Sansevieria trifasciata are better dead than alive for airborne particulate matter removal

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Abstract

Particulate matter (PM) is a common air pollutant linked to many human deaths and illnesses worldwide. Once emitted in the air, PM is most effectively removed by plants in phytoremediation. While the physical mechanics and factors of phytoremediation have been well-studied, there has been little attention regarding its biological mechanisms. In this empirical study, we measure the net effect of biological processes in *Sansevieria trifasciata* on its ability to remove PM from an enclosed space by comparing the time taken for PM to decrease in enclosures containing living specimens versus dried and pressed specimens. Our results show that live specimens are in fact worse at removing PM from their enclosures as compared to dried and pressed spec-

imens. This suggests that biological processes can be detrimental to PM removal for some plants species.

Keywords—phytoremediation, air pollution, particulate matter, *Sansevieria trifasciata*, Stefan flow, dry deposition

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1 Introduction

Particulate matter (PM) is a significant component of air pollution.[1] Human exposure to PM is associated with cardiovascular, respiratory, and other detrimental health conditions.[2] $PM_{2.5}$, a subset of PM with diameter smaller than 2.5 µm, has alone been estimated to cause 3.3 million premature deaths per year, worldwide.[3]

Given its highly varied origins,[4;5;6;7] PM is difficult to tackle at its sources of emission, and has to be complemented by remediation measures after its release into the atmosphere[8]. Then, phytoremediation—the mitigation of pollutants by plants—is the one of the few cost-effective methods of removing PM from the air.[8] In particular, these phytoremediation methods include the use of urban trees and forests,[9;10;11;12;13] indoor potted plants,[14;15] green walls,[16;17] or active biofilters.[18;19]

To improve the efficiency of phytoremediation and thus PM removal from the atmosphere, it is important to identify exactly which factors have a direct impact on a plant's ability to remove PM

from the air.

In terms of physical mechanisms, PM is believed to be captured by plants through the process of dry deposition, in which PM is transferred to the surface of the plant in three stages.[20] First, PM is transported from the atmosphere to the quasi-laminar sublayer (a thin millimetre or smaller layer around the plant with minimal turbulence) via eddy diffusion and gravitational sedimentation effects. Then, the PM are transported from the sublayer to the surface of the leaf through diffusion, interception, impaction and sedimentation. Lastly, PM interacts with the surface of the plant and may adhere to it by either depositing directly on the plant surface, or by embedding into the plant wax over time.[21] PM deposited on leaves may also eventually be washed off by rainfall,[22] while a certain percentage of incident PM may undergo resuspension into the surrounding air.[23] Therefore, external morphological characteristics which affect the rate of dry deposition such as the root structure,[19] leaf shape,[24;25] arrangement,[26] and surface microstructure[21;27;23;28] consequently influence a plant's ability to capture PM from the air. By identifying these factors and the nature of their effects, we can make better decisions about which species of plant, structure of green wall, or form of biofilter would most efficiently remove PM from the air. It may even be possible to genetically engineer plants in order to maximise these factors for PM removal.

Research about the effects of biological processes on PM phytoremediation is scarce. While direct biological mechanisms of PM removal a la metabolism are unlikely, some studies suggest that there may be secondary effects at play, by showing that light intensity is positively correlated with PM removal in an enclosed space[29;30]. To our knowledge, however, there are no existing studies investigating the source of these effects, and the magnitudes or nature of their contribution to PM removal. For example, we could hypothesise that increased light intensity induces the widening of stomatal pores in plants, increasing the effective surface area available for dry deposition. But how does this compare to the negative effect of a stronger Stefan flow pushing PM away from the leaf surface[31]? To begin answering these questions, it is important to first determine the net marginal effect of biological processes on PM removal rates. Then, further studies of these biological processes can help us maximise the efficiency of PM phytoremediation by informing our selection of plant species.

In response to this gap in literature, we designed and conducted an empirical study to investigate

the net effect of biological processes on PM removal in plants. We do so by preparing a control consisting of a set of dried and pressed plant specimens, then comparing its efficiency of PM removal in an enclosed experimental chamber against a set of live specimens.

2 Materials and Methods

2.1 Materials

In this study, we quantified PM removal by measuring the rate of decrease of both $PM_{2.5}$ and PM_{10} of air in a small enclosed experimental chamber. We formed 3 treatment and control groups: (i) a pot with living specimens, (ii) a pot with dried and pressed specimens, and (iii) an empty control group. These groups would allow us to estimate the marginal effects of biological processes and surface area provided by the plant leaves on PM removal rate.

The experimental chambers was formed by 3 'open-bottom' acrylic enclosures of size $40\,\text{cm} \times 40\,\text{cm} \times 60\,\text{cm}$ ($L \times W \times H$) taped onto a large rubber sheet. Within each chamber is the control or treatment, a PM sensor, a ceramic bowl to contain the PM source, and a small USB-powered fan for air circulation. Three 2.5 mm diameter holes were drilled into the walls of each chamber: one was used as a cable pass-through for the PM sensor and fan, sealed using a silicone sealant; the other two were used as venting ports for excess PM (Figure 1).

The plant specimens used are individuals of the species *Sansevieria trifasciata*, a common ornamental plant. A total of three potted *S. trifasciata* of similar size were obtained from a local distributor. Each pot contained multiple individual plants chosen by the distributor so that the leaf areas of each pot were roughly equivalent. To form the two treatment groups, one set of specimens was removed from its pot, dried while pressed under pressure (a common plant preservation technique), then placed back into the pot; the other set was left unmodified.

We used a low-cost laser scattering sensor to measure the levels of $PM_{2.5}$ and PM_{10} in the range $0.0\,\mu\text{g}\,\text{m}^{-3}$ to $999.9\,\mu\text{g}\,\text{m}^{-3}$.[32] The sensors were connected to a Raspberry Pi Zero, a small single-board computer, to collect readings every minute. Small quantities of dried plant matter were burnt in the ceramic bowls in order to generate PM.

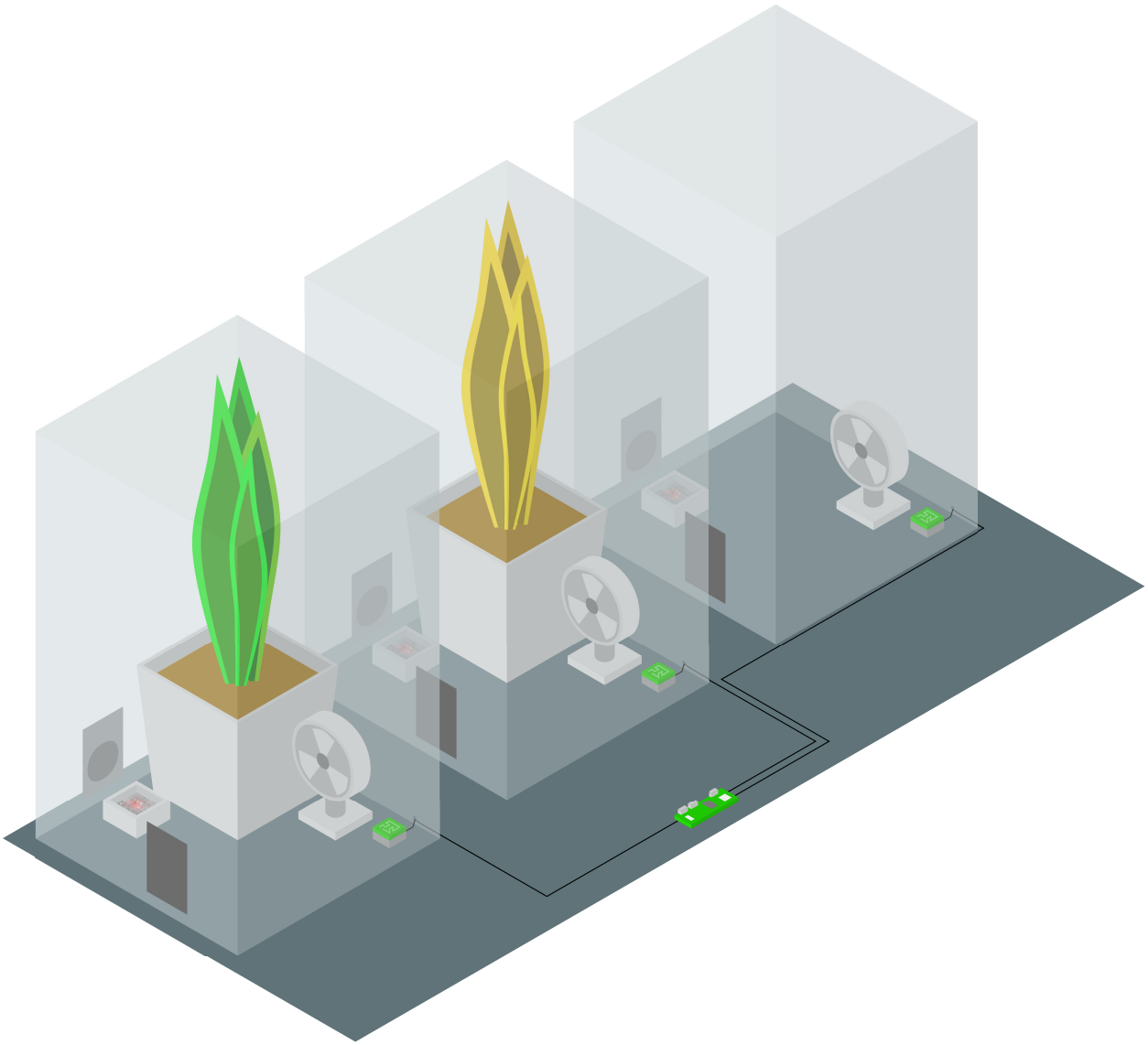

Figure 1: Left to right within each experimental chamber: a ceramic bowl to contain the PM source, the treatment or control, a small USB-powered fan, and a PM sensor. Each chamber has three 2.5 mm diameter holes: one was used as a cable pass-through, sealed using a silicone sealant; the other two were used as venting ports for excess PM (shown covered in black-coloured tape). The PM sensors were all connected to a Raspberry Pi Zero, a small single-board computer, to collect readings.

2.2 Experimental Procedure

For each trial, we placed and ignited a small quantity of dried plant matter in the ceramic bowl. The two venting holes were then left open to allow the PM to escape until the concentration of $PM_{2.5}$ fell to $950.0\,\mu g\,m^{-3}$, within range of the sensors. Then, we sealed the venting holes with tape, ensuring that each chamber is fully sealed before the concentration of $PM_{2.5}$ dropped to $900.0\,\mu g\,m^{-3}$. The trial was then left to run for at least 6 hours in the same lighted room, with about 24 hours in-between each trial.

We rotated the 3 treatment groups evenly about the 3 chambers for a total of $n = 45$ trials—15 trials for each treatment or control, each set of 15 is split equally about each chamber.

2.3 Statistical Methods

Statistical analyses and plots were generated using *R* and its related packages[33;34]. Each $PM_{2.5}$ and PM_{10} concentration in the experimental chamber Y was modelled to exponentially decay with time t, modified with effects due to the presence of additional surface area provided by leaves of the live and dead plants (represented by X_s), and the presence of some biological activity in the live plant only (represented by X_b); and effects due to difference in experimental chambers and sensor calibrations (represented by control variables X_B, X_C). For example, the trials with dead plants was encoded with $X_s = 1$ and $X_b = 0$, while those with live plants are encoded with $X_s = X_b = 1$. All explanatory and control "X" variables are binary indicator variables. Suitability of the model was checked with the Bayesian information criterion.

$$Y = \exp\{\beta_0 + \beta_1 t + \beta_2 X_B + \beta_3 X_C + \beta_4 t X_B + \beta_5 t X_C + \beta_6 t X_s + \beta_7 t X_b\}$$

The data was fit using a log-linked generalized linear model with Gamma random component. Of interest are the marginal effect of additional surface area provided by leaves of the live and dead plants, β_6; and the marginal effect of biological activity in the live plant only, β_7. We can also obtain the estimated half-life of PM in each condition with $(\ln 2)/\lambda$, where $\lambda = \beta_1 + \beta_4 X_B + \beta_5 X_C + \beta_6 X_s + \beta_7 X_b$ (obtained from the terms with time t).

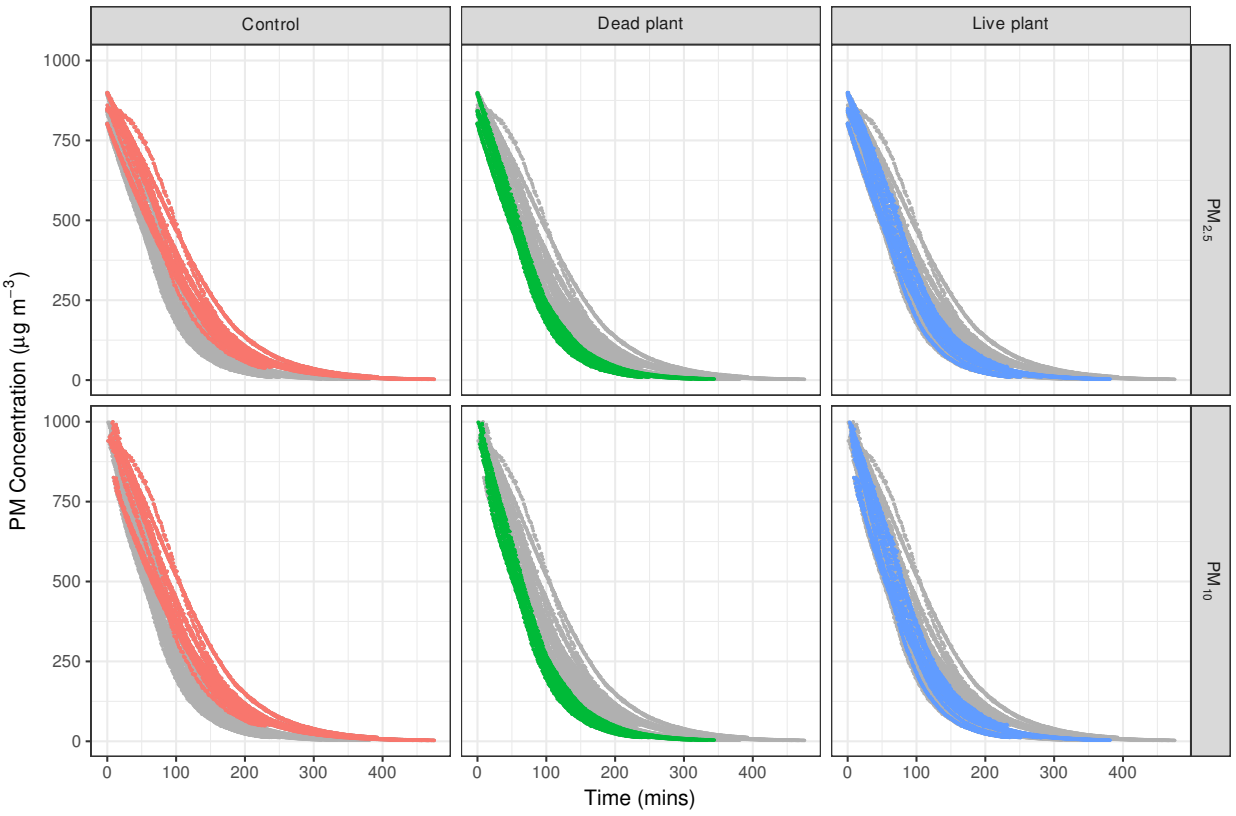

Figure 2: Scatter plots of PM concentration against time, after controlling for differences due to experimental chambers and sensor calibrations. Grey-coloured points in the background are readings from other conditions within the same PM type.

3 Results and Discussion

3.1 Results

All coefficient estimates are significantly non-zero (Table 1). As compared to the empty control, trials using the dead plant reduce the half-life of airborne PM in the experimental chamber; compared to using the dead plant, trials using the live plants increase the half-life of airborne PM. This result is true and the effect sizes are non-trivial across all experimental chambers, for both $PM_{2.5}$ and PM_{10} (Figure 2 and Table 2).

	Coefficient	Estimate	Std. Error	95% confidence interval
$PM_{2.5}$	β_0	7.077	0.005 820	[7.066 , 7.088]
	β_1	−0.012 76	0.000 032 11	[−0.012 83 , −0.012 70]
	β_2	0.054 00	0.009 023	[0.036 03 , 0.071 97]
	β_3	0.1127	0.007 823	[0.097 16 , 0.1283]
	β_4	−0.006 306	0.000 063 74	[−0.006 435 , −0.006 177]
	β_5	0.002 750	0.000 039 90	[0.002 670 , 0.002 830]
	β_6	−0.004 961	0.000 025 15	[−0.005 011 , −0.004 910]
	β_7	0.001 932	0.000 027 04	[0.001 879 , 0.001 985]
PM_{10}	β_0	7.192	0.005 814	[7.181 , 7.203]
	β_1	−0.012 78	0.000 031 67	[−0.012 84 , −0.012 72]
	β_2	0.063 64	0.009 038	[0.045 78 , 0.081 51]
	β_3	0.1576	0.007 910	[0.1419 , 0.1733]
	β_4	−0.006 396	0.000 063 18	[−0.006 523 , −0.006 270]
	β_5	0.002 558	0.000 039 65	[0.002 479 , 0.002 637]
	β_6	−0.005 015	0.000 024 21	[−0.005 063 , −0.004 967]
	β_7	0.001 944	0.000 025 96	[0.001 893 , 0.001 995]

Table 1: Summary of coefficient estimates from the regression. Highlighted rows are statistics for the coefficients related to X_s, encoding the presence of surface area provided by leaves of either the dead or live plants; and X_b, encoding the presence of some biological activity.

	Chamber	Control	Dead plants	Live plants
$PM_{2.5}$	A	54.3; [54.0, 54.6]	39.1; [38.9, 39.4]	43.9; [43.4, 44.4]
	B	36.3; [36.0, 36.7]	28.8; [28.6, 29.1]	31.4; [31.0, 31.8]
	C	69.2; [68.2, 70.2]	46.3; [45.7, 46.9]	53.1; [52.2, 54.2]
PM_{10}	A	54.2; [54.0, 54.5]	39.0; [38.7, 39.2]	43.7; [43.3, 44.2]
	B	36.1; [35.8, 36.5]	28.7; [28.4, 28.9]	31.2; [30.8, 31.6]
	C	67.8; [66.9, 68.8]	45.5; [44.9, 46.1]	52.1; [51.2, 53.1]

Table 2: Estimated half-lives (in minutes) of PM for each condition, in each chamber. Intervals shown are the 95% confidence intervals.

3.2 Possible Mechanisms

As expected, the introduction of additional surface area from leaves of either dead or live plants reduces the half-life of airborne PM in the experimental chambers, likely since there is more area available for dry deposition to occur. What is unexpected, however, is the marginal increase in half-life due to the net effects of biological activity in the live plants. We consider these biological effects to be either due to primary or secondary effects.

Primary biological effects refer to any direct interaction between plant cells and PM such that the PM is degraded, absorbed, or otherwise removed from consideration. Such primary effects are unlikely, since PM is usually much larger than the pore sizes of plant cell walls[35], so that the cells cannot interact directly with PM.

More likely are secondary effects, in which biological processes affect the efficacy of physical mechanisms of PM removal. For example, transpiration increases surrounding humidity, promoting PM coagulation[36;37;30]; photosynthesis and exposure to light induces opening of the stomata in some plants, making the intercellular air space (IAS) surfaces within leaves available for dry deposition[38]. Negative secondary effects are possible too, and are likely the cause for the marginal increase in PM half-life we can attribute to the live plants in this experiment. In particular, we suspect that transpiration in the live plants produced a significant magnitude of Stefan flow, where gas molecules flow away from an evaporating surface[31]; thereby pushing PM away from the quasi-laminar sublayer, interfering with the process of dry deposition and thus reducing PM removal efficiency.

3.3 Implications

Previous studies have shown that increasing light intensity improves PM phytoremediation in certain plant species[29;30]. In this article, we show that in *Sansevieria trifasciata*, biological processes (including photosynthesis) have a net *negative* effect on PM phytoremediation. These seemingly contradictory results suggest that the biological factors of PM phytoremediation are complex, and still need to be elucidated. Then, a deeper understanding of the biological factors at play can better inform our choice of plant species to maximise PM phytoremediation.

For example, plants which utilise the Crassulacean acid metabolism (CAM) pathway, typically understood of as an adaptation to arid environments, tend to have smaller IAS[39], and transpire less in the day than at night[40]. Indeed, the *Sansevieria trifasciata* plants we use in this study utilise this CAM pathway. Does this imply that CAM plants are worse PM phytoremediators because they do not release much water vapour for PM coagulation and have less available IAS for dry deposition? Or are they better because a reduced rate of transpiration implies a weaker Stefan flow? How do the answers change from day-time to night-time?

As far as we know, these questions of secondary biological mechanisms in PM phytoremediation have received little attention in the literature. In showing the net negative effect of biological activity on PM phytoremediation, taken in contrast with prior literature demonstrating a positive effect of light intensity, we hope that our study will motivate and contribute towards the further study of these complex biological effects.

4 Data Availability Statement

All data, models, and programs generated and used during the study are available online at `https://github.com/ning-y/plants-pm-data`.

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6 Declaration of Conflicting Interests

The authors declare no conflict of interest.

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