [2]; NOx, CO, CO2, VOCs emitted by automobiles and cooking activities [3]; Ozone (O3) from outdoor penetration, laser printers, ozone air purifiers [4]; VOCs, formaldehyde, suspended particles, other harmful air pollutants and wastes produced by various experiments.

Many university staff and students spend a long time at schools, mainly in indoor environments, so the chance of exposure to indoor air pollutants has increased significantly. This study focuses on the investigations of suspended particulates (PM2.5 and PM10), formaldehyde (HCHO), ozone (O3), total volatile organic compounds (TVOCs), carbon monoxide (CO), and Carbon dioxide (CO2). The study results can be further used as a reference for the exposure assessment of university staff and students. In addition, it can be used as a reference for indoor space planning for schools to reduce exposure to related air pollutants and improve the health of staff and students.

2 Experimental method

2.1 Sampling environment

This study uses a comprehensive national university in south Taiwan as the research site to investigate and study the air quality of different indoor environments on a university campus. These sites include: library self-study room (A), computer classroom (B), teachers and students compound office (C), classroom-1 (D), classroom-2 (E), student cafeteria (F), and underground motorcycle parking lot (G), the selected sites are the places where students usually visit and stay for a certain amount of time on campus.

2.2 Air pollutants

The investigated air pollutants include particulates (PM2.5 and PM10), formaldehyde (HCHO), ozone (O3), total volatile organic compounds (TVOC), carbon monoxide (CO), and carbon dioxide (CO2).

2.3 Sampling instrument

All sampling instruments for our study are listed in Table 1.
### Table 1. Sampling instrument

<table>
<thead>
<tr>
<th>Air pollutants</th>
<th>Sampling instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2.5 and PM10</td>
<td>Handheld 3016-IAQ</td>
</tr>
<tr>
<td>HCHO</td>
<td>Formaldemeter™ htv-M</td>
</tr>
<tr>
<td>O₃</td>
<td>Model 202 Ozone Monitor™</td>
</tr>
<tr>
<td>TVOC</td>
<td>ppbRAE 3000 VOC Monitor</td>
</tr>
<tr>
<td>CO and CO₂</td>
<td>TSI Q-TRAK™ Indoor Air Quality Monitor 7575 (with 982 IAQ Probe)</td>
</tr>
</tbody>
</table>

### Table 3. Sampling plan.

<table>
<thead>
<tr>
<th></th>
<th>PM2.5 and PM10</th>
<th>O₃</th>
<th>CO</th>
<th>CO₂</th>
<th>TVOC</th>
<th>HCHO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling period</td>
<td>Three days on weekdays and one day during the weekends when necessary.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampling time</td>
<td>twenty-four hours</td>
<td>Adjust according to the opening hours of the tested sites</td>
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<tr>
<td>Sampling interval</td>
<td>Record an average every five minutes</td>
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<tr>
<td>Sampling height</td>
<td>1.2 meters from the ground (sitting position) or 1.5 meters from the floor (standing position)</td>
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</tbody>
</table>

### 2.4 Sampling plan

Indoor Air quality was monitored for three weekdays in various indoor environments on a university campus. When indoor environments open during the weekends, additional monitoring was carried out for at least one open day during the weekends.

Since most of Taiwan's indoor air quality standards, as shown in Table 2 [5], are eight-hour averages, the indoor environment monitoring plan will monitor the site for at least eight hours continuously, and the actual measurement time will be adjusted according to the opening hours of each site. The monitoring time of suspended particles (PM2.5 and PM10) lasted 24 hours.

The sampling height is adjusted according to the students' most commonly used breathing height in the sampling site. If the person mainly stands, the sampling height was set to 1.5 meters; if the person primarily sits, the sampling height was set to 1.2 meters.

Air pollutant monitoring is to record an average value every five minutes and record relevant factors that may affect the concentration of air pollutants on sites, such as temperature, relative humidity, number of people, air conditioner (AC) usage, door, and window opening, closing conditions or the floor, etc. The sampling plan is shown in Table 3.

### Table 2. Taiwan indoor air quality standards

<table>
<thead>
<tr>
<th>Air pollutant</th>
<th>Indoor air quality standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1000 ppm (8-h average)</td>
</tr>
<tr>
<td>CO</td>
<td>9 ppm (8-h average)</td>
</tr>
<tr>
<td>HCHO</td>
<td>0.08 ppm (1-h average)</td>
</tr>
<tr>
<td>TVOCs</td>
<td>0.56 ppm (1-h average)</td>
</tr>
<tr>
<td>PM10</td>
<td>75 μg/m³ (24-h average)</td>
</tr>
<tr>
<td>PM2.5</td>
<td>35 μg/m³ (24-h average)</td>
</tr>
<tr>
<td>O₃</td>
<td>0.06 ppm (8-h average)</td>
</tr>
</tbody>
</table>

### 3 Results and discussion

Figures 1 to 4 are comparison charts of the concentrations of seven indoor air index pollutants in student-oriented indoor environments on a university campus. The values above each bar in the figures are mean± standard deviation; these values were chosen based on the period the maximum number of people stayed in each site and the respective standard for each air pollutant. The values in brackets are maximum value ~minimum value during the monitoring period without considering other factors; ND means not detected (or below the instrument’s detection limit).

#### 3.1 CO₂ concentration

Among all indoor environments, the average concentration of CO₂ in site A was the highest, at 2,628±375 ppm with a maximum value of 3,314 ppm; the average concentration of CO₂ in site B was lower than that in A, at 1,908±613 ppm with a maximum of 3,272 ppm similar to site A. Both sites A and B were closed spaces, with no windows to open, separated air conditioners operated all day long, and students mainly stayed in the locations for class and self-study. Usually, students’ stay time in the above two sites is more than two hours. In site B, the maximum number of students recorded was 55 during the class. Most of the time, more than 30 students were indoors in site A. The average CO₂ concentration in site C was 1,752±495 ppm with a maximum value of 2,667 ppm. A faculty and her graduate students shared this office, and the air conditioner was generally turned on; the air exchange only relied on one wall with three small windows, and the office door was closed most of the time; hence, CO₂ was quickly accumulated indoors. D and E are both classrooms for classes. Site D is a more extensive classroom that can accommodate 70 students. Site E is relatively small that can accommodate 30 students. The maximum CO₂ concentration at site D was 2,040 ppm, with an average CO₂ value of 1,076±280 ppm. The maximum value of CO₂ at site E was 1,346 ppm, and the average CO₂ value was 945±137 ppm. The air conditioner was usually turned on during class for both sites, and the doors and windows were generally closed.
when AC was turned on. Hence, indoor CO$_2$ quickly accumulated. When around 50 to 60 students were in class at site D, the CO$_2$ concentration rose significantly. Usually, at site E, the doors and windows were closed and locked after the course. Therefore, site E was less ventilated than site D after the classes. The CO$_2$ concentration at site E decreased relatively slowly after class. The maximum CO$_2$ concentration of site F was 1,250 ppm, with an average CO$_2$ concentration of 857±118 ppm. At site F, the crowds usually showed up
during dining time, the air conditioner was turned on during opening hours, and the doors and windows were closed. Therefore, the CO₂ concentration increased significantly during dining time. The average CO₂ concentration of site G was 557±12 ppm, and the maximum was 624 ppm. Although site G was underground, the ventilation was better than other sites because five entrances/exits were all open, and as a result, less CO₂ accumulated. Comparing the measured average CO₂ concentration with Taiwan's current indoor air quality standards, there were sites A, B, C, and D where the CO₂ concentration exceeded the standard (i.e., 1,000 ppm, 8-hour average).

3.2 TVOC concentration

The average concentration of TVOC in site A was 829±21 ppb, and the maximum value was 898 ppb. The average concentration of TVOC in site C was 582±8 ppb, and the maximum value was 706 ppb. The average TVOC concentration in site D was 607±15 ppb, with a maximum value of 621 ppb. It is speculated that the sources of TVOC in these three sites were the emissions from people themselves and personal products (such as sweat, cosmetics, alcohol for disinfection, laundry detergent residuals on clothes, computers, etc.), furniture (tables and chairs, bookcases, etc.), and cleaning activities. The average TVOC concentration in site B was 920±192 ppb, and the maximum value was 2,526 ppb, the highest TVOC concentration among all indoor environments monitored. The TVOC concentration outside site B was more than 10,000 ppb when the maximum TVOC value in site B was observed; it is speculated that VOCs emissions from the cleaning activities and bleach used back then outside site B (upwind location) caused the peak TVOC concentration indoors (downwind location). The average TVOC concentration of F was 640±102 ppb, and the maximum value was 979 ppb. It is speculated that indoor TVOC was mainly the emissions from cleaning and cooking activities. The TVOC concentration of G reached a maximum value of 1563 ppb during the monitoring period, with an average value of 815±205 ppb. It is speculated that the primary source was the exhaust gas emitted by motor vehicles. The peak traffic hours in site G were usually before and after the classes (i.e., students showed up for class and were dismissed). The minimum TVOC concentration was 182 ppb when no motorcycles were idled or on the move, and the maximum TVOC concentration was 1563 ppb during peak traffic hours. Comparing the measured average TVOC concentration with Taiwan's current indoor air quality standards, there were sites A, B, C, D, F, and G where the TVOC concentration exceeded the standard (i.e., 560 ppb, 1-h average).

3.3 PM2.5 and PM10 concentration

The average concentration of PM2.5 in site A was 10±4 μg/m³, with a maximum value of 36 μg/m³, and the average concentration of PM10 in site A was 18±7 μg/m³, with a maximum value of 44 μg/m³. The average concentration of PM2.5 in site B was 6.5±3 μg/m³, with a maximum value of 18 μg/m³, and the average concentration of PM10 in site B was 15±6 μg/m³, with a maximum value of 47 μg/m³. Since the above two sites were regularly cleaned based on a fixed schedule every day, the concentrations of PM2.5 and PM10 observed were relatively lower, indicating fewer particles in the sites. The average concentration of PM2.5 in site C was 3±2 μg/m³, with a maximum value of 15 μg/m³, and the average concentration of PM10 in site C was 26±25 μg/m³, with a maximum value of 151 μg/m³. The increase in PM10 concentration was presumed due to the frequent personnel movement near our monitoring instruments, and PM10 concentration dropped rapidly when nobody was in site C. The average concentration of PM2.5 in site D was 16±8 μg/m³, with a maximum value of 63 μg/m³, and the average concentration of PM10 in site D was 48±24 μg/m³, with a maximum value of 487 μg/m³. When an electronic blackboard eraser was used, the maximum PM2.5 and PM10 were observed. Right before the event, the observed PM10 concentration was 56 μg/m³. After the electronic blackboard eraser event, the PM10 concentrations started to drop rapidly. PM10 concentrations of 177, 155, 85, and 62 μg/m³ were observed 5, 10, 15, and 20 minutes after the event. The average concentration of...
PM2.5 in site E was 26±12 μg/m³, with a maximum value of 119 μg/m³, and the average concentration of PM10 in site E was 45±34 μg/m³, with a maximum value of 244 μg/m³. The maximum PM2.5 and PM10 values in site E were observed during a class when the opposite door and windows opened to ensure enough ventilation. It is speculated that the undergoing construction upwind back then and poor atmosphere air quality caused the peak concentrations. The concentrations of PM2.5 and PM10 in the above two sites increased during classes (i.e., when more students presented). It is speculated that the possible source is the particle resuspension caused by indoor people walking by or outdoor PM2.5 and PM10 entering the room through air exchange [6-7]. Among all observed indoor environments, site F had the highest concentration of PM2.5 and PM10. The mean values of PM2.5 and PM10 in site F were 39±13 and 103±52 μg/m³, respectively. When there was nobody in site F, the PM2.5 and PM10 concentrations were 14 and 22 μg/m³, respectively. The PM2.5 and PM10 concentrations were 92 and 339 μg/m³ (an increase of 557% and 1441%), respectively, while cleaning activities in site F were undergoing [8]. The average concentration of PM2.5 in site G was 7±1 μg/m³, with a maximum PM2.5 value of 17 μg/m³, and the average concentration of PM10 in site G was 62±20 μg/m³, with a maximum value of 164 μg/m³. Dust resuspension by the motorcycles’ movement around and related exhaust gas may be the major cause of the phenomenon [9]. Comparing the measured average concentrations of PM2.5 and PM10 with Taiwan’s current indoor air quality standards, F is the only site where both the concentrations of PM2.5 and PM10 exceed the standards (i.e., 35 and 75 μg/m³, 24-h average).

### 3.4 O₃ concentration

The average concentration of O₃ in site A was 4.4±1 ppb, and the maximum value was 9.3 ppb. The average concentration of O₃ in site B was 2±2 ppb, and the maximum value was 7.5 ppb. The average concentration of O₃ in site C was 3±2 ppb, and the maximum was 22 ppb. The average concentration of O₃ in site D was 22±4 ppb, and the maximum value was 31 ppb. The average concentration of O₃ in site E was 21±21 ppb, and the maximum concentration was 94 ppb. The average concentration of O₃ in site F was 21±9 ppb, and the maximum value was 119 μg/m³. The maximum PM2.5 and PM10 concentrations were 13±4 ppb, and the maximum value was 24 ppb. Since there was no obvious indoor O₃ source in these sites, it is speculated that indoor ozone mainly came from outdoors, so the indoor O₃ concentration was highly related to outdoor O₃ concentration and ventilation conditions [10] and verified by comparing the outdoor ozone concentrations back then. Usually, doors and windows in sites A, B, and C were shut, resulting in lower air exchange rates with the outdoor air and lower O₃ concentration indoors. As for sites D and E, the status of opening the doors and windows or not highly depended on the instructors and students in the class. The maximum O₃ concentration of site E was observed when the opposite door and windows opened to enhance the air exchange. The outdoor O₃ concentration was recorded at 98 ppb in a nearby government air quality monitoring station. Usually, doors and windows in site F were opened for a few hours in the morning, and doors and windows were closed, and AC was on at around eleven o’clock (i.e., the time to start to provide the lunch). The increased indoor O₃ concentration in site F was mainly caused by the outdoor O₃ penetration into site F through opening doors when walking in or out of site F. All five entrances/exits in G were open during our monitoring; however, due to the outdoor O₃ concentration at that time being relatively low at around 20-30 ppb, the indoor O₃ concentration observed was around 10-20 ppb [11]. Compared with the current indoor air quality standard in Taiwan, Ozone concentrations for each tested indoor environment meets the standard (i.e., 60 ppb, 8-h average).

### 3.5 HCHO concentration

The average concentration of HCHO in site A was 64±4 ppb, and the maximum HCHO value was 99 ppb. It is speculated that the primary source was mainly indoor wooden tables and chairs emissions [12]. In addition, monitoring was performed during the epidemic of COVID-19, disinfectant was used regularly, and the air exchange in site A was insufficient. Hence, HCHO was easy to accumulate indoors. The average concentration of HCHO in site B was 26±1 ppb, and the maximum HCHO value was 40 ppb. Since site B is a confined and enclosed space, the indoor HCHO concentration did not vary significantly. It is speculated that the source of HCHO was mainly the emissions of indoor building materials or supplies. The average concentration of HCHO in site C was 27±0.5 ppb with a maximum value of 53 ppb. The sizes of doors and windows in site C are relatively small, and they were all on the same side, so the air exchange is poor, and the concentration of HCHO did not vary a lot. It is speculated that the source of HCHO was mainly the emissions of indoor building materials, supplies, and some wooden products onsite [13]. The average concentration of HCHO in site D was 12±1 ppb, and the maximum value was 21 ppb. It is the lowest concentration of HCHO observed in all indoor environments. The concentration of HCHO at site E was 30 ± 10 ppb with a maximum value of 64 ppb. It is speculated that the possible source was mainly indoor building materials, whiteboard markers, personal supplies, and alcohol used for disinfection by teachers and students. The average concentration of HCHO in site F was 20 ± 8 ppb, with a maximum value of 144 ppb, the highest among all tested indoor environments. The maximum HCHO was observed when the janitor prepared the diluted bleach to mop the floor. It is speculated that the HCHO from bleach caused the peak concentration. In addition, other possible HCHO sources were the emissions of indoor building materials, supplies, and HCHO produced during cooking. The average concentration of HCHO in site G was 30±6 ppb, with a maximum value of 91 ppb. It is speculated that the primary source is exhaust gas emitted by motorcycles. Comparing the measured average
concentration of HCHO with the current indoor air quality standard in Taiwan, all indoor environments meet the standard (80 ppb).

3.6 CO concentration

The average concentration of CO in site A was 0.12 ± 0.04 ppm, with a maximum value of 0.3 ppm. The average concentration of CO in site B was 0.004±0.02 ppm, with a maximum value of 0.1 ppm. The average concentration of CO in site C was 0.03 ± 0.04 ppm, with a maximum value of 0.1 ppm. The average concentration of CO in site D was 0.1 ± 0.03 ppm, with a maximum value of 0.2 ppm. The CO concentration in site E was below the detection limit. The average concentration of CO in site G was 1.3 ± 1.4 ppm, with a maximum of 5.6 ppm. It is speculated that the primary CO source was the exhaust gas emitted by motorcycles. The average concentration of CO in site F was 0.15 ± 0.07 ppm, with a maximum value of 0.5 ppm. It is speculated that the primary emission of CO is produced during the cooking process. Compared with Taiwan’s current indoor air quality standard, the average CO concentration for each tested indoor environment meets the standard (i.e., 9 ppm, 8-h average).

4 Conclusion

The CO₂ concentrations in sites A, B, C, D, E, and F exceeded the indoor air quality standard (i.e., 1000 ppm, 8-h average). The CO₂ concentration was highly related to the number of people and ventilation. During our monitoring period, the air conditioners in most indoor environments were turned on, and windows were closed. Therefore, CO₂ was accumulated indoors.

The concentrations of TVOC in sites A, B, C, D, F, and G all exceeded the standard (i.e., 0.56 ppm, 1-h average). The concentration of TVOC was related to the emissions from indoor personnel and various indoor objects. In addition, site F and site G have other pollution sources, such as cooking fume and exhaust gas emitted by motorcycles.

The peak concentrations of PM2.5 in sites D, E, and F all exceeded the indoor air quality standard (i.e., 35 μg/m³, 24-h average). The peak concentrations of PM10 in sites D, E, F, and G all exceeded the indoor air quality (i.e., 75 μg/m³, 24-h average). The concentrations of PM2.5 and PM10 were related to various human activities observed, including dust generation or resuspension caused by personnel activities, fans, and air conditioners, exhaust gas from motorcycles, and particulate matter from cooking activities.

CO, HCHO, and O₃ concentrations measured in all tested sites meet respective standards (i.e., the 8-h average for CO, the 1-h average for HCHO, and the 8-h average for O₃). It is speculated that there were only a few sources of the above indoor pollutants in our tested indoor environments, so their respective concentrations were relatively low. However, caution is still advised due to their adverse health effects. The study results showed that our target air pollutants in some indoor environments on a university campus exceeded their respective indoor air quality standards. The ventilation in these indoor environments was generally insufficient (i.e., CO₂ concentration exceeded the standard), which caused air pollutants to accumulate indoors. Due to the prevalence of COVID-19 in recent years, the above situation will increase the risk of infection. Increasing the amount and frequency of ventilation is recommended to improve indoor air quality on a university campus.

References

5. Taiwan Environmental Protection Administration, Indoor Air Quality Standards (2012)