Phytoremediation of Airborne Particulate Matter in Indoor Environments

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ABSTRACT

This research is motivated by the urgent need to protect people from the adverse health effects of $PM_{2.5}$ (particles smaller than 2.5 µm in size) exposure by using potted plants as air filters in indoor environments. We quantified the ability of three different plant species for removing airborne particles by conducting experiments in an environment-controlled chamber. The plants selected were Christmas plant (*Araucaria heterophylla*, a needle-leaved plant), Ficus plant (*Ficus retusa*, a small-leaved plant), and Croton plant (*Codiaeum variegatum*, a broad-leaved plant). The particle deposition velocities ranged from (32.4±10.6 to 41.0±10.8) cm/h for the Christmas plant, (0.6±1.6 to 2.53±3.27) cm/h for the Ficus plant, and (−0.09±3.8 to 6.07±6.28) cm/h for the Croton plant, depending on the particle size. On extrapolating those results to a small residential room, we found that 35–44 Christmas plants (the most effective species) would be required for reducing the steady-state $PM_{2.5}$ concentration by 10% at an air exchange rate of 0.5 h^{-1}.

Keywords: Air pollution; Indoor plants; Buildings; Particles; Deposition velocity.

INTRODUCTION

Air pollution is one of the greatest public health crisis facing India today. Inhaling polluted air containing $PM_{2.5}$ is estimated to have caused about 579,819 premature deaths (6.7% of total deaths) in India in 2009 according to the Global Burden of Disease (GBD) project (IHME, 2021). The same project estimated that in 2019, exposure to $PM_{2.5}$ caused about 978,237 premature deaths (10.43% of total deaths) in the country, a shocking increase of ~68% over the year 2009. Overall, exposure to $PM_{2.5}$ is the second leading cause of premature deaths in India as shown in Figure 1 Therefore, solutions are urgently required for protecting the public from the adverse health effects of exposure to $PM_{2.5}$.

There is some awareness in the country about the ill-effects of outdoor air pollution; however, air pollution inside buildings such as homes and offices is grossly underestimated. It should be emphasized that human-beings typically spend up to 87% of their time in buildings (Klepeis et al., 2001), and many of the adverse effects of "outdoor" air pollution. can be attributed to inhalation of those pollutants by people when they are inside buildings (Chen et al., 2012; Massey et al., 2012). A study conducted in urban houses in Agra found that the indoor and outdoor concentrations of $PM_{2.5}$ were 109 μgm^{-3} and 123 μgm^{-3}, respectively (Massey et al., 2012). For roadside houses, the indoor and outdoor concentrations of $PM_{2.5}$ were reported to be 161 μgm^{-3} and 160 μgm^{-3}, respectively. These concentrations are about 2.7 to 4.0 times greater than the 40 μgm^{-3} PM limits set by the national ambient air quality standard (*National Ambient Air Quality Standards (NAAQS)*, 2009). Based on the large amount of time people spend indoors, and the high values of indoor $PM_{2.5}$ concentrations reported in Indian homes, it becomes clear that indoor exposure (exposure is defined as concentration of the pollutant multiplied by the inhalation time) to $PM_{2.5}$ is a serious health concern for the nation (Pant et al., 2016).

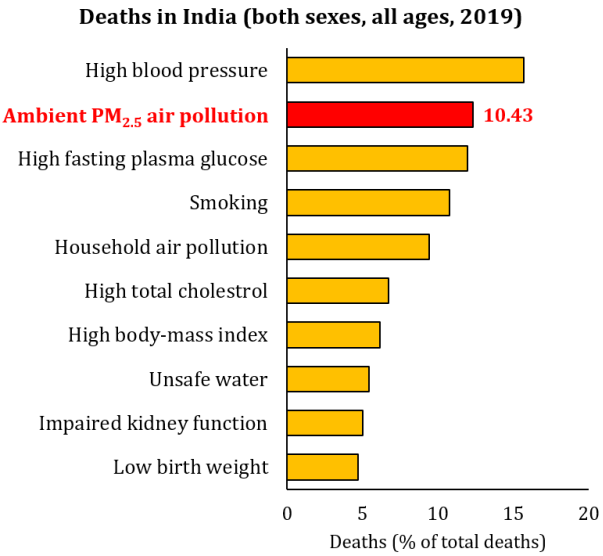

Figure 1. The major causes of premature deaths in India. (IHME, 2021)

The realization that much of the exposure to $PM_{2.5}$ happens indoors, presents a unique opportunity to protect people from the adverse health effects of air pollution by filtering/purifying the indoor air. Indoor plants can serve as natural air purifiers since they are known to remove pollutants from the air through stomatal uptake (absorption) and non-stomatal deposition (adsorption)(Brilli et al., 2018). Additionally, plant-associated microorganisms also seem to participate in removing air pollutants (Sandhu et al., 2007; Weyens et al., 2015). In addition to improving air quality, indoor plants might also help in improving people's mood, attention, and productivity (Jumeno & Matsumoto, 2016). However, the plant species need to be carefully selected since some

species can themselves become a source of air pollutants such as volatile organic compounds (VOCs) (Yang et al., 2009) and allergens (Ledford, 1994). In light of the above discussion, this investigation is motivated by the urgent need to protect people from the hazardous health effects of airborne $PM_{2.5}$ by using indoor plants as an air purification method that can be easily implemented by one and all. The investigation aims to quantify the potential of different indoor plant species towards removing $PM_{2.5}$ from the air and assess the real-world benefits of keeping plants in occupied indoor spaces.

METHODOLOGY

Selected plant species

To check the effectiveness of indoor plants for removing airborne particles, we tested three different plant species under controlled environmental conditions. The selected plants included christmas plant (*Araucaria heterophylla*, a needle-leaved plant), Ficus plant (*Ficus retusa*, a small-leaved plant), and Croton plant (*Codiaeum variegatum*, a broad-leaved plant), as shown in Figure 2. The total leaf area and volume of those plants (four plants from each species) were measured to be 5003.63±290.21 cm^2 and 130.12±3.25 cm^3, 24455.84±846.17 cm^2 and 629.4±15.7 cm^3, and 8740.45±302.41 cm^2 and 252.2±6.30 cm^3 for the Christmas, Ficus and Croton plants, respectively.

Christmas plant (Araucaria heterophylla) | Ficus plant (Ficus retusa) | Croton plant (Codiaeum variegatum)

Figure 2. The studied plant species (Front and top views).

Experimental chamber and equipment

We fabricated a 210 liter Plexiglas chamber (59.5 cm × 59.5 cm × 59.5 cm), as shown in Figure 3, in which the temperature was maintained at 26±1 °C using a thermoelectric cooling system. The chamber was supplied air using a vacuum pump with a mass flow controller (Gilair Plus by Sensidyne), such that the air exchange rate (AER) was maintained at 0.5±0.05 h^{-1}. The air was filtered using an activated carbon and HEPA filter (Coda® Xtra Inline® Filters-GREEN CXGR-001) installed in the air supply line. Thus, we maintained the chamber's pressure slightly above atmospheric, which helps prevent infiltration of outside particles into the chamber. Three fans were installed in the chamber (two at a vertical wall and one at the top wall) to provide well-mixed conditions. The study continuously monitored the temperature and relative humidity (RH) inside the chamber by using an indoor air quality (IAQ) probe (Greywolf DSIAQ-PLUSTAB10-DSII) together with the size-resolved particle concentration by using a laser particle spectrometer (Grimm 11-A).

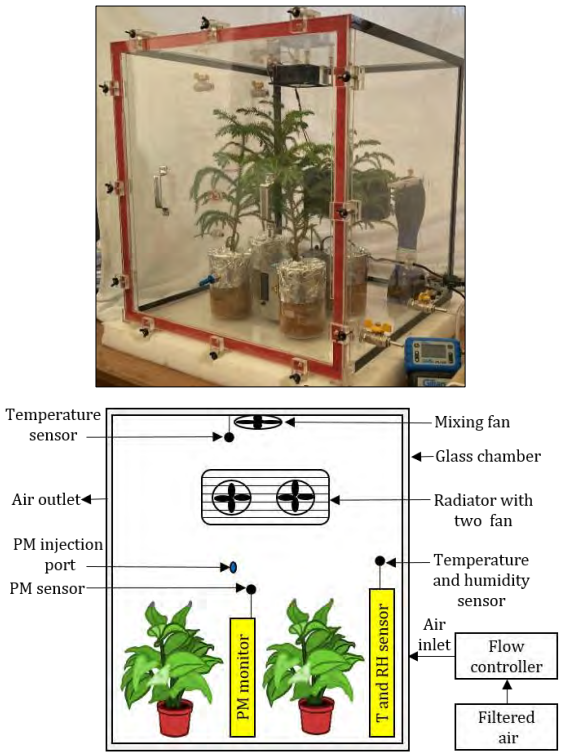

Figure 3. Experimental setup (Actual and schematic).

Experimental procedure

To study the PM removal by the different plant species, this investigation measured the particle (generated using an incense stick) removal rates inside the environmental chamber, with and without the plant specimens kept inside (details provided in the next paragraph). We first cleaned the chamber with distilled water and dried it, and then placed either four empty-pots (control experiment) or four potted-plants (treatment experiment) inside the chamber. Subsequently, the chamber was ventilated for about 0.5 hours, until the chamber's total PM count reached below 9000 particles/l ($PM_{2.5}$ < 1 μg/m^3). Next, particles were injected inside the chamber until the PM concentration reached above 5×10^6 particles/l ($PM_{2.5}$ between 350–750 μg/m^3), and we monitored the size-resolved concentration of PM inside the chamber with time using the laser particle spectrometer kept inside the chamber. The experiments were concluded after about 2.5 hours from the time particles were injected in the chamber, when the PM concentration reached

below 9000 particles/l. We tested each plant species three times (three control and three treatment experiments) by using the same protocol to quantify the repeatability of the experimental results.

Quantifying particle deposition velocities

To quantify the size-resolved PM removal rates by the different plant species, we estimated the deposition velocities for different particle sizes, which is analogous to the heat transfer coefficient, and characterize the PM uptake by plant surfaces. To calculate the PM deposition velocity for the plants, we used a simple mass balance model to estimate the contributions of the chamber and plant surfaces towards PM removal. Assuming well-mixed conditions inside the chamber and neglecting the inlet particle concentration and particle agglomeration, the concentration balance for a particular particle size is given by:

$$\frac{dC}{dt} = -AER \times C - \frac{v_C \times A_c \times C}{V} - \frac{n \times v_p \times A_p \times C}{V} \quad (1)$$

where C is the real-time particle concentration inside the chamber (in particles/cm^3) corresponding to a particular size, t the time (in h), AER the air exchange rate (in h^{-1}), n the number of plants kept inside the chamber, v_C and v_p the deposition velocities (in cm/h) on the chamber and plant surfaces, respectively, A_c and A_p the areas (in cm^2) of the chamber and plant surfaces, respectively, and V the air volume inside the chamber (in cm^3). We estimated the size-resolved deposition velocities on the plant surfaces (v_p) by measuring the real-time concentration of the particles injected inside the chamber (with and without the plant specimen inside) together with other physical parameters (AER, A_c, A_p, and V).

Effectiveness of plants for PM removal

To quantify the effectiveness of indoor plants for PM removal in real indoor settings, equation 1 was modified to account for infiltration of outdoor particles and indoor particle sources, as given below:

$$\frac{dC}{dt} = -AER \times (C - C_{out}) - \frac{n \times v_p \times A_p \times C}{V} - \frac{v_r \times A_r \times C}{V} + \frac{E}{V} \quad (2)$$

where C_{out} is the real-time concentration of outdoor PM (in particles/cm^3), E the PM generation rate due to indoor sources (particles/h), v_r the indoor PM particle deposition velocity for room surfaces, and A_r the area of room surfaces (cm^2).

By assuming C_{out}, C, E, and AER values as constant, equation 2 can be used to obtain the steady-state indoor PM concentration (with n indoor plants kept inside) as:

$$C_{with\ n\ plants} = \frac{AER \times C_{out} + \frac{E}{V}}{AER + \frac{v_r \times A_r}{V} + \frac{n \times v_p \times A_p}{V}} \quad (3a)$$

In the absence of plants ($n = 0$) the indoor PM concentration would be given by:

$$C_{without\ plants} = \frac{AER \times C_{out} + \frac{E}{V}}{AER + \frac{v_r \times A_r}{V}} \quad (3b)$$

To quantify the impact of keeping plants on the reduction in the indoor PM concentration, we defined ε as:

$$\varepsilon = \frac{C_{without\ plants} - C_{with\ n\ plants}}{C_{without\ plants}} \times 100 \quad (4)$$

Finally, we calculated the required number of plants (n) for achieving a desired level of PM reduction (ε) by substituting $C_{with\ n\ plants}$ and $C_{without\ plants}$ into equation 4 from equations 3a and 3b, respectively, as follows:

$$n = \frac{\varepsilon}{1 - \varepsilon} \times \frac{AER + \frac{v_r \times A_r}{V}}{\frac{v_p \times A_p}{V}} \quad (5)$$

RESULTS AND DISCUSSIONS

Figure 4(a) shows the variation of normalized concentration of 0.25 µm sized particles with time for the experiment conducted with and without the Christmas plant placed inside the environmental chamber. It can be seen that when Christmas plants were kept inside the chamber, the particle concentration decayed much faster than that without the plant, which was due to the PM uptake by the plant surfaces. However, no such effect was observed when Ficus plants were kept inside the chamber as shown in Figure 4(b), meaning that the particle uptake by the Ficus plants was very small. The PM uptake by the Croton plants was also very small (results not shown). From the decay data obtained for different particle sizes, we also estimated the size-resolved deposition velocities for different plant species, as shown in Figure 5. From the figure, it can be observed that deposition velocities ranged between 32.4±10.6 to 41.0±10.8 cm/h, 0.6±1.6 to 2.5±3.27 cm/h, and −0.09±3.8 to 6.07±6.28, for the Christmas, Ficus, and Croton plants, respectively, which were similar in magnitude to those reported by Panyametheekul et al. (2018).

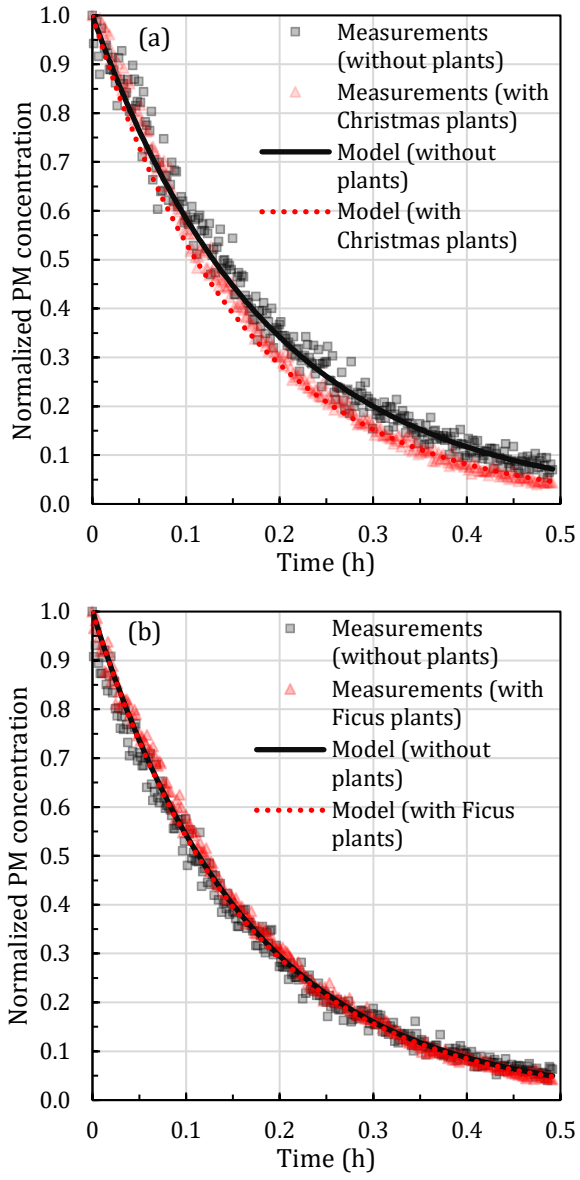

Figure 4. Normalized concentration decay of 0.25 µm sized particles inside the environment chamber in the absence and presence of a) Christmas and b) Ficus plants.

The deposition velocities were significantly higher for the Christmas plant as compared to the other plant species probably because Christmas plant has needle-shaped leaves containing mucus oils on its surfaces, which creates favorable conditions for particle deposition and prevents them from being blown away (He et al., 2020). The deposition velocities were also found to be nearly constant with particle sizes for the different plant species because the particles generated by the incense stick had a narrow size range (0.25 µm to 0.50 µm). Nevertheless, particle sizes used in this study well represents the typical indoor particle size (Li & Hopke, 1993).

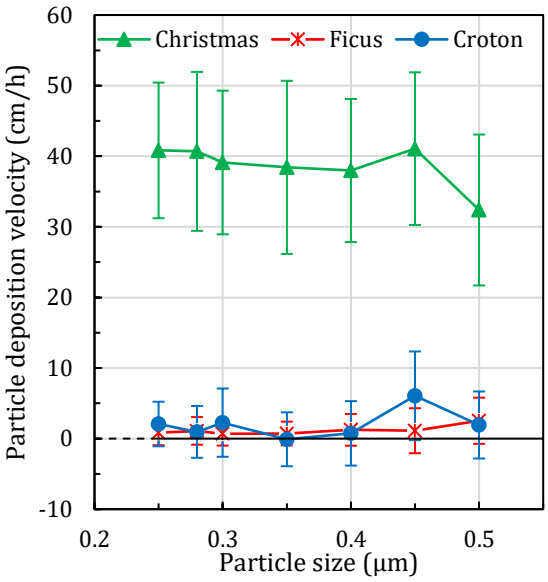

Figure 5. Size resolved particle deposition velocities of three indoor plant species. Error bars show one standard deviation.

To extrapolate the results to realistic indoor conditions, we used equation 5 to estimate the number of Christmas plants required for obtained a given amount of PM reduction (ε) in a small residential room since Christmas plants had the highest particle removal rates. The room was assumed to 3.0 m × 3.6 m × 2.4 m in size, with a surface area to volume ratio of 3 m^{-1}, a representative value for furnished rooms (Nazaroff & Nero, 1988). We selected two typical values of $PM_{2.5}$ deposition velocities on indoor surfaces (v_r): 3.7 cm/h and 9.0 cm/h, representing rooms in urban and rural indoor environments, respectively (Riley et al., 2002). The $PM_{2.5}$ deposition velocities on plant surfaces (v_p) was assumed to be 39 cm/h, which is the average value obtained from our measurements.

Figure 6a and 6b show the number of plants required for achieving desired percentage reductions in $PM_{2.5}$ for the urban and rural indoor environments, respectively, at different AERs. From the figures, it can be observed that in both environments, as the requirement of $PM_{2.5}$ reduction (ε) increases, the number of plants also increase significantly. For example, for achieving 10% reduction in indoor $PM_{2.5}$ concentrations ($\varepsilon = 10\%$), the required number of Christmas plants are 35 and 44 for urban and rural indoor environments, respectively, at an AER of 0.5 h^{-1}. However, at the same AER, for achieving 50% reduction in indoor $PM_{2.5}$ concentrations ($\varepsilon = 50\%$), the required number of plants exceeds 300 in both indoor environments. Figure 6 also shows that as the AERs increase, a much larger number of plants are required for achieving the same $PM_{2.5}$ reduction levels. Thus, indoor plants only seem to be a feasible option for reducing $PM_{2.5}$ in those indoor settings that have low AERs.

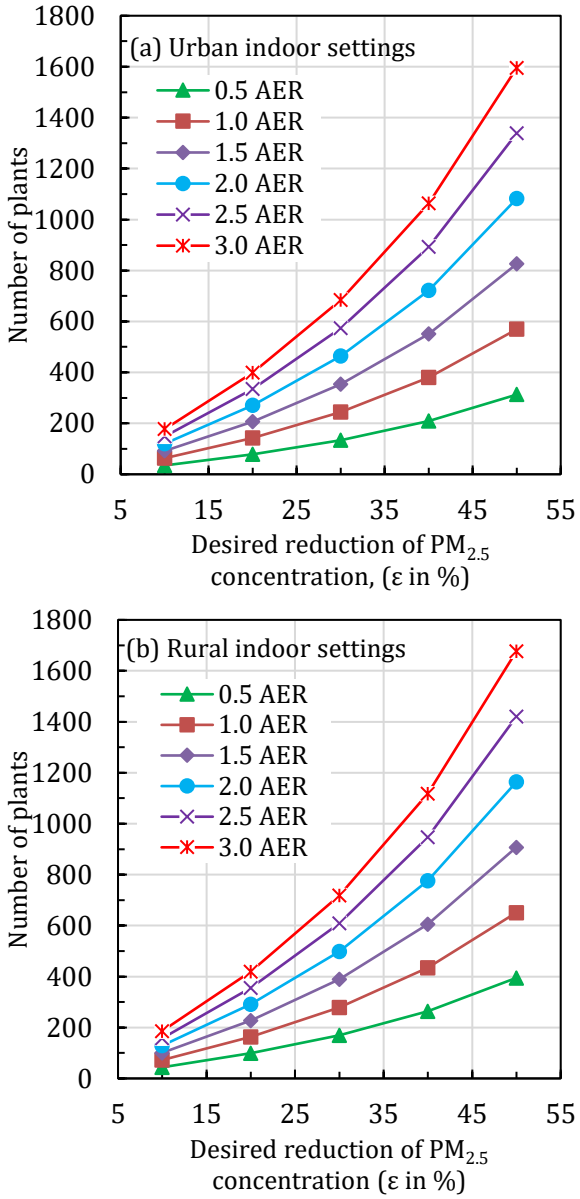

Figure 6. Christmas plants required for $PM_{2.5}$ reductions at different AERs (in h^{-1}) in a) urban and b) rural indoor environments.

CONCLUSIONS

This investigation estimated the particle deposition velocities for three different plant species by conducting experiments in an environmental chamber and using a simple mass balance model. The plant species tested were Christmas plant (*Araucaria heterophylla*, a needle-leaved plant), Ficus plant (*Ficus retusa*, a small-leaved plant), and Croton plant (*Codiaeum variegatum*, a broad-leaved plant). The estimated particle deposition velocities ranged between (32.4±10.6 to 41.0±10.8) cm/h, (0.6±1.6 to 2.53±3.27) cm/h, and (−0.09±3.8 to 6.07±6.28) cm/h for the Christmas, Ficus, and Croton plants, respectively, for particle sizes between 0.25–0.50 µm. Thus, the Christmas plant was found to be most suitable for particle removal from indoor environments since it had the highest deposition velocities.

We further estimated that 35–44 Christmas plants would be required for reducing the steady-state $PM_{2.5}$ concentrations by 10% at an air exchange rate of 0.5 h^{-1} in a small residential room of size 3.0 m × 3.6 m × 2.4 m. At higher air exchange rates, a much larger number of plants would be required for achieving the same $PM_{2.5}$ reduction levels. Thus, indoor plants only seem to be a feasible option for reducing $PM_{2.5}$ in indoor settings at low air exchange rates.

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