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Comparative Study of Indoor Plants for PM2.5 Absorption

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Abstract*— Indoor PM2.5 air pollution, which varies due to ventilation, indoor habits, and urban outdoor sources, has garnered growing interest in using ornamental plants for mitigation. The project herein was conducted to explore whether leaf hair density, surface area, and stomatal density are effective determinants of PM2.5 reduction through comparative studies on six common household plant species: spider plants, aloe vera, rubber plants, peace lily, English ivy, and Boston fern. Conducted in homemade semi-airtight growth chambers with a household Temtop PM Monitor to monitor the released tobacco smoke and PM2.5 concentration over time, the experiment revealed significant differences in reduction of PM2.5. English ivy demonstrated the highest real average absorption rates per hour (6.21%), followed by peace lily (6.00%) and spider plant (5.33%), calculated with leakage accounted for. Still, control trials revealed that leakage could confound the relationship between plant species and PM2.5 absorption but does not greatly impact the comparativeness of English ivy's effectiveness out of the six species. As English ivy and peace lily also rank highly in leaf surface area, stomatal density, and morphology, these data suggest that strategically choosing ornamental plants with these traits would be helpful in mitigating indoor PM2.5 levels. Further research could isolate any of the plant characteristics, particularly stomatal density, to explore its implication on PM2.5 capture.

***Index Terms:* PM2.5, ornamental plants, indoor air quality, household health.**

I. INTRODUCTION

$PM_{2.5}$ or air particles of less than 2.5 µm, has been estimated to cause over 48,000 premature deaths per year [1]. Inhalation of $PM_{2.5}$ is also known to cause various acute health problems such as asthma, wheeze, and stroke [2]. Long term effects include, but are not limited to, lung cancer, Alzheimer's, and Parkinson's Disease [3]. Although PM10 is known to cause similar health effects, $PM_{2.5}$ is of more environmental concern to scientists and the public as their smaller size prolongs its retention time in the air, further exacerbating their effects in the environment [4, 5, 6]. The smaller diameter of $PM_{2.5}$ also ensures its deeper penetration into the respiratory pathway than its PM10 counterpart, which leads it to pose greater health risks than PM10 as well [7]. While PM10 can only reach the nasal mucosa, $PM_{2.5}$ can be inhaled as far as into the bronchial airways [8].

The greatest outdoor source of $PM_{2.5}$ is gasoline powered vehicles, and others include factory smoke [9]. Despite the major sources coming from the outdoors, indoor $PM_{2.5}$ levels may also pose unhealthy risks as outdoor air gets brought indoors through ventilation instead of recirculating indoor air [10]. As people spend 90% of their time indoors, that combined with the lack of ventilation in most homes raise the global concern to monitor indoor $PM_{2.5}$ intake. In addition to the variability of $PM_{2.5}$ concentration infiltrated from the outdoors, indoor activities such as smoking and cooking can also contribute to indoor PM2.5 exposure [11]. In an indoor mahjong setting, the geomean and median $PM_{2.5}$ concentrations (caused by cigarette smoke) measured by Du et al. were 276 and 347 µg/m^3, which, compared to the USEPA standards, 250.5-350.4 µg/m^3 is ranked as "very unhealthy" [12, 13]. In fact, a smoke-free household could inhale 70% less $PM_{2.5}$ than smoking households do [14]. Weather is also an extraneous factor that could alter $PM_{2.5}$ air quality. In a former study by Tian et al conducted in the cities Jinan and Qingdao of China, $PM_{2.5}$ levels saw an average reduction of 32% and 21%, respectively, from before and during rain events [15].

Increasing amounts of research have been highlighting the ability of plants and trees to capture $PM_{2.5}$. Factors such as the leaf area index, thickness of the leaf wax layer, and the density of stomata are involved in the process of $PM_{2.5}$ absorbability [16]. Within the phyllosphere, which is the visible habitat of plants occupied by microorganisms, the stomata are capable of gas exchange–hence, the absorption of $PM_{2.5}$– while the leaf surfaces and trichomes are where $PM_{2.5}$ tends to deposit on [17]. Although some research suggests the possibility of active phytoremediation of gaseous pollutants, more recent discoveries are emphasizing the feasibility of passive remediation instead [18, 16, 19]. As the aperture of stomata is typically 4-10 nm, and the variation depends on CO_2 concentrations, light intensity, and humidity, PM2.5 has the feasibility of entering the stomata in terms of size alone [20, 16]. However, researchers have discovered that $PM_{2.5}$ tends to situate on the adaxial (lower) side of leaves rather than the abaxial side (where most stomata are located), while other gaseous pollutants such as methane and benzene may be metabolized by plants through stomatal entrance [21, 22]. Another researcher in Beijing reported a contrasting finding: tree leaves with high stomatal density (>189 mm^{-2}) trapped significantly more $PM_{2.5}$ [23]. Hence, the correlation between

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stomata density and PM2.5 trapping is yet to be established.

An old study by NASA is considered the origin of all the internet sources stating the efficiency of indoor pot plants for air quality improvement. Through testing with trichloroethylene, formaldehyde, and benzene, Wolverton et al. found a 10.5% and 23.0% removal of trichloroethylene by Ficus and peace lily, an 89.8% and 79.5% removal of benzene by English ivy and peace lily, 70.0% and 47.7% reduction of formaldehyde by mass cane and Ficus. Plants with flowers such as pot mum and gerbera daisy demonstrated outstanding ability in chemical consumption (61% and 50% of formaldehyde, 53% and 67.7% of benzene, and 41.2% and 35% for trichloroethylene) [24]. Another study conducted in South Korea by Sharma et al., using snake plants, Swiss cheese plants, ZZ plants, and jade plants reported a $PM_{2.5}$ reduction of up to 64.61% in a standard apartment with ventilation [25].

This study aims to individually experiment on the abilities of various ornamental plants to absorb PM2.5, specifically cigarette smoke, which is a major source of indoor air pollution. In addition to nicotine, tobacco smoke contains thousands of chemicals, most notably benzene, formaldehyde, and arsenic [26]. By selecting plants with distinctive features such as leaf area index, leaf morphology, and stomatal density, this paper looks forward to establishing some type of association between any of these traits with $PM_{2.5}$ capture.

II. METHODOLOGY

A. Selection of Plants

Boston fern, spider plant, peace lily, English ivy, aloe vera, and rubber plants were the six species selected that are prevalent in blog posts and other research articles that experimented with specific chemicals such as benzene and trichloroethylene. Selecting these same species that are effective in capturing gaseous pollutants in this experiment with $PM_{2.5}$ can help determine whether the mechanisms for these two processes are identical. Furthermore, these common household plants were also selected for their availability in markets, low costs for purchase, and availability in smaller sizes. The plants were purchased from the same local nursery in Zhengzhou, China. Recommended font sizes are shown in Table 1.

B. Semi-Airtight chambers

The chambers were modified from the same brand of four 18-Liter water jugs made of polyethylene terephthalate (PET) due to their availability for a household project. These jugs are commonly used in household water dispensers, albeit the ones utilized here are new and solely for research, and their walls are often filled with texture and ridges. The specific dimensions are 26cm (diameter) * 48cm (height). To seal and reseal the jugs, the same brand of clear scotch tape was used throughout the process, obtained at a local market. All four jugs were cut open at the halfway point to place the plants inside, and another circular opening was annealed on the side of the jugs, 10 cm above the bottom and 0.5 cm in diameter to fit the $PM_{2.5}$ monitor.

C. PM2.5 Monitor

For measuring, the household device TemTop M2000C PM monitor was used. This device utilizes a laser technology that graphically scans the particles in the air, and then transmits the data visually to users in a numerical format. The unit of measurement used for the $PM_{2.5}$ readings is µg/m^3. In addition to $PM_{2.5}$ levels, this device also measures PM10 and CO2 concentrations.

D. Data Collection

Each trial, three layers of tape were used to seal the perimeter of the water jug, lid, and the device entrance after the plant had been situated. Before taping the lid and the monitor opening, cigarette smoke was let into the chamber from the lid nozzle while the PM monitor would be plugged into the hole on the side. Immediately after the release of tobacco smoke, the lid is completely sealed and taped. As the device only measures up to 999.9 µg/m^3, enough of the smoke was diffused out of the bottle through the 0.5cm opening on the side before the beginning concentration was measured, the device taken out, and all openings taped shut for six hours.

After the four-gallon water jugs were sealed shut with three layers of tape for six hours, the tape is quickly removed at one opening before the Temtop monitor is plugged in to measure $PM_{2.5}$ concentration. All chambers were disturbed during the beginning measuring stage so that the particles trapped on the jugs could become airborne and accounted for in the readings. A valid trial is defined as when final $PM_{2.5}$ readings are taken only after six hours; some trials completed using five-hours are discarded from skewing the data set. Four to six valid trials were run on each species of plant, averaged out between the three replicates per species and the four-gallon water jugs to reduce bias.

As per the possible imperfections and variance in modification per each jug, the leakage trials were conducted three trials per water jug. The same triple-layering of the tape, time frame of six hours, and device were used, only this time without any plants. Since the tobacco smoke particles could settle on the ridges and walls of the water jugs, the chambers were, again, shaken a decent amount, and the highest concentration was recorded before the numbers started to drop. be in 24 pt Regular font. Author name must be in 11 pt Regular font. Author affiliation must be in 10 pt Italic. Email address must be in 9 pt Courier Regular font.

E. Analysis Methodology

The raw data collected consisted of beginning $PM_{2.5}$ concentrations after the cigarette smoke had been injected into the chambers (x_i), the resulting $PM_{2.5}$ concentrations after the smoke had been inside the chamber (x_f) for six hours (t), the species of plants in a particular chamber per trial.

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Subsequently, the data were calibrated into the hourly absorption rate of $PM_{2.5}$ for each plant and trial (R). The formula was used as below:

$$R = \frac{(x_f - x_i)}{t x_i} \times 100$$

The rates were taken from each valid trial, averaged, and plotted onto bar graphs along with sample standard deviations to validate the statistical significance. All organizing and calculations with the data and bar graphs were completed and generated using Google Sheets. The box plot with the hourly absorption rate was generated using Excel spreadsheet.

III. RESULTS

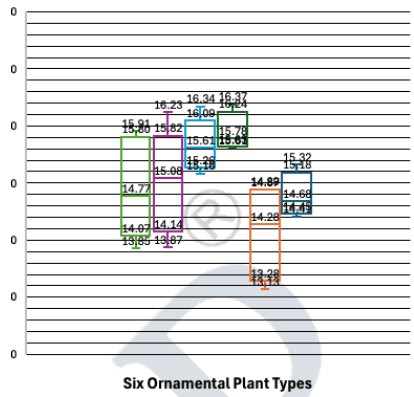

Fig. 1. Each value in the five number summaries is expressed as a percentage of $PM_{2.5}$ that each plant, on average, absorbed over the six-hour time frame. The outliers were not removed when generating the curve, except the few trials completed over five-hours instead of six.

Table I: Leakage Trial Data in Hourly Absorption

Leakage	Trial 1	Trial 2	Trial 3	Average	Deviation
Box 1	9.943568788	10.36481134	9.827859407	10.04541318	0.2825925596
Box 2	9.337044534	10.14202268	9.227157819	9.568741677	0.4995068588
Box 3	9.468177855	10.25292973	9.582879503	9.767995697	0.4238630448
Box 4	9.691100139	8.643744031	9.373935554	9.236259908	0.5370797355

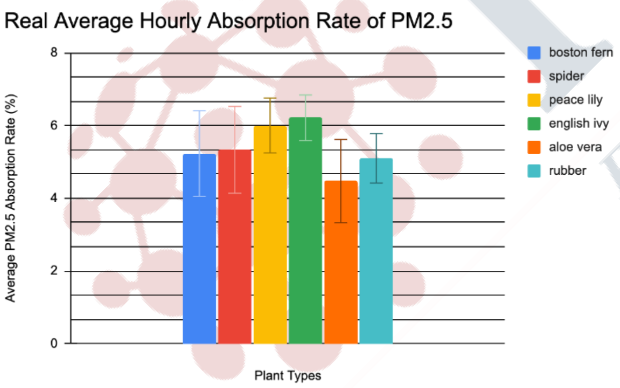

Fig. 2. The real absorption rates represent the difference between the average of the nominal absorption rates, or the values presented in Figure 1, and the average of leakage rates for all trials and chambers. The outliers for the leakage trials were omitted from the average leakage. The standard deviations from the hourly nominal rates and the leakage rates are conjoined and presented as error bars for each plant species.

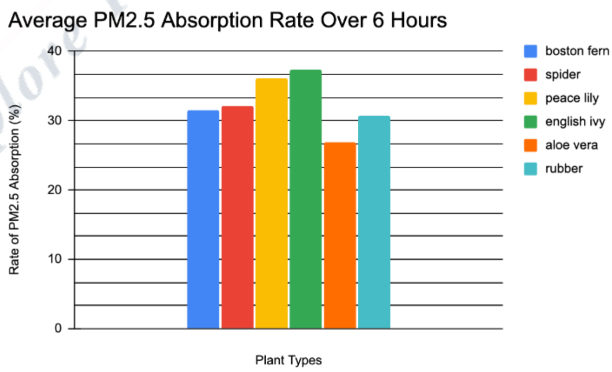

Fig. 3. The average absorption rates over six hours are a holistic representation of exactly how the data values were obtained directly from the experimental procedures, as all final concentration readings were taken after six hours. The values here are still the real absorption rates as leakage has been also subtracted from each average.

From Figure 1, The five number summaries of average hourly $PM_{2.5}$ absorption for the six plant types are as follows (%): Boston fern (13.88, 14.07, 14.77, 15.80, 15.91), Spider plant (13.87, 14.14, 15.08, 15.82, 16.23), Peace lily (15.16, 15.26, 15.61, 16.09, 16.34), English ivy (15.61, 15.63, 15.78, 16.24, 16.37), Aloe vera (13.13, 13.28, 14.28, 14.87, 14.89), Rubber plant (14.41, 14.45, 14.68, 15.18, 15.32).

Out of the sampled six species of common houseplants, English ivy ranked the highest for median hourly absorption rate at 15.78%. Peace lily situates at two out of six for its 15.67%, and last place overall is Boston fern at 14.28% (Figure 1). However, these absorption rates are nominal and could be significantly greater than the plants' actual capture capacity as further leakage trials have revealed.

The average leakage of $PM_{2.5}$ was revealed to be 9.24±0.54 µg/m^3 up to 10.05±0.28 µg/m^3 (Figure 2). Since the minimum and the maximum leakage measurements over all four chambers overlap in standard deviation, the need to further categorize absorption levels for each numbered chamber is unnecessary. The leakage readings, however, decrease the actual hourly $PM_{2.5}$ capture rate (%) to 5.23±1.17, 5.33±1.19, 6.00±0.75, 6.21±0.63, 4.47±1.14, 5.10±0.68, for Boston fern, spider plant, peace lily, English ivy, aloe vera, and rubber plant, respectively over the six-hour span (Figure 3). Still, English ivy's rate of $PM_{2.5}$ absorption is still comparable to other species, with its error bar barely overlapping with the last plant on the list, rubber plant.

As the hourly rate cannot be assumed to work for other durations and starting $PM_{2.5}$ exposure levels, the closest representation of the raw data, the average six-hour absorption of $PM_{2.5}$, is represented by a bar graph. Standard deviations have been omitted out of this graph as they overlap due to extraneous variables. In the same order of plants as the figure, the average six-hour $PM_{2.5}$ capture rates are 31.48%, 32.09%, 36.10%, 37.38%, 26.93%, 30.69% (Figure 4).

IV. DISCUSSION

A. Effectiveness of Ornamental Plants in PM2.5 Regulation

Relying on indoor plants could be especially beneficial for households located in cities where the outstanding outdoor $PM_{2.5}$ concentration hinders the effectiveness of ventilation in mitigating indoor $PM_{2.5}$. In highly urbanized and polluted areas such as Beijing, where the annual average outdoor $PM_{2.5}$ concentration in 2023, 34.3 µg/m^3, could be even higher than the indoor level, using plants with high stomatal density, leaf surface area, and textured leaf morphology are a viable and affordable option [27]. Certainly, in rural areas where the $PM_{2.5}$ concentrations are as low as 6.41 µg/m^3 identified by Kilpatrick et al. in the United States for instance, outdoor ventilation may be more effective than plant passive remediation [28].

By considering the leakage, the actual absorption rate of $PM_{2.5}$ by the six types of household plants only ranges from 4.63±0.75% µg/m^3 to 6.05±0.40% µg/m^3, which is insignificant in completely mitigating the indoor $PM_{2.5}$ levels on an hourly scale over six hours (Figure 2). The median $PM_{2.5}$ concentration for 93 smoking homes tested by Semple et al. is 31 µg/m^3, which is in the moderate zone according to USEPA AQI standards [14, 13]. With the English Ivy specifically, results reveal a six-hour reduction of 37.77 % µg/m^3 all starting from the hazardous level (350.5-500 µg/m^3) and reducing the $PM_{2.5}$ levels until good to moderate (0.0-35.4 µg/m^3) [13]. It is crucial to note that the hourly average $PM_{2.5}$ absorption rate calculated using five-hour trials depict higher outlying values than six-hour trials, which suggests a non-linear, most likely exponential or logistic correlation. The hourly absorption rates nor the six-hour absorption rates for all selected plants cannot be therefore carried over to other exposure durations and starting concentrations of $PM_{2.5}$ but bolster the plants' effectiveness in regulating hazardous $PM_{2.5}$ concentrations over several hours.

B. Leaf Hair Density

The trichome, a structure in epidermal plant cells, is characterized by a central stalk that expands unicellular rays of appendages [29]. Trichome distribution and density can vary by species due to genetics and environment. In fact, it is one of the many defense mechanisms that plants have evolved to protect against different environmental factors, biotic and abiotic. By secreting chemicals such as alkaloids, trichomes can repel herbivore predators and other insects [30]. Under more arid and hot conditions, xeromorphic plants such as succulents, cacti, and aloe vera have especially dense and long trichomes [31].

Since aloe vera out of the six selected species of plants is the only one genetically adapted to live under arid climates, it can be assumed that aloe vera has the relatively highest trichome density on the list. However, since aloe vera ranks as the one of the lowest captors of $PM_{2.5}$, trichome density could probably be disregarded as a variable for $PM_{2.5}$ absorption. Furthermore, English ivy, the species with the most $PM_{2.5}$ absorption in the experiment, generally has less trichomes. As it flourishes in environments with low light and vegetation, the hedera family genetically would not necessitate the evolution of dense trichomes for survival [32]. The spider plant, ranking third on absorption, is also intolerant of direct sunlight, which could evolutionarily lead to less trichomes than aloe vera [33].

The English Ivy is often characterized with clusters of white trichomes that radiate in all directions, leading to its distinctive fuzzy texture [34]. In contrast, aloe vera is coated with a wax-like cuticle to minimize water loss in dry environments [35]. Despite their misleading appearances of seemingly dense trichomes on the Ivy and sparse trichomes on the aloe, every species differs in the physical characteristics of trichomes, not necessarily dictating the trichome density. Yet, the trichome density does not eliminate the possibility of physical morphology of leaves caused by trichome type to be a confounding factor, which will be explored in a later section.

C. Leaf Surface Area

As the study lacks technological equipment, the following data are compiled from other research sources and are used to either corroborate or refute visual observations made of the plants used for this experimental study. From observations alone, the plants with the highest leaf surface area or LAI should be spider plant, English ivy, and peace lily. The plant with the highest absorption rate, English Ivy/Hedera helix, has a measured leaf area of 66.46±3.46 cm^2 [36]. Spider plants, third in mean absorption ranking, used in a study with variable nutrients and media has been reported to have, at maximum, 21.6 leaves, each with an area of about 30.9 cm^2 [37].

As the maximum of the spider plant surface area does not exceed the average English Ivy measured leaf area, the absorption rate could have a direct association with the leaf surface area. Although it is crucial to note the lack of validity with the surface area data between the two species, it is visually evident in this study that the leaf surface area of either the English Ivy or the spider plant exceeds that of other plants, specifically, the Boston fern, aloe vera, and rubber plant.

D. Stomatal Density

The stomata are responsible for the transpiration of CO_2 in plants, hence aiding the efficiency of photosynthesis and helps minimize water uptake [38]. Ranging in size, shape, and numbers, the stomata distribution and density can look different for varying plant species. Under certain environmental conditions, the stomata aperture may even adjust to minimize or maximize gas exchange [39]. Since particulate matter is usually considered a mixture of fine particles, and not necessarily a gaseous substance, exploring whether stomatal density has an impact on the $PM_{2.5}$ absorption could entail whether plants uptake $PM_{2.5}$ through the stomata.

For English Ivy, stomata are present on the lower (abaxial) surfaces of leaves only, at a density of 125–240 mm−2 [29]. Sitting at second for $PM_{2.5}$ absorption, the peace lily has stomata density at 30 mm^{-2} on the abaxial side and 4 mm^{-2} on the adaxial side [39]. At much lower values, the stomatal density for aloe vera is only 9 mm^{-2} on the abaxial surface and 8 mm^{-2} on the adaxial surface [40].

It seems that the stomatal density might have a somewhat positive effect on the effectiveness of $PM_{2.5}$ absorption in plant species, noting that the density for English ivy is much greater than the density for aloe vera, at about 16 to 30 times higher on the abaxial side of leaves. If there is a correlation, the abaxial surface stomata density also has a clearer relationship with the absorption rate more so than the adaxial stomata density, considering that English ivy had none on the adaxial, and that peace lily has 4 less than aloe vera.

E. Plant Morphology

Plant morphology refers to the visual characteristics of a plant species. Although it could be related to the anatomy of a plant, which only deals majorly with internal structure, morphology usually only indicates the external traits such as texture and shape [41]. Starting with English ivy again, these plants tend to have medium to medium fine leaf textures. Specifically with the juvenile ivies that have been used in this study, they tend to have a furrier texture while adults don't [42]. Peace lilies have leaves that are relatively large and glossy, even in juveniles, but they do have considerable sunken green veins that adds nuance to its leaf topography [42]. Coming in third for $PM_{2.5}$ absorption, spider plants have narrow, strap-shaped leaves. While their leaves aren't composed of specific textures like hairs or wax, each leaf has one distinct channel that folds down the middle [43], a structure possibly aiding the retention of $PM_{2.5}$ particles on each leaf.

F. Limitations

The confounding leakage was arguably the greatest limiting factor, resulting majorly from the imperfections on the modified water jugs as chambers. Other elements such as the difference in ventilation and atmospheric $PM_{2.5}$ levels also provide sources of uncertainty for the data. Lack of professional airtight equipment has greatly increased the nominal $PM_{2.5}$ capture rate over six hours, as well as the standard deviations that enlarged due to the slight differences in each trial and each chamber.

This study also did not continuously measure the $PM_{2.5}$ levels due to the lack of monitors to supply all four chambers, as well as the low battery-life of the handheld device. Although the five-hour trials suggest a non-linear correlation between absorption and time, the specific type of relationship between the two variables are unable to be deduced without a complete absorption scatter plot curve.

Features of the six ornamental plants also lack direct data due to lack of appropriate equipment to visualize and generate accurate data. Although leaf surface area and leaf morphology can be somewhat compared between the six plants based on observations alone, first-hand numerical measurements for trichome and stomata density could have been useful to link the validity of the absorption rates to the traits that each plant specialize in. By reviewing these values from other credible research papers, they can still highlight the possible traits that make $PM_{2.5}$ absorption especially effective in some plants over others.

V. CONCLUSION

Out of the six plants tested, Boston fern, spider plant, peace lily, English ivy, aloe vera, and rubber plant, English ivy (15.78% per hour, 37.38% per six hours) ultimately demonstrated the most potential for mitigating extreme indoor $PM_{2.5}$ levels, followed by peace lily (36.10% per six hours) and spider plant (32.09% per six hours), starting with hazardous $PM_{2.5}$ levels that got reduced to moderate after six hours.

Despite variables such as airtightness, ventilation, and atmospheric $PM_{2.5}$ levels that confounded the leakage and standard deviation, English ivy's effective $PM_{2.5}$ capture rate still managed to exceed other tested plant species by barely overlapping error bars on the hourly absorption rate. As English ivy ranks high in terms of stomatal density, and rough leaf morphology, these traits are very likely associated with its heightened ability to regulate $PM_{2.5}$ levels. Thus, future research could focus on individually testing any of these plant characteristics more rigorously, especially exploring stomatal gaseous exchange as a viable mechanism for plants and $PM_{2.5}$ interaction.

As well, it is revealed that indoor plants such the English ivy and peace lily are relatively effective in removing $PM_{2.5}$ from the atmosphere starting from potent concentrations over a longer period (i.e. six-hours). Additional absorption curves calibrated over a continuous time frame may help solidify the exponential/logistical relationship between the $PM_{2.5}$ reduction by plants and time. Furthermore, researching the trends of the absorption curve could also highlight the plants' ability to metabolize overtime, which is a crucial indicator of plant health under the effects of $PM_{2.5}$ and air pollution in general.

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