Investigation of Indoor Air Quality in six office buildings in Chengdu, China based on continuous monitoring data

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Abstract. Indoor air pollution is of a growing concern in China. The nation’s growing urban work force spends prolonged periods in office, thus office indoor air quality (IAQ) can be a key determinant of worker’s wellbeing, yet, IAQ literature on China’s office space remains scarce. To address such knowledge gap, this study conducted continuous monitoring in six office towers in Chengdu, China to investigate two major indoor pollutants: PM$_{2.5}$ and CO$_2$. The participating office buildings were Grade-A certified and fully occupied. Indoor concentration for PM$_{2.5}$ and CO$_2$ ranged between 1-459 μg/m$^3$ and 375-1102 ppm respectively, with considerable intra-building and inter-building variability. Time-series analysis suggests diurnal and weekly pattern for indoor CO$_2$, and temporal association between indoor and ambient PM$_{2.5}$. Filtration and ventilation efficiencies varied across buildings, and these buildings experienced various degrees of penetration by outdoor PM$_{2.5}$ and indoor accumulation of CO$_2$ on a daily basis. On days with ambient pollution, indoor pollution persisted. Multivariate model predicts an average of 0.6 μg/m$^3$ increase in indoor PM$_{2.5}$ for every 1 μg/m$^3$ increase in ambient PM$_{2.5}$. To our knowledge, this is the first systematic study of office buildings in China with findings potentially inform future IAQ management strategies.

1. Introduction
Indoor air quality (IAQ), as defined by major indoor pollutants such as particulate matter with diameter less than 2.5 micron (PM$_{2.5}$) and carbon dioxide (CO$_2$), plays a key role in shaping health [1-3]. Indoor PM$_{2.5}$ has both outdoor and indoor sources [4-5]. PM$_{2.5}$ exposure is linked to adverse health effects [6-10], and the growing awareness of negative health implications of PM$_{2.5}$ has motivated outdoor emission control and the mitigation of indoor concentration [11-12]. CO$_2$ plays a role in IAQ as discovered by past studies on Sick Building Syndrome (SBS): high CO$_2$ concentration is a risk factor for occupant health and can reduce workers’ productivity [13-15]. Despite their importance in IAQ and effects on human health, limited information is available about PM$_{2.5}$ and CO$_2$ in Chinese office space.

China has a growing urban workforce spending prolonged periods of time inside office buildings. There is a growing interest in understanding major indoor pollutants, namely PM$_{2.5}$ and CO$_2$, in office, and office building’s effectiveness in protecting office workers from outdoor pollution. There is recent effort in China to understand IAQ of large urban structures, such as department stores, however, to date there is no reported systematic study on such in office buildings. Additionally, past office studies mostly relied on daily averages and didn’t analyze pollutants’ hourly variation during work time [27-28].

Given the significant impact office IAQ potentially has on office workers, this study conducted a systematic survey of office buildings in southwest China. This six-building study is a pilot effort to understand office IAQ, as represented by PM$_{2.5}$ and CO$_2$, in China.
2. Methods
Chengdu, capital city of Sichuan Province, was selected because it has a fast-growing urban workforce and is understudied for its indoor air quality. Building selection criteria include: Grade A classification, currently occupied, located in metropolitan Chengdu, constructed within the last five years, and have not gone through major renovation in last 12 months. Ten buildings enrolled and six followed through the monitoring session. All building management offices consented to the study and provided building information (Table 1). Each building had at least two participating floors. The monitoring campaign was conducted over a four-week period in autumn. DST PM$_{2.5}$/$\text{CO}_2$ monitor (PureLiving Environmental Solutions (Shanghai), Ltd) was deployed to floor center; data were logged wirelessly every five minutes. Each monitor was installed one meter above floor to represent the typical breathing zone of an office worker. Monitor calibration was performed prior, during and after deployment by manufacturer. Concurrent outdoor PM$_{2.5}$ data were obtained through data published by China Environmental Monitoring Center. Data analysis was conducted in R language.

Concurrent indoor and outdoor pollution data were matched based on shortest distance between coordinates. Building filtration efficiency and air exchange rate were calculated based on Ren et al.

| Building | City | Area | Building Height (m) | Floors | Ceiling Height (m) | Floor Area (m$^2$) | Average Occupant Density (person/m$^2$) | Sampling Period |
|----------|------|------|---------------------|--------|-------------------|--------------------|----------------------------------------|-----------------|
| B        | East | 95   | 22                  | 3.0    | 1500              | 0.17               | 10/26-11/23/2016                       |
| H        | North| 212  | 43                  | 2.8    | 1713              | 0.14               | 10/26-11/23/2016                       |
| I        | Center | 248  | 50                  | 3.0    | 3651              | NA**               | 10/26-11/23/2016                       |
| J        | South | 163  | 40                  | 2.8    | 1800              | 0.14               | 10/26-11/23/2016                       |
| P        | South | 130  | 31                  | 2.0    | 1333              | 0.17               | 10/26-11/23/2016                       |
| R*       | South | 123  | 29                  | 2.7    | 2717              | 0.14(0.05*)        | 10/26-11/23/2016                       |

*Half of floor 7 of Building R is building sales showroom. **Not provided by building management.

3. Results
3.1 Building Characteristics
Study buildings were located in different areas of Chengdu, with an average building height of 188.2 m, average floor area of 2119 m$^2$, and average floor height of 2.65 m after furnishing (Table 1). Selected floors all had central HVAC system, double-pane windows that can be opened manually, and open floor layout with installed cubicles as work stations.

3.2 Indoor PM$_{2.5}$
There was considerable intra-building variability in indoor PM$_{2.5}$ concentration (Table 2), except for Building I, from which measurements were obtained from two adjacent floors. Highest indoor PM$_{2.5}$ concentration (459 $\mu$g/m$^3$ from Building B) approximates that of the outdoor (I/O: 0.97). Indoor PM$_{2.5}$ concentration is significantly different between work hours (8:00 am-6:00 pm) and non-work hours (6:00 pm-8:00 am next day) for buildings I, P, and R ($p <0.05$); it is also significantly different between workdays and weekends for buildings B, I, P, and R ($p <0.05$). For all buildings, indoor PM$_{2.5}$ concentrations followed that of the outdoor (Figure 1).

Time-series cross-correlation analysis indicates positive correlation between indoor and outdoor PM$_{2.5}$, with greatest correlation value occurring at lag one, suggesting immediate temporal association. Building-specific analysis shows diurnal and weekly pattern from indoor PM$_{2.5}$ hourly concentration: increase during non-work hours followed by decrease during work hours, while weekend concentration is significantly higher than weekdays ($p < 0.05$).
Table 2. Summary statistics of indoor PM$_{2.5}$ and indoor CO$_2$.

| Building | Floor | Indoor PM$_{2.5}$ (μg/m$^3$) | Indoor CO$_2$ (ppm) |
|----------|-------|-------------------------------|---------------------|
|          | Mean (Min, Max) | Inter-floor Difference ($p$) | Mean I/O Ratio | Mean (Min, Max) | Inter-floor Difference ($p$) |
| B        | 4     | 86 (2, 327) | <0.001 | 0.56 | 472 (397, 908) | <0.001 |
|          | 22    | 97 (6, 459) |          | 0.97 | 470 (396, 634) |          |
| H*       | 8     | 71 (5, 178) | <0.001 | 0.85 | 572 (395, 1090) | <0.001 |
|          | 25    | 48 (4, 261) |          | 0.56 | 541 (378, 1081) |          |
|          | 35    | 35 (4, 149) |          | 0.42 | 533 (384, 761) |          |
| I        | 8     | 50 (1, 227) | 0.085  | 0.62 | 543 (391, 779) | <0.001 |
|          | 9     | 45 (0, 186) |          | 0.52 | 514 (382, 708) | <0.001 |
| J        | 2     | 62 (4, 188) | <0.001 | 0.56 | 470 (378, 1102) | <0.001 |
|          | 36    | 97 (6, 334) |          | 0.88 | 512 (386, 1002) |          |
| P        | 10    | 53 (3, 263) | 0.137  | 0.57 | 525 (385, 856) | <0.001 |
|          | 24    | 44 (1, 175) |          | 0.51 | 501 (375, 1026) |          |
| R        | 7     | 36 (1, 238) | <0.001 | 0.38 | 462 (383, 641) | 0.168 |
|          | 18    | 39 (1, 276) |          | 0.40 | 495 (396, 757) |          |

*Data from Building H floor 25 and 35 were combined for analysis.

Figure 1. Hourly PM$_{2.5}$ (μg/m$^3$) for each floor in six building with concurrent ambient PM$_{2.5}$ concentration (blue).

Because China’s National Standard for Indoor Air Quality (GBT18883-2002) has not set reference for indoor PM$_{2.5}$, ambient air quality standard (GB 3095-2012) was used as a reference for threshold analysis (between 75 μg/m$^3$ and 150 μg/m$^3$ for mild pollution, above 150 μg/m$^3$ for heavy pollution) [24-25]. The amount of time indoor PM$_{2.5}$ is above mild and heavy pollution levels is assessed in relation to outdoor pollution level. During sampling period, Chengdu experienced 14 days of mild pollution, during which all buildings experienced elevated indoor PM$_{2.5}$ concentration (Figure 2).
3.3 Indoor Carbon Dioxide

Indoor CO$_2$ concentration exhibited intra-building variability, except for Building R (Table 2). Highest CO$_2$ concentration was 1102 ppm (Building J), while the lowest was 375 ppm (Building P). Time-series analysis of hourly indoor CO$_2$ concentration for each floor indicates diurnal variation, where indoor CO$_2$ concentration is significantly higher during work hours ($p <0.05$) and during weekdays ($p <0.05$). A detailed examination of hourly indoor CO$_2$ variation suggests that concentration remained stable during non-work hours, and concentration increases starting between 8:00 am and 11:00 am, peaks between 1:00 pm and 2:00 pm, and decreases to non-work hour level around 8:00 pm. On weekends (10/29 and 10/30, 11/05 and 11/06, 11/12 and 11/13), indoor CO$_2$ concentration remained stable throughout the day. All buildings reported indoor CO$_2$ concentration
exceeding 550 ppm (40 cfm per person); four buildings reported concentration above 945 ppm (20 cfm per person). During sampling period, all floors experienced a portion of the day with elevated indoor CO₂ (Figure 3, left panel). On days with mild ambient pollution (ambient 24-hour average PM₂.₅ above 75 μg/m³), indoor CO₂ was above 550 ppm for predominate portion of the day for most floors (Figure 3, right panel).

### 3.4 Linear Modelling of Indoor PM₂.₅ Concentration

Indoor and outdoor PM₂.₅ concentrations are positively correlated. Among studied buildings, indoor PM₂.₅ concentration in Building B showed strongest correlation with outdoor (R² =0.72) while Building I showed the weakest (R² =0.25). Multivariate linear modelling shows that indoor PM₂.₅ concentration was significantly different between buildings (data not shown). Moreover, every 1μg/m³ increase in outdoor PM₂.₅ is associated with 0.604 μg/m³ increase in indoor PM₂.₅ (p <0.0001).

There is significant day-time variation in PM₂.₅ concentration (Table 3). Indoor PM₂.₅ concentration was significantly lower during work time (compared to non-work time) in Building I, Building P and R. Only Building P observed significant reduction in indoor PM₂.₅ during weekdays (compared to weekend). The adjusted I/O ratio was 1.18 in Building B, indicating the ineffective filtration performance. Other buildings’ filtration systems reduced outdoor PM₂.₅ infiltration at various levels (I/O: 0.405-0.852).

**Table 3. Summary of building-specific fixed effect estimates for indoor PM₂.₅ concentration.**

| Building Code | Work Time | Weekday | Outdoor PM₂.₅ | R² |
|---------------|-----------|---------|---------------|----|
| B             | 5         | -4      | 1.18**        | 0.88 |
| H             | 0         | 1       | 0.44**        | 0.61 |
| I             | -44**     | 1       | 0.41**        | 0.48 |
| J             | 0         | 2       | 0.85**        | 0.74 |
| P             | -16*      | -27*    | 0.48**        | 0.57 |
| R             | -19*      | 0       | 0.45**        | 0.66 |

*p<0.05  **p<0.001

### 4. Discussion

#### 4.1 Limited Protection of Chengdu Office Buildings against Outdoor PM₂.₅ Pollution

The six office buildings studied in Chengdu are each unique in their own way, yet they represent an urban environment that dominates the lives of office workers. Indoor PM₂.₅ concentration measured in this study falls within the range reported by earlier studies [22,23]. Indoor-outdoor PM₂.₅ concentrations are positively correlated, and indoor concentration lags shortly behind that of the outdoor, suggesting immediate temporal association. High penetration rate of outdoor PM₂.₅, a reflection of limited filtration capacity, further suggests that theses office buildings do not effectively protect indoor environment from outdoor pollution. What is more concerning is that in the presence of ambient pollution (outdoor PM₂.₅ above 75 μg/m³) buildings experienced prolonged periods of elevated indoor PM₂.₅ concentration.

All six studied buildings had filtration system, although filtration efficiency varied across buildings, on average these buildings experienced estimated 40% reduction of outdoor PM₂.₅ concentration. On a daily basis, the relationship between indoor and outdoor PM₂.₅ is complicated: indoor PM₂.₅ concentration is higher during non-work hours, suggesting that there is penetration from outdoor while the filtration system is off. Conversely, reduction in indoor PM₂.₅ during work hour suggests that building filtration system is turned on.

Building protection against PM₂.₅ is further reduced on days with elevated outdoor pollution. This study observed prolonged periods of elevated PM₂.₅ concentration on days with ambient pollution. While there is no consensus on standard for indoor PM₂.₅ level based on China’s GBT18883-2002, studied office indoor PM₂.₅ frequently exceeded the pollution threshold using ambient GB 3095-2012 as reference,
4.2 Carbon Dioxide as Indoor Pollutant

CO₂ poses a particular concern for the studied buildings. Indoor CO₂ concentration reported in this study is comparable to that of existing literature [14-15]. There was considerable within-building variability of CO₂ concentration, which suggests the lack of internal mixing. All studied buildings experienced indoor CO₂ above global background [29]. During weekdays, indoor CO₂ concentration gradually increased during work hour, a likely result of human contribution combined with low (or ineffective) ventilation [25]. Reported indoor CO₂ concentration was frequently above 550 ppm, 945 ppm and 1400 ppm—levels where previous studies have reported discomfort, 15% and 50% cognitive impairment respectively [14-15]. Moreover, in the presence of ambient pollution, studied buildings experienced greater portion of the day above 550 ppm and 1400 ppm, a possible result of reduced natural ventilation by closing windows.

4.3 Limitations

Findings from this study are based on one season of monitoring, because seasonality may influence office IAQ via penetration of outdoor pollutants, and thus limits the generalizability of this study to longer periods of time. This study also lacked direct measurement of air ventilation and filtration efficiency, which could better inform indoor-outdoor relationship. Lastly, the analysis assumed well-mixed air on each floor, disregarding potential variability between microenvironments.

5. Conclusion

This study is one of the first to highlight indoor pollution in China’s office buildings. Using time-series data, this study provided a more detailed examination of hourly concentration variation during work time. More office exposure assessment studies are needed to better understand in-office PM₂.₅ and CO₂ pollution and how continuous monitoring combined with ventilation and filtration strategies can improve office IAQ.

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