Investigation of Indoor Air Quality and Identification of Plant’s Capabilities in Removing Air Pollutants in Urban Residential Buildings

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Abstract. Indoor air pollution has been a severe problem in China since the 1970s. Currently, the primary indoor air pollutants are PM$_{2.5}$ and PM$_{10}$ in China. This study has investigated the PM performance inside a case study apartment, and the correlations between the indoor PM concentrations and the ambient PM concentrations have been identified and analysed. The results indicated that the indoor PM concentrations could not meet the requirements of the China Indoor Air Quality Standard (GBT18883-2012). The inside particulate matters were mainly originating from the ambient environment. Moreover, plants could reduce the indoor PM concentrations in a stable indoor environment during the unoccupied period, and the cleaning efficiency can be increased by install as many plants as possible into the space.

1. Introduction
Indoor air pollution is a severe problem in China since the 1970s, according to the report from Sinton et al. [1]. Currently, over 60% of Chinese people express their worries about indoor air quality [2]. Moreover, the primary indoor air pollutants are particulate matters (PM$_{2.5}$ and PM$_{10}$), stated by the China Indoor Environment Monitoring Committee [3]. Zhang et al. [4] evaluated indoor PM$_{2.5}$ concentrations in 6 residential buildings in Beijing, and the results reveal that average indoor PM$_{2.5}$ concentrations during measuring period exceeded the China standard values, even windows and doors were closed to stop outside PM flowing inside. The study from Zhou et al. [5] proved that indoor PM concentrations in a residential building in Tianjin could be over 100 times higher than the Chinese standard values.

The indoor air pollution is significantly affected by the ambient air pollution, as many studies have proved that the indoor PM closely follows the corresponding outdoor concentrations in a room without any indoor pollutant sources [6][7][8]. Kuo and Shen [9] observed a similar increasing concentration of PM$_{2.5}$ and PM$_{10}$ in both indoor and outdoor environment during a heavy pollution day and interpreted that outdoor particulate matters come inside through building’s ventilation system. Baek et al. [10] studied the ratio of indoor PM concentration to outdoor concentrations in Korean urban areas and concluded that ambient air quality is a vital factor in determining the quality of indoor air.

China has been experiencing severe air pollution problems in recent years due to the rapid industrialization and urbanization, and increasing energy consumption [11] [12] [13]. The readings of PM$_{2.5}$ concentrations in most urban areas have exceeded acceptable national standards and are often worse in winter, particularly in north China due to fuel combustion for heating [14]. Shao et al. [15] illustrated that over three-quarters of the population in China urban areas were exposed to the air...
quality that does not meet the national ambient air standards, and the primary contaminants in the ambient air are PM$_{2.5}$ and PM$_{10}$. Heavy air pollution usually happened most in the north part of China. According to the latest report from the National Environment Protect Department, Hebei, Tianjin, Beijing, Shandong, and Henan are top five air polluted provinces in 2017. Table 1 indicated that in the past three years, PM$_{2.5}$ concentrations in these provinces and municipalities exceeded the annual guideline value of Grade I of the China Indoor Air Quality Standard (GBT18883-2012).

| Province or Municipality | Yearly average PM$_{2.5}$ concentrations (μg/m$^3$) | China Indoor Air Quality Standard (GBT18883-2012) | The requirement of the Grade I |
|--------------------------|--------------------------------------------------|--------------------------------------------------|-------------------------------|
|                          | 2015 | 2016 | 2017 | PM$_{2.5}$, Annual mean: | 15 |
| Henan                    | 80.7 | 77.0 | 77.7 | 24-hour mean: | 35 |
| Beijing                  | 80.4 | 63.4 | 64.6 | PM$_{10}$, Annual mean: | 40 |
| Hebei                    | 77.3 | 62.2 | 73.7 | 24-hour mean: | 50 |
| Tianjin                  | 71.5 | 63.4 | 72.4 |                    |     |
| Shandong                 | 66.4 | 64.1 | 60.3 |                    |     |
| Hubei                    | 65.9 | 59.7 | 58.6 |                    |     |

In the future, with the continuing growth of the economy, China will face more severe air pollution, and it still will take several decades to bring back the clear blue sky [13]. People begin to tackle the air pollution inside their home. In Beijing, a market study shows that the sales volume of the household air purification systems has increased dramatically since 2013 when severe air pollution has become an alarming matter in the city [16]. In 2011 and 2012, the air purification systems were sold 1.12 million sets and 1.26 million sets respectively. Then an extremely increasing happened in 2013, the total number of sets of air purification systems sold reached 2.4 million [17].

However, not all the families could afford these products. On the other hand, these products consume electricity and then increase building energy consumption, and indirectly increase the fossil fuel consumption, like coal (69% of total energy consumption was contributed by the coal combustion in China in 2015), which continuing polluted ambient air.

Alternatively, passive methods, such as the use of plants, have gained recognition and many studies have tested the efficiency of plants in removing air containments [18] [19] [20] [21]. Plants can clean our atmosphere directly by intercepting particulate matters. Taking trees as an example, trees can directly remove particles from the atmosphere and then affect its concentrations [22] [23]. In some cases that some captured particles can be absorbed into the tree, although most of them are retained on the plant surface. Chen et al. [24] claimed some garden plants have exceptional abilities in removing air particulate matters and then improve significantly ambient air quality.

Up to the present, many studies related to indoor air quality were carried out in public buildings in China. Moreover, some of them have demonstrated the plants’ capabilities to remove air containment, such as TVOCs, formaldehyde, and NO$_2$. Indoor PM concentrations of residential buildings and the capabilities of plants to remove the PM have not been extensively investigated. A significant gap in knowledge remains for future research. Thus, this study will investigate the indoor PM concentrations in a case residential building and identify the plants’ capabilities regarding the reduction of PM levels.

2. Field measurement study

2.1 Case study building
The residential building selected for this study was located in Shandong province, one of the most polluted areas in China. It was built in 2010 and has 12 apartments in total. Each apartment contains a
living room, one bedroom, one kitchen, and one toilet, as Figure 1 indicated. The floor areas for the living room and bedroom were 30m$^2$ and 10m$^2$ respectively.

![Figure 1. Floor planning of the case study building.](image)

The living room of the apartment has ten potted plants randomly placed in the living room (Figure 2).

![Figure 2. Plants in the living room and bedrooms](image)

2.2 Measurements carried out

Three scenarios were made for the measurements, indicated in Table 2. Scenario 1 was conducted from 8:00 am to 17:00 pm when the apartment was unoccupied. Scenario 2 was carried out from 17:00 pm to the 8:00 am during the unoccupied period. Scenario 3 was designed for investigating the plants’ effects on the indoor PM concentrations by moving all the plants to the bedroom A.

| Date             | Time       |
|------------------|------------|
| Scenario 1       | 11th November 2018 | unoccupied |
| Scenario 2       | 14th November 2018 | Occupied   |
| Scenario 3       | 16th November 2018 | unoccupied |
Four portable hand-held detectors of BRAMC-SMART-126 models, which have been certified by the Department of Environment Protection of Central Government, are used to measure the PM concentrations at the inlet and outlet of the case study building simultaneously (Figure 3). During the unoccupied period, doors of the living room, bedroom, kitchen, and toilet were all close while during the occupied period, the door of the bedroom was opened due to the occupant’s operation.

![Figure 3. Portable hand-held detectors of BRAMC-SMART-126 model.](image)

### 3. Measuring results

Table 3, 4 and Table 5 have summarized the measuring results of these three scenarios. On average, only the indoor PM$_{2.5}$ concentrations of scenario 1 have met the requirement of the China Indoor Air Quality Standard (GBT18883-2012), as the value was 7µg/m$^3$ lower than the required value (28 µg/m$^3$ vs. 35 µg/m$^3$). For other scenarios, both the internal PM$_{2.5}$ and PM$_{10}$ concentrations exceeded the required values of the China Standard, indicating a polluted indoor environment.

#### Table 3. Performance of PM$_{2.5}$ and PM$_{10}$ of scenario 1

| Time          | PM$_{2.5}$ |         | PM$_{10}$ |         |
|---------------|------------|---------|-----------|---------|
|               | Living room| Bedroom | Outdoor PM$_{2.5}$| Living room| Bedroom | Outdoor PM$_{10}$|
|               | Indoor PM$_{2.5}$ (µg/m$^3$) | Indoor PM$_{2.5}$ (µg/m$^3$) | PM$_{2.5}$ (µg/m$^3$) | Indoor PM$_{10}$ (µg/m$^3$) | Indoor PM$_{10}$ (µg/m$^3$) | PM$_{10}$ (µg/m$^3$) |
| 08:00-09:00   | 37         | 40      | 79        | 41      | 46      | 90         |
| 09:00-10:00   | 33         | 39      | 81        | 40      | 45      | 92         |
| 10:00-11:00   | 31         | 39      | 74        | 39      | 43      | 83         |
| 11:00-12:00   | 29         | 37      | 50        | 38      | 44      | 55         |
| 12:00-13:00   | 28         | 34      | 37        | 36      | 41      | 40         |
| 13:00-14:00   | 22         | 30      | 38        | 31      | 35      | 41         |
| 14:00-15:00   | 25         | 29      | 48        | 30      | 34      | 53         |
| 15:00-16:00   | 23         | 29      | 47        | 30      | 34      | 52         |
| 16:00-17:00   | 26         | 30      | 48        | 31      | 32      | 53         |
| Average       | 28         | 34      | 56        | 35      | 39      | 62         |

#### Table 4. Performance of PM$_{2.5}$ and PM$_{10}$ of scenario 2

| Time          | PM$_{2.5}$ |         | PM$_{10}$ |         |
|---------------|------------|---------|-----------|---------|
|               | Living room| Bedroom | Outdoor PM$_{2.5}$| Living room| Bedroom | Outdoor PM$_{10}$|
|               | Indoor PM$_{2.5}$ (µg/m$^3$) | Indoor PM$_{2.5}$ (µg/m$^3$) | PM$_{2.5}$ (µg/m$^3$) | Indoor PM$_{10}$ (µg/m$^3$) | Indoor PM$_{10}$ (µg/m$^3$) | PM$_{10}$ (µg/m$^3$) |
| 17:00-18:00   | 130        | 127     | 234       | 162     | 159     | 282        |
| 18:00-19:00   | 118        | 119     | 209       | 171     | 173     | 256        |
Table 5. Performance of PM$_{2.5}$ and PM$_{10}$ of scenario 3

| Time          | Living room PM$_{2.5}$ (ug/m$^3$) | Living room PM$_{10}$ (ug/m$^3$) | Bedroom PM$_{2.5}$ (ug/m$^3$) | Bedroom PM$_{10}$ (ug/m$^3$) | Outdoor PM$_{2.5}$ (ug/m$^3$) | Outdoor PM$_{10}$ (ug/m$^3$) |
|---------------|----------------------------------|----------------------------------|-------------------------------|-------------------------------|--------------------------------|--------------------------------|
| 08:00-09:00   | 65                               | 111                              | 52                            | 80                            | 80                             | 64                             |
| 09:00-10:00   | 54                               | 113                              | 50                            | 85                            | 85                             | 63                             |
| 10:00-11:00   | 55                               | 104                              | 48                            | 78                            | 78                             | 60                             |
| 11:00-12:00   | 56                               | 99                               | 40                            | 77                            | 77                             | 62                             |
| 12:00-13:00   | 57                               | 97                               | 40                            | 67                            | 67                             | 57                             |
| 13:00-14:00   | 53                               | 88                               | 44                            | 68                            | 68                             | 55                             |
| 14:00-15:00   | 59                               | 94                               | 40                            | 72                            | 72                             | 48                             |
| 15:00-16:00   | 58                               | 96                               | 39                            | 73                            | 73                             | 48                             |
| 16:00-17:00   | 57                               | 99                               | 38                            | 75                            | 75                             | 45                             |
| Average       | 56                               | 100                              | 43                            | 73                            | 73                             | 56                             |

4. Analysis and discussion

Figure 4, 5 and 6 have shown the changing tendency for these three scenarios. It is clear that the internal PM concentrations were lower than the ambient PM concentrations for both three scenarios. Moreover, a consistent changing tendency has been observed between the internal PM concentrations and the ambient PM concentrations. Therefore, there is no doubt that the indoor particulate matters were originated from the ambient environment.
In scenario 1, the PM concentrations of the living room were slightly lower than the PM concentrations of the bedroom. In scenario 2, the living room and the bedroom have a similar internal PM concentration during the occupied hours between 17:00 pm and midnight. Then the PM concentrations of the bedroom performed at a slightly higher level than the living rooms during the rest occupied hours. In scenario 3, the PM concentrations of the living room were higher than the PM concentrations of the bedroom.

Figure 7 to 9 have shown the I/O ratios of the internal PM concentrations to the ambient PM concentrations of each scenario. In scenario 1, the I/O ratios of the living room were slightly lower than the I/O ratios of the bedroom. The values of the bedroom were 0.65 and 0.68 for PM\textsubscript{2.5} and PM\textsubscript{10} on average respectively. For the living room, the I/O ratios of PM\textsubscript{2.5} and PM\textsubscript{10} were 0.53 and 0.60 respectively.

In scenario 2, the living room and the bedroom have similar I/O ratios, as the values ranged from 0.67 to 0.72 on average.
In scenario 3, the I/O ratios of the bedroom were significantly lower than the living room. The average I/O ratios for PM$_{2.5}$ and PM$_{10}$ of the bedroom were 0.43 and 0.42 respectively, while for the living room, the average I/O ratios were 0.66 and 0.65 for PM$_{2.5}$ and PM$_{10}$ respectively.

In summary, scenario 2 has higher I/O ratios than scenario 1 and 3 on average. Moreover, during the unoccupied period (scenario 1 and scenario 3), a consistent phenomenon has been observed, i.e., the I/O ratios were lower in the room which has plants than the room without plants. In scenario 1 and 3, the plant was the only variable that affects the indoor PM performance. In particularly after moving the plants to the bedrooms, the I/O ratios were significantly lower than the living room.

The following bullets have summarized the critical findings based on the analysis above:

- First, the indoor environment tends to have a lower PM concentration during the unoccupied period, than the occupied period. For example, in scenario 1 and 3, the living room has I/O ratios ranged between 0.53 and 0.60 on average while in scenario 2, the I/O ratios were 0.68 on average. The potential reason for the high I/O ratios should be the occupants’ internal activities, which increased the resuspension of particulate matters [25].
- Second, plants could reduce internal PM concentrations for a stable indoor environment. For example, in scenario 1, the living room has a slightly lower I/O ratios than the bedroom. In scenario 3, I/O ratios of the bedroom become smaller than the living room after moving the plants to the bedroom.
- For a smaller space, plants could achieve a lower I/O ratio than in a bigger space. For example, in scenario 1, the I/O ratios of the living room (floor areas: 20m$^2$) were 0.53 and 0.60 for PM$_{2.5}$
and PM$_{10}$ respectively while in scenario 3, the I/O ratios of the bedroom (floor areas: 10m$^2$) were 0.43 and 0.42 for PM$_{2.5}$ and PM$_{10}$ respectively.

The published studies could further validate the findings mentioned above. For example, Wolverton et al. [26] indicated that plants could remove containments from the air in a laboratory study with a small and sealed chamber. However, Dingle et al. [27] stated that in most field studies, plants make no differences regarding indoor air quality. Therefore, a conflict was created between the lab studies and the field studies. On the one hand, the reduction of pollutant concentration by plants in chamber studies has proved that plants are capable of removing air containment. On the other hand, field studies indicated that plants are not efficient in cleaning the air in practice. Two reasons may explain the difference between these studies:

- First, the main reason for the difference was that the initial lab work was done with many plants in a small space. Chambers can create a relatively stable environment for the plants. To establish this in real space may need to install several times houseplants that in the chamber. Thus, installing one or two plants for a big space will not make significant differences regarding air quality.

- Second, air pollutants in real buildings can be giving off continuously by the building materials and human activities. In some cases, it is possible that materials can produce air pollutants faster than plants remove them. Human activities also can continually affect the pollutants level inside; there may be not enough time for plants to absorb it. In the lab studies, the pollutants only were introduced once, and then the air was monitored to examine the reduction in pollutants concentration. Therefore, laboratory studies and field measurements are very different cases.

5. Conclusion
This study has investigated the PM performance inside a case study apartment, and the correlations between the indoor PM concentrations and the ambient PM concentrations have been identified and analyzed. The results indicated that the indoor PM concentrations could not meet the requirements of the China Indoor Air Quality Standard (GBT18883-2012). Moreover, the inside particulate matters were mainly originating from the ambient environment. Plants could reduce the indoor PM concentrations during the unoccupied period. Some suggestions from this field measurements were listed below:

- Ambient particulate matters contributed a significant proportion of the indoor PM concentrations. Therefore, measures, such as increasing the building airtightness level, should be taken to reduce the penetrations of the particulate matters from the outside environment to an indoor environment.

- Usually, plants could remove particulate matters in a stable indoor environment. In particularly for a small space, the cleaning efficiency of the plants can be increased along with the increasing of the number of plants. Thus, it can be concluded that there is no doubt that plants can clean air in practice. The problems need to consider is how many of them can provide enough capability to clean air.

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