

Article

# Assisted Deposition of PM<sub>2.5</sub> from Indoor Air by Ornamental Potted Plants

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**Abstract:** This study clarifies whether vegetation can promote the decrease of indoor PM<sub>2.5</sub> concentration. The indoor PM<sub>2.5</sub> concentration in two periods of 2013 in Wuhan city was simulated by cigarette burning in a series of sealed chambers. Six common indoor potted plants were selected as samples to investigate the effect of plants on PM<sub>2.5</sub> decline. The effects of potted plants on PM<sub>2.5</sub> decline were analyzed from three aspects: plant species, leaf characteristics and relative humidity. The results show that the presence of potted plants accelerated the decline of PM<sub>2.5</sub>. The additional removal rates (excluding gravity sedimentation of PM<sub>2.5</sub> itself) for *Aloe vera* and *Epipremnum aureum* were 5.2% and 30% respectively, when the initial PM<sub>2.5</sub> concentration was around 200 µg/m<sup>3</sup>. The corresponding values were 0% and 17.2%, respectively, when the initial PM<sub>2.5</sub> was around 300 µg/m<sup>3</sup>. *Epipremnum aureum* was the optimum potted plant for PM<sub>2.5</sub> sedimentation, due to its rough and groove leaf surface, highest LAI (leaf area index, 2.27), and strong humidifying capacity (i.e., can promote chamber humidity to 65% in 30–60 minutes.). Actual indoor studies have also confirmed that a certain amount of *Epipremnum aureum* can promote the decrease of indoor PM<sub>2.5</sub>. This paper provides insights on reducing the concentration of fine particulate matter by indoor greening efforts.

**Keywords:** potted plant; PM<sub>2.5</sub>; indoor; *Epipremnum aureum*

## 1. Introduction

Over the last two decades, the impact of PM on human health have drawn increasing attention [1]. In particular, particulate matter with diameter of 2.5 µm or less (PM<sub>2.5</sub>), owned larger specific surface area and bigger adsorption ability, along with various toxic compounds, e.g., heavy metals, acid oxides, organic pollutants and pathogenic microorganisms [2,3] accumulated in human bronchi and lungs [4], cause premature mortality, pulmonary inflammation, accelerated atherosclerosis, and altered cardiac functions [5]. Besides, continuous exposure to high levels of PM<sub>2.5</sub> may trigger cardiovascular diseases [6]. Therefore, PM<sub>2.5</sub> has become a major concern for air pollution control because of its harmful impact on human health.

Urban residents spend 80% or more of their time indoors—at home, work, school or in leisure activities [7,8], and long-term exposure to indoor PM<sub>2.5</sub> particles is a major threat to public health. Researchers have carried out extensive researches on the sources and control strategies of indoor PM<sub>2.5</sub>. The high pollution levels that are found in most large cities are transported into the indoor

atmosphere by ventilation and infiltration airflows [1]. Solutions to reduce indoor  $PM_{2.5}$  are categorized into three aspects: reducing outdoor  $PM_{2.5}$  sources, reducing indoor  $PM_{2.5}$  sources and reducing the transport of outdoor  $PM_{2.5}$  into the indoor atmosphere. The most widespread approach in commercial buildings is the use of cloth filters, which are integrated in mechanical ventilation systems [1]. Portable, high-efficiency particulate air cleaners help remove residential indoor  $PM_{2.5}$ , although the cost is unaffordable for most families.

In the search for eco-friendly and sustainable control measures, the ability of plants to capture and remove atmospheric PM particles has been widely investigated [9–13]. Scholars from various countries constructed fields and simulations (i.e., wind tunnels [14] and models [15]) on different scales to investigate PM deposition by plants. They focused on the following aspects: (i) vegetation factors, such as forest coverage, forest structure, vegetation species [16,17], tree structure and leaf characteristics [18]; (ii) meteorological conditions, such as precipitation, wind speed and boundary layer heights, air temperature, as well as relative humidity (RH) [14]; and (iii) PM characteristics, e.g., particle size distribution, chemical components, etc. [19]. These studies were usually carried out outdoors, some valuable conclusions had been obtained, which have important guiding significance for urban greening.

Over the last three decades, researches have demonstrated that indoor potted plants can significantly reduce the concentrations of most urban air pollutants, i.e.  $NO_2$ ,  $CO_2$ , VOC, especially benzene and formaldehyde [20–25]. While it was established that urban vegetation can decrease outdoor  $PM_{2.5}$  levels, the specific role of potted plants in elimination of indoor  $PM_{2.5}$  particles is unknown. Thus, this study aimed at investigating the specific role of potted plants in indoor  $PM_{2.5}$  reduction. In particular, this work endeavors (i) to explore the effect of different potted plants on  $PM_{2.5}$  removal, (ii) to investigate the influence of potted plants on  $PM_{2.5}$  under different indoor  $PM_{2.5}$  concentrations, (iii) to further illustrate the difference in  $PM_{2.5}$  deposition caused by potted plants, (iv) and to provide reference suggestions for indoor greening efforts.

## 2. Materials and Methods

### 2.1. Material and Equipment

#### 2.1.1. Potted-Plants Selection

Six potted plants bought from local markets were chosen as samples: *Chlorophytum comosum*, *Spathiphyllum floribundum*, *Epipremnum aureum*, *Ficus elastica*, *Sansevieria* and *Aloe vera* (Figure 1). We chose plants of similar age and growth status, with plant height of 25–35 cm.



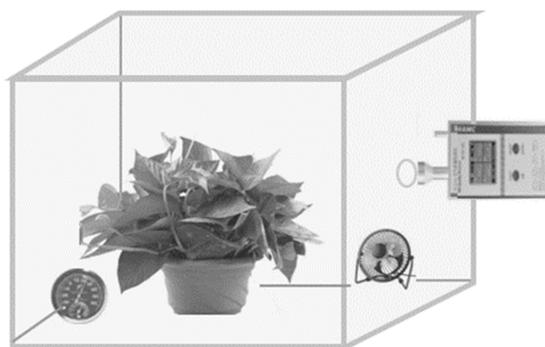
**Figure 1.** Picture of potted plants: (a) *Chlorophytum comosum*, (b) *Spathiphyllum floribundum*, (c) *Epipremnum aureum*, (d) *Ficus elastica*, (e) *Aloe vera*, (f) *Sansevieria*.

### 2.1.2. Testing Instrument

Blounton HOL-1209 air quality detector (Brenton medical technology (Beijing) Co., Ltd., China) was employed as a PM<sub>2.5</sub> detector, the measuring range of the instrument was 0–999 µg/m<sup>3</sup>, and its precision was ±10%. This instrument can simultaneously measure PM<sub>2.5</sub> concentration and RH. A blank chamber was used to calibrate the detector. Mean values were obtained from two replicates of sample tests to reduce uncertainties.

### 2.1.3. Experiment Equipment

Particulate matter produced from cigarette smoke was mainly below 10.0 µm, and particulate matter below 2.5 µm in size accounted for more than 80% [26], therefore, cigarette smoke was chosen as the source of PM<sub>2.5</sub> in this study. Experiments were conducted using a series of closed chambers with a volume of 60 L (40 cm length × 30 cm width × 50 cm height), as seen in Figure 2. To eliminate the effect of electrostatic force, the test chamber was made of glass panels with thickness of 6 mm [27]. A 1 cm round hole with a piston was made in the middle of the front face, used to insert the probe of the instrument. To prevent any leak during the tests, the chamber was sealed by both glue and adhesive foam-rubber insulation tape, and the test hole was sealed with a rubber stopper unless measuring. A small fan fixed inside each chamber to provide complete mixing of the smoke and a thermometer was used to check temperature and calibrate RH. The laboratory was illuminated over the experimental periods.



**Figure 2.** The experimental setup.

## 2.2. Experimental Method

### 2.2.1. Removal Efficiency of PM<sub>2.5</sub> by Potted-Plants and Its Influencing Factors

According to the historical air quality data of Wuhan in 2013, the average concentration of PM<sub>2.5</sub> ranged from 11 µg/m<sup>3</sup> to 284 µg/m<sup>3</sup>. The monitoring data of indoor PM<sub>2.5</sub> in Wuhan in 2013 [28] was taken as a reference (40–340 µg/m<sup>3</sup>). Taking into account the impact of the most disadvantageous conditions, the initial PM<sub>2.5</sub> concentration in this experiment were set to around 200 µg/m<sup>3</sup> and 300 µg/m<sup>3</sup>, respectively.

The leaves of the potted plants were first washed and naturally dried, and the pots were wrapped in plastic bags. Each potted plant was placed inside the test chamber, and an empty chamber served as blank control. All the test chambers were filled with equal amounts of cigarette smoke (cigarette burning time inside was controlled and a fan was used to mix the smoke). The top door of each chamber was closed until PM<sub>2.5</sub> concentration was in the test range. PM<sub>2.5</sub> and RH were recorded every 10 minutes for 180 minutes. The experiment was carried out in a temperature-controlled laboratory at 20 ± 3 °C. All experiments were repeated twice.

After the experiment, six kinds of plant leaves were picked, and nail polish was applied to them to obtain the epidermis [29]. Fine structure of the leaf surface was observed by inverted fluorescence microscope (BDS 200-FL, Chongqing Optec Instrument CO., LTD, Chongqing, China).

For determination of the leaf area index (LAI, leaf area/ground area, dimensionless), three pieces of large, medium and small leaves were taken from the six potted plants. After scanning, the area of each leaf was measured according to the principle that the pixel ratio in Photoshop software was equal to the area ratio, and the corresponding average value was recorded. Total plant area is the product of average leaf area and leaf number. The maximum vertical projected area of the plant was taken and the method of area measurement was the same as above. The leaf area index is the ratio of the two areas [30–32].

### 2.2.2. Actual Indoor Study

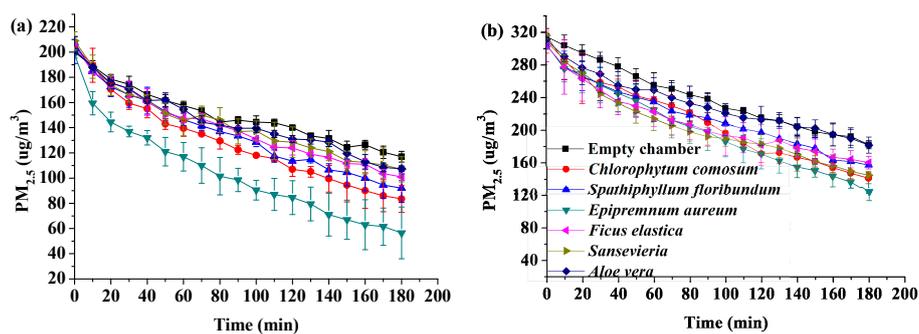
Two rooms with the same internal structure and external conditions, adjacent to each other with an area of 16 m<sup>2</sup> were selected as test rooms. After closing for a week, the indoor PM<sub>2.5</sub> concentrations were basically the same. Eight pots of *Epipremnum aureum* were placed in one room, and there was no potted plant in the other room. After a cigarette was burned in both rooms, PM<sub>2.5</sub> concentration values were recorded every 10 minutes and continuously monitored for 180 minutes. Since the test room area was less than 50 m<sup>2</sup>, one measuring point was set according to the requirements of the indoor air monitoring technical guidelines in the *Indoor Air Quality Standard* (GB/T 18883–2002) [33]. The measuring point was located in the center of the room, 120 cm above the ground. The experiment was repeated twice under similar conditions and the experimental data were averaged.

## 3. Results and Discussion

### 3.1. Deposition Effect of PM<sub>2.5</sub> by Potted Plants under Different PM<sub>2.5</sub> Concentrations

The variation of PM<sub>2.5</sub> particles in the chamber with potted plant exhibited a downtrend similar to those in the empty chamber under different PM<sub>2.5</sub> concentrations (Figure 2). Moreover, the test chamber with potted plants showed superior performance on PM<sub>2.5</sub> removal than the empty chamber in both conditions, except that *Aloe vera* exhibited poor PM<sub>2.5</sub> removal efficiency at high PM<sub>2.5</sub> concentrations. Besides, for most potted plants, PM<sub>2.5</sub> curves declined more sharply at low PM<sub>2.5</sub> concentrations (*Sansevieria* was an exception), while it was better under high concentration conditions in terms of total PM<sub>2.5</sub> removal, suggesting that the density of the particles settling upon the leaf surface increased with increasing PM<sub>2.5</sub> concentration [34].

Additionally, the maximum PM<sub>2.5</sub> removal rate for the six potted plants, as well as the empty chamber, occurred in the first hour (Figure 3), and total PM<sub>2.5</sub> removal rate in the empty chamber exceeded 40% under both conditions, indicating that gravitational sedimentation was an effective way in decreasing the concentration of solid particles [27]. However, the removal rate of PM<sub>2.5</sub> in test chambers were higher than that in the empty chamber under both conditions, suggesting that the presence of potted plants promoted the deposition of PM<sub>2.5</sub>. The most intuitive reason can be attributed to the presence of potted plants occupying a certain volume in the chamber, thereby shortening the effective distance between PM particles and collectible surfaces [27].



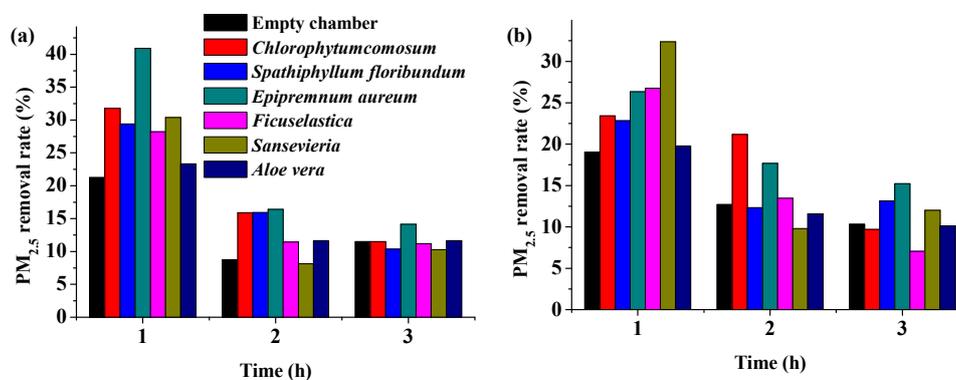
**Figure 3.** Temporal variation curves of  $PM_{2.5}$  particle concentrations under different initial  $PM_{2.5}$ , (a) when initial  $PM_{2.5}$  was around  $200 \mu\text{g}/\text{m}^3$ , (b) when initial  $PM_{2.5}$  was around  $300 \mu\text{g}/\text{m}^3$ . The upper and lower limits of the concentration error bar represent standard deviation of  $PM_{2.5}$  concentrations.

### 3.2. Influencing Factors of $PM_{2.5}$ Deposition by Potted Plants

To investigate the dust settlement capability of different potted plants, influencing factors included plant species, leaf characteristics and RH were investigated as follows.

#### 3.2.1. Influence of Plant Species

As seen in Figures 3 and 4, the decline rates of  $PM_{2.5}$  particles in chambers with different potted plants were considerably different. Significant removal efficiency (71.5% at high  $PM_{2.5}$  and 59.2% at low  $PM_{2.5}$ ) was observed in the chamber with *Epipremnum aureum*, while the chamber with *Aloe vera* showed a slight advantage over the empty chamber. Relatively stable removal rates were observed in the three chambers with *Sansevieria*, *Spathiphyllum floribundum* and *Ficus elastica*, while for *Sansevieria*, the  $PM_{2.5}$  removal rate increased at high  $PM_{2.5}$ .



**Figure 4.** Removal rate per hour for  $PM_{2.5}$  under different initial  $PM_{2.5}$  concentrations: (a) initial  $PM_{2.5}$  was around  $200 \mu\text{g}/\text{m}^3$ , (b) initial  $PM_{2.5}$  was around  $300 \mu\text{g}/\text{m}^3$ .

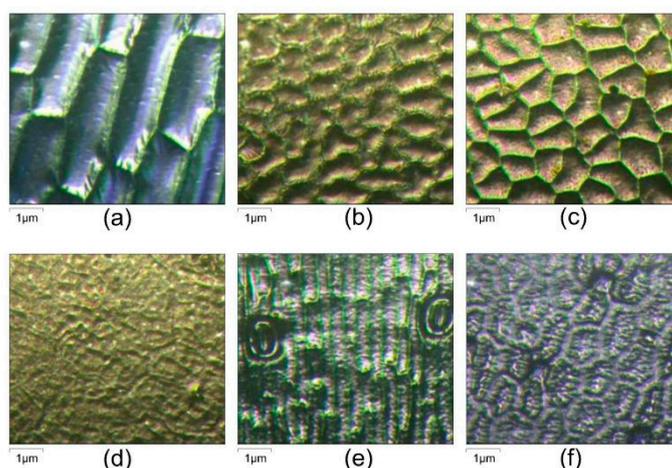
Figure 4 showed removal rates of potted plants at different initial  $PM_{2.5}$  concentrations for every hour.  $PM_{2.5}$  removal rates in the test chamber with potted plants were higher than that of the empty chamber in the first hour. It decreased with time in the next two hours, except for *Sansevieria*, which exhibited a higher removal rate in the third hour than that in the second hour.

When ignoring the gravity sedimentation of  $PM_{2.5}$  itself, the additional removal rates for *Aloe vera* and *Epipremnum aureum* were 5.2% and 30% respectively, when the initial  $PM_{2.5}$  concentration was around  $200 \mu\text{g}/\text{m}^3$ . The corresponding values were 0% and 17.2%, respectively, when the initial  $PM_{2.5}$  was around  $300 \mu\text{g}/\text{m}^3$ . This indicated that there were other reasons accounting for these results.

### 3.2.2. Leaf Surface Characteristics and LAI

The removal of PM pollutants from the air by plants was typically due to deposition [35]. The morphological features of a leaf are considered to be an important factor affecting PM deposition [18,36]. Studies have shown that leaves with fine groove-like tissues, fluff, sticky, waxes and roughened surfaces was conducive to the adsorption of PM [18,37,38]. Moreover, leaf surface roughness was closely related to the number of retained particulates, with rougher surfaces corresponding to more rugged folds and grooves and a stronger retention ability [38]. However, leaves with relatively smooth leaf surfaces, and grooves that are shallow and sparse have relatively weak dust retention abilities [39].

All six potted plants have a waxy layer on the leaf surface. Images from inverted fluorescence microscope observation showed that there were roughened surfaces with grooves on the leaves of *Chlorophytum comosum*, *Spathiphyllum floribundum*, and *Epipremnum aureum*; *Chlorophytum comosum* and *Epipremnum aureum* had obvious ridges on their leaf surface, as shown in Figure 5. By comparison, *Ficus elastica* and *Aloe vera* showed less rough and flat surfaces, which were not conducive for dust to settle. A distinctive rough and tumorous leaf surface structure appeared in *Sansevieria*. In general, the high removal rate of PM in test chambers with *Chlorophytum comosum* and *Epipremnum aureum* was correlated with their leaf characteristics.



**Figure 5.** Leaf morphologies of six potted plants ( $10 \times 10$ ): (a) *Chlorophytum comosum*, (b) *Spathiphyllum floribundum*, (c) *Epipremnum aureum*, (d) *Ficus elastica*, (e) *Sansevieria*, (f) *Aloe vera*.

Other studies have shown that the LAI of a plant is positively correlated with the dust retention capacity of the plant [40]. After measurement and calculation, the order of LAI for six potted plants used in this study was as follows: *Epipremnum aureum* (2.27) > *Ficus elastica* (1.41) > *Spathiphyllum floribundum* (1.09) > *Aloe vera* (0.83) > *Chlorophytum comosum* (0.51) > *Sansevieria* (0.26). Considering the leaf surface structure presented above, *Epipremnum aureum* had favorable leaf characteristics and the highest LAI value, which was consistent with the highest PM<sub>2.5</sub> removal rate in the test chamber. However, the lowest PM<sub>2.5</sub> removal rate occurred in the test chamber with *Aloe vera*, not *Sansevieria* with the lowest LAI value. These findings suggest that PM<sub>2.5</sub> removal rate was not always positively correlated with the LAI value.

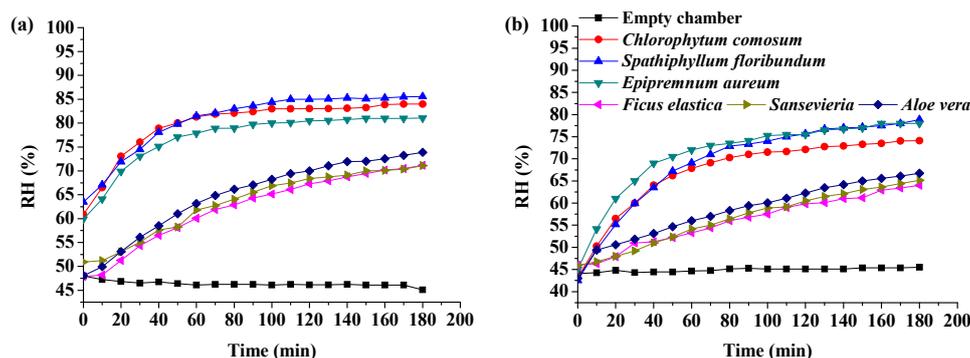
### 3.2.3. Influence of RH

Due to the difference among season, location, and meteorological variables, as well as characteristics of PM<sub>2.5</sub>, the correlation between RH and PM<sub>2.5</sub> differed in most studies [41–43]. However, there were some consistent conclusions: RH was positively correlated with sulfate and nitrate concentration, but negatively associated with organic carbon (OC) and elemental carbon (EC) concentration [1,44,45]. According to a study, total carbon (TC) accounts for about 66% of the total mass of PM<sub>2.5</sub> after cigarette

burning, and OC accounts for the majority of TC [46]. In this study, cigarette smoke was used as the source of PM<sub>2.5</sub>, which resulted in a high carbon content in PM<sub>2.5</sub> components.

The hygroscopicity of PM particles increased with the increase of RH, especially when the humidity was above 65%, which promoted the aggregation of fine particles into larger particles [47]. Figure 6 showed that the trend of RH curve for the same plant under different PM<sub>2.5</sub> conditions was almost the same. Moreover, the six potted plants can be classified into two groups. The first was group A, which included *Epipremnum aureum*, *Chlorophytum comosum* and *Spathiphyllum floribundum*, showing a fast-rising trend in RH in early stage of the experiment, and RH in the group A chambers increased to 65% in a very short time, i.e., 30 min for (a) and 60 min for (b). The other three plants were assigned to group B. RH in the group B chambers increased slowly and finally remained around 70%. The time that group B spent to attain the same RH (65%) was twice as long as group A. The RH in the empty chamber remained stable throughout the experiment.

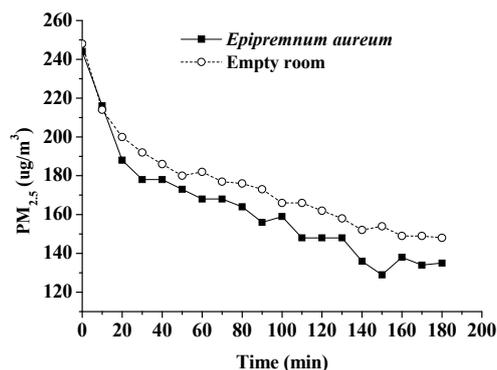
Combining the above PM<sub>2.5</sub> data, the three potted plants that caused the fastest decline of PM<sub>2.5</sub> belonged to group A when initial PM<sub>2.5</sub> was around 200 µg/m<sup>3</sup>, which confirmed that the PM<sub>2.5</sub> deposition was positively correlated with the increase of RH in this study. However, the corresponding relationship changed with the increase of PM<sub>2.5</sub>; the order of *Spathiphyllum floribundum* in group A was replaced by *Sansevieria* in group B (Figure 6(b)), the most likely reason being the inadaptability of *Spathiphyllum floribundum* to high PM in its flowering period. The underlying causes need to be further explored.



**Figure 6.** Variations of RH in the test chamber during PM<sub>2.5</sub> monitoring: (a) initial PM<sub>2.5</sub> was around 200 µg/m<sup>3</sup>, (b) initial PM<sub>2.5</sub> was around 300 µg/m<sup>3</sup>.

### 3.3. Actual Indoor Study

On the basis of the PM<sub>2.5</sub> removal performance of the six potted plants, *Epipremnum aureum* was selected for the actual study. The initial PM<sub>2.5</sub> concentrations in both rooms were around 250 µg/m<sup>3</sup> (Figure 7). At 20 min, PM<sub>2.5</sub> concentration in the room with *Epipremnum aureum* started lower than the empty room, in the entire evaluation period. Final PM<sub>2.5</sub> concentrations of the two rooms were 148 (empty room) and 135 µg/m<sup>3</sup> (room with *Epipremnum aureum*), respectively, and the corresponding removal rates were 40.8% (empty room) and 46.0% (room with *Epipremnum aureum*), respectively. Results from the actual study indicated that the presence of *Epipremnum aureum* enhanced the deposition of PM<sub>2.5</sub>, although the performance was not so positive as that in the test chamber. The possible reasons were as follows: (i) particulate pollutants were transported to leaf surfaces by gravity sedimentation or impaction [31], while the *Epipremnum aureum* were too small (about 30 cm) in comparison with indoor height (280 cm). They cannot provide more contact area for PM<sub>2.5</sub> deposition, (ii) eight pots of *Epipremnum aureum* were not enough to significantly increase RH of the room with 16 m<sup>2</sup>, resulting in poor aggregation settlement, and (iii) the experimenter's movement may cause resuspension of fine particles.



**Figure 7.** Temporal variation curves of PM<sub>2.5</sub> concentrations in an actual indoor environment.

#### 4. Conclusions

Potted plants in a sealed chamber have the potential to improve PM<sub>2.5</sub> deposition in this study, especially those with rough and groove leaf surfaces, as well as high LAI, like *Epipremnum aureum*. The presence of *Epipremnum aureum* in the test chamber promoted the removal rates of PM<sub>2.5</sub> to 71.46% (when initial PM<sub>2.5</sub> was around 200 µg/m<sup>3</sup>) and 59.25% (when initial PM<sub>2.5</sub> was around 300 µg/m<sup>3</sup>) in three hours, respectively, while the removal rate of PM<sub>2.5</sub> in the empty chamber was around 42.0% under both conditions. In the actual indoor study, the effect of *Epipremnum aureum* on deposition was not as significant as the test chamber. Other factors, such as plant height and density, should be taken into account in terms of indoor applications. In general, a certain number of potted plants like *Epipremnum aureum* are beneficial in reducing indoor PM<sub>2.5</sub>, while in practical application, considering the limitations of indoor spaces, indoor vertical greenery will be an optimum method to promote PM<sub>2.5</sub> settlement. In addition, there exist inadequate aspects in this research. A quantitative study on the contribution of each factor need to be further undertaken.

**Author Contributions:** Y.C. organized this study, conducted the study design, and drafted the manuscript. F.L. contributed to the study design, and revision of the manuscript. Y.W. contributed to the conduct of the experiment. Y.Y. contributed to the conduct of the experiment. Z.W. contributed to purchase of the plants and participated in the actual study. X.L. contributed to calculation of LAI. K.D. contributed to observation of leaf characteristics.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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