Airborne particulate matter accumulation on common green wall plants

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Abstract

In order to better design greening systems for effective particulate matter (PM) removal, it is important to understand the impact leaf traits have on PM deposition. There are however, inconsistences amongst the leaf traits that have previously been correlated with PM accumulation. The aim of this paper was to identify vegetation characteristics of green wall plants that were associated with the accumulation of particulate matter. To determine patterns associated with different leaf morphologies, eleven plant species were sampled across 15 sites, over a 6 month duration. PM deposition was determined gravimetrically and its associated size fractions determined microscopically. Linear mixed models were used to identify statistical patterns relating to differences in PM deposition across plant species. PM deposition and the relative frequencies of particle size fractions were found to be statistically different amongst species, sites and months. Green wall plants were shown to be effective at PM accumulation as all of the plant species assessed had equivalent PM removal efficiency, with minimal evidence of influential leaf characteristics that could enhance PM removal.

Keywords

Particulate matter, air pollution, green walls, living walls, sustainability, urban air quality, biofiltration

Introduction

Air pollution is a major risk factor to human health (Dockery et al., 2007) and is a widespread environmental concern (Rai 2016). Airborne particulate matter (PM), is one of the common ‘criteria pollutants’ (USEPA 2004). It is a heterogeneous solid–liquid mixture, containing toxic substances that is transported in the atmosphere, sometimes over long distances (WHO 2005; Yu et al. 2006; Oishi 2016). Health problems caused by exposure to particulate pollution are related to the sizes of atmospheric particles (Dockery et al., 1993; Nemmar et al., 2002; EEA, 2007). Compared to large particles, small particles are both more damaging to health (WHO 2006), and more stable in the air and are slower to achieve natural sedimentation on land surfaces (Lin et al. 2018).

There is a strong relationship between increased levels of ambient PM exposure and adverse health conditions (WHO 2013). Coarse particles (PM_{10}), fine particles ($PM_{2.5}$) and ultra-fine particles ($PM_{0.1}$ and smaller) are known for their toxicity and ease of inhalation (Solomon et al. 2012). PM exposure can cause cardiac and respiratory diseases (Polichetti et al. 2009), including asthma (Anderson et al. 2013), atherosclerosis (Araujo 2011), lung cancer and cardiopulmonary diseases (Pope et al. 2011; Solomon et al. 2012). ~~Technologies~~ Actions that reduce our exposure to particulate matter are therefore paramount to ensure healthy and safe ambient environmental conditions.

Vegetation has significant potential in urban regions as a sink for PM (Popek et al. 2013; Räsänen et al. 2014). PM is removed from the ambient air by adhesion to leaf surfaces (Ottelé et al. 2010; Sternberg et al. 2010), with additional sequestration evident from penetration of the wax layer of leaves if the PM contains organic pollutants of a lipophilic nature (Dzierzanowski et al. 2011). Vegetating urban landscapes with trees is a process constrained by many factors, including space limitations, sunlight availability, sub-surface infrastructure, the size ratio between the tree and adjacent buildings and the suitability of the prevailing soil (Johnston and Newton 2004). Green walls in comparison, do not consume additional space at the street level, instead utilizing pre-existing building surfaces, thus increasing the particulate collection area of the building due to the large surface area presented by plants (Ottelé et al. 2010).

Vegetation characteristics such as leaf orientation, shape, size and surface morphology have been identified as significant factors associated with different ~~increased~~ PM deposition (Litschke and Kuttler 2008; Petroff et al. 2008; Chen et al. 2016; Leonard et al. 2016). Macrostructural leaf traits that have been shown to increase PM accumulation include whorled leaf arrangements and larger leaf area; whilst advantageous microstructural traits include pubescence, low stomatal densities, rough surfaces and thick waxy epicuticles (Chaturvedi et al. 2013; Popek et al. 2013; Mo et al. 2015). Additionally, the chemical composition and structure of the epicuticular wax has also been found to be influential on PM accumulation (Dzierzanowski et al., 2011; Leonard et al., 2016). Similarly, the structure of leaf hairs can also alter PM deposition, with some leaf hairs exhibiting hydrophobicity, attracting charged particles such as heavy metals found in PM (Fernàndez et al., 2014). Nonetheless, the plant traits that have been correlated with increased PM accumulation are inconsistent amongst previous research. For example, different ideal leaf shapes for PM removal have been concluded from different studies, with Beckett et al. (2000), Dzierzanowski et al. (2011) and Wang et al. (2011) noting the positive effects of needle like leaves in comparison to broad leaved species for PM accumulation. Leonard et al. (2016), in contrast, found that lanceolate leaves demonstrated more effective PM accumulation than both needle-like and linear leaves.

Advantageous microstructural traits are also inconsistent throughout the literature, with some previous studies noting the importance of epicuticular wax on PM deposition (i.e. Dzierzanowski et al., 2011; Sæbo et al., 2012), whilst others have found a negative relationship between PM deposition and epicuticular wax (i.e. Liu et al., 2012). Similarly, leaf hair presence has been associated with high PM accumulation in many studies (i.e. Beckett et al. 2000; Kardel et al. 2012; Ram et al. 2014), however, Perini et al. (2017) detected a negative association between PM capture and leaf hairs. In view of these discrepancies, it remains important to determine the relationships between green wall plants, leaf traits and ambient PM accumulation; so as to maximize practical PM reduction with appropriate plant use.

Aim

The PM deposition capacity of plants has received insufficient research attention (Pugh et al. 2012). Whilst the influence of individual leaf traits on PM accumulation is noted in the literature, the interactions between different leaf combinations is not yet understood (Leonard et al. 2016). Additionally, uncertainty remains surrounding the impact of individual leaf traits on PM retention due to variable conclusions from previous studies (Weerakkody et al. 2018). In order to better design greening systems for maximum PM removal, the impact leaf traits have on PM deposition must be better known. Previous research on the ability of plants to reduce ambient PM has been heavily focused on single species testing, usually using climbing plant species such as *Hedera helix* (Ottelé et al. 2010; Sternberg et al. 2010; Cheetham et al. 2012). Research on green walls and their capacity to reduce PM is limited to a few studies

(Perini et al. 2017), and is thus not yet well understood. Given the high leaf density presented by most green wall systems, it is probable that their PM accumulation potential is substantial.

The aim of this paper was to assess the effectiveness of plant species within green walls in Sydney Australia for accumulating ambient particulate matter, and to identify vegetation characteristics that result in maximum pollutant attenuation. The authors hypothesise that differences will emerge between the species PM accumulation capacity and that the higher accumulating species will exhibit similar traits which will be favourable in PM attenuation.

Method

Sample Sites

Fifteen sites within the urban Sydney, Australia region were selected based on the presence of similar outdoor green walls. Green walls were of a modular design, produced by Junglefy P/L, Sydney Australia. The sites varied in location, use, primary ambient pollutant sources and overall air quality (see Table 1 below). All sampled leaves were taken from pre existing *in situ* green walls. All 15 sites had their green walls installed a minimum of 24 months prior to sampling. It was not possible to standardise the year of green wall implementation in the current study, as these walls had been installed to various enterprises years prior to the study. Whilst the exposure time was not known, the sample size used was sufficient to randomize these effects within, but not amongst species. Thus leaf life expectancy is another characteristic that will differentiate between the various species in their capacity to collect PM. Furthermore, only young mature leaves were selected. Additionally the rainfall volume was consistent across the sampling area and rainfall events temporally standardised the leaves through time.

[Table 1 near here]

Ambient PM Concentrations

The ambient PM concentrations at each site was assessed using a DustTrack II 8532 laser densitometer (TSI, Shoreview, Minnesota). At each site, each PM size fraction (Particulates <10µm in diameter - PM_{10} and Particulates <2.5µm in diameter - $PM_{2.5}$) were sampled obtaining a time weighted average. Air quality samples were restricted to collection between 10 a.m. and 3 p.m. to avoid spikes created by peak hour commuters (Irga et al., 2015). Samples were taken once a month at each site for the projects 6 month duration (June 2017 – November 2017). The *in situ* PM conditions were monitored to determine any correlations between ambient PM conditions and species PM accumulation.

PM Deposition

To determine the effect of different plant species on PM accumulation, 11 species present amongst the test sites with different shapes, sizes and morphologies were chosen (Table 2, see below, before ~~above~~ ***Statistical Analysis***). Not all plant species were present at each site.

Leaf arrangement (whorled, opposite or alternate) and leaf shape (elliptic, lanceolate, needle like, linear or obovate) were determined for the sampled species as per Leonard et al. (2016). At each site, 5 replicate leaves of each species were hand-picked and individually sealed into pre-labelled sample bags to minimize PM loss~~.~~, and was consistent amongst treatmnets. This form of sample collection has been used in other studies (i.e. in Leonard et al. 2016). The position of leaf samples was randomized across the green walls at each sampling occasion and month to randomize variations in green wall characteristics at each site. Samples were taken monthly for a 6 month period from June to November, 2017.

From the 5 replicate leaves, 3 were used to determine the deposited PM mass using the Chen et al. (2016) dry gravimetric technique. This was carried out by weighing the intact leaves, then removing PM using a camel hair brush and reweighing. The brush used was soft bristled and leaves were handled carefully, to avoid removing any leaf component in this process i.e. wax layers and leaf hairs. The leaf was then sized with a leaf area meter (Licor LI-3000-A, Nebraska, USA) to obtain an accurate area measurement. The amount of PM collected for each species was expressed per unit area of leaf, as PM was dusted from both adaxial and abaxial surfaces. Previous studies (Dzierzanowski et al. 2011; Leonard et al. 2016) similarly expressed their results. The deposited PM content was then calculated using Formula 1.

Formula 1:

$$PM\ Deposition\ \left(\frac{mg}{cm^2}\right) = \frac{(Mass\ of\ intact\ leaf - initial\ mass\ of\ leaf)}{Total\ surface\ area\ of\ leaf}$$

PM Size Fractions

To quantify the proportional contribution of different particle size fractions to the PM deposited on the green wall plant species, on the remaining 2 leaves from each species, for each site and month, a 2 cm length of adhesive tape was placed onto the middle upper surface of each leaf, pressed down, gently removed and placed onto a microscope slide. Weerakkody et al. (2017) observed that the leaf blade had less variable PM distribution compared to leaf tip, base, mid rib and edges, and as such the leaf blade only was sampled for the current study. Images of the microscope slides were then taken using a Nikon Automated Upright Fluorescence Microscope at x20 magnification for 15 random surface points on each slide. Each image was then analysed using NIS-Elements Viewer 4.20, which generated data for the diameter for each particle present on the image. From this, two PM size fraction ranges ~~bins~~: $PM_{<5}$ and $PM_{>5}$ were categorized using MS Excel. Leaves can accumulate a range of different PM size fractions, and as such microscopic analysis was used to determine the probability of small and large sized PM deposition (PM < 5 mg cm^{-2} and PM > 5 mg cm^{-2}). Thus, each species will have a probability density result for PM < 5 mg cm^{-2} and PM > 5 mg cm^{-2} with these PM ranges being expressed for each species.

[Table 2 near here]

Statistical Analysis

Mean values for particle counts per image for the two PM fractions ($PM_{<5}$ and $PM_{>5}$) were determined for the eleven species for each month (June–October), at each site in which they occurred, from six replicate samples per species per site. Principal components analysis was performed using square root transformed ambient airborne PM data recorded near the green walls (two fractions, $PM_{2.5}$ and PM_{10}), with the first principal component (capturing 91% of the variance in the ambient PM data set) used as an independent variable in subsequent analyses.

To test for differences among species and whether leaf PM accumulation was related to ambient PM concentration, linear mixed models (LMMs) were fitted, using species as a fixed categorical factor (11 levels), ambient PM PC as a fixed continuous factor, and a species x ambient PM PC interaction term. To control for variation across months and variation within species across sites, two random factors were used; the month in which observations were recorded, and a nested species x site term. Where significant differences were found among species or for the species x ambient PM interaction, pairwise comparisons between species, or between slopes were made using a Tukey correction for multiple comparisons. Following this, the relationships between the two PM fractions were explored for each species, first using paired sample *t*-tests (repeated for all species), followed by LMM modelling of $PM_{>5}$ as a function of $PM_{<5}$, including a species x $PM_{<5}$ interaction term to test if the relationship between deposition of the PM fractions was consistent across species.

To test the effect of leaf traits on leaf PM deposition and their relationship with ambient PM, models were built with terms for the leaf traits (a fixed categorical factor with four levels), ambient PM (as a fixed continuous factor), a leaf trait term nested within species (fixed factor, included to test for differences among species with the same leaf traits), a leaf trait x ambient PM interaction term (fixed factor) and a leaf traits/species x ambient PM (fixed factor, included to test for differences in the relationships between ambient PM among species within leaf trait groups). The same random terms used in the first two models were also used in these models. In all models accumulated leaf PM data was log transformed prior to analysis.

Results & Discussion

Differences among species and relationship with ambient PM

Significant differences were found among species for the accumulation of both $PM_{<5}$ (χ^2_{10} = 75.1, P < 0.0001; Fig. 1a) and $PM_{>5}$~~10~~ (χ^2_{10} = 71.0, P < 0.0001; Fig. 1b); similar to the results of ~~previous studies (~~Leonard et al. (2016),~~;~~ Weerakkody et al. 2017~~,~~ and 2018~~)~~. No significant relationship was found between $PM_{<5}$ deposition and ambient PM concentration (χ^2_1 = 0.1, P = 0.7; Fig. 2a), and no significant interaction among species accumulated PM and ambient PM was detected (χ^2_{10} = 4.3, P = 0.9). For $PM_{>5}$, a significant interaction among species and ambient PM emerged (χ^2_{10} = 23.3, P < 0.01; Figs. 2b and 2c). The interaction was found to be generated by three species showing a significant association between higher accumulated PM and greater ambient PM (*C. comosum variegatum*: Variegated Spider Plant, *N. exaltata bostoniensis*: Boston Fern, and *N. glabra*: Goldfish Plant), and a further three species having a significant association between lower accumulated PM and greater ambient PM (*N. gracilis*: Walking Iris, *P. obtusifolia*: Baby Rubber Plant, and *P. xanadu*: Xanadu; Fig. 2c). With this difference likely driven by leaf trait differences, specifically between the small linear and large rosette species. More specifically, of the listed species, two small linear species (*N. exaltata bostoniensis*: Boston Fern, and *N. glabra*: Goldfish Plant) were found to have higher accumulated PM at greater ambient PM; whilst two of the large rosette species (*N. gracilis*: Walking Iris and *P. xanadu*: Xanadu) were found to have lower accumulated PM at greater ambient PM. Whilst the green wall species accumulated ambient PM, this was found to not be influential on reducing ambient PM conditions. This finding is not surprising as other studies have indicated that x amount of green walls would need to be implemented to make x amount effect on ambient conditions.

[Figure 1 near here]

[Figure 2 near here]

The density of the accumulated $PM_{<5}$ fraction was found to be significantly greater than the $PM_{>5}$ fraction density across all species (Fig. 3). This trend has also been observed in previous studies (i.e. observed in: Freer-Smith et al. 2005; Ottelé et al. 2010; Perini et al. 2017; Weerakkody et al. 2017, 2018). This finding suggests that green walls may be more effective at reducing smaller PM size fractions (e.g. Weerakkody et al. 2017), or that leaves are more capable or retaining smaller PM (e.g. Przybysz et al. 2014). The variation in PM deposition across size fractions is thought to be due to different deposition velocities resulting from the different aerodynamic behaviour displayed by different sized particles (Slin 1982; Weerakkody et al. 2017). For example, the increased turbulence in the boundary layer around a deposition surface has a greater effect on the turbulent transfer of smaller PM size fractions (Slinn 1982; Petroff et al. 2008). Additionally, the effects of deposition velocities vary amongst the various processes in which dry deposition can occur i.e. interception, impaction and sedimentation under gravity (Weerakkody et al. 2017), resulting in the PM deposition differences across size fractions.

[Figure 3 near here]

Regression of the $PM_{>5}$ fraction against the $PM_{<5}$ fraction resulted in a significant species x $PM_{<5}$ interaction ($\chi^2_{10} = 33.6$, $P = 0.0002$; Fig. 4a), driven by *N. exaltata bostoniensis* (Boston Fern) accumulating less $PM_{>5}$ for a given amount of $PM_{<5}$ when compared to *C. comosum* *variegatum*: Variegated Spider Plant, *N. gracilis*: Walking Iris, *P. obtusifolia*: Baby Rubber Plant, *P. Xanadu*: Xanadu, and *S. wallisii*: Peace Lily (Fig. 4~~b~~).

[Figure 4 near here]

The effect of leaf traits on PM deposition

Significant differences were found among species within leaf trait groups for $PM_{<5}$ accumulation ($\chi^2_7 = 41.3$, $P < 0.0001$; Fig. 5a), and also for $PM_{>5}$ ($\chi^2_7 = 42.1$, $P < 0.0001$; Fig. 5b), with the small linear-leaved species showing relatively large interspecific variation for both PM fractions. Significant differences among the leaf trait groups were found for $PM_{<5}$ ($\chi^2_3 = 33.9$, $P < 0.0001$; Fig. 6a), with the small linear-leaved species demonstrating lower accumulation of these particles compared to the medium and large rosette plant groups, mostly due to the low $PM_{<5}$ accumulation values recorded for *P. madagascariensis* (Variegated mintleaf), and *N. exaltata bostoniensis* (Boston Fern) (Fig. 3a). The medium linear, and medium and large rosette groups did not differ significantly for accumulation of the $PM_{<5}$ fraction (Fig. 6a). Leaf trait groups differed significantly for the deposition of $PM_{>5}$ ($\chi^2_3 = 31.4$, $P < 0.0001$; Fig. 6b). Whilst the small linear and medium rosette groups did not significantly differ for leaf deposition of $PM_{>5}$, the medium linear and large rosette groups showed comparatively higher values for $PM_{>5}$ (Fig. 6b). ~~The majority of previous studies~~ On the contrary, most of the results of other researches have observed higher PM deposition rates for smaller sized leaves (e.g. Freer-Smith et al. 2005; Weerakkody et al. 2017, 2018). The reasoning behind this is thought to be due to a reduced tendency of smaller leaves to move with the wind, and thus resuspend accumulated PM (Leonard et al. 2016), combined with larger edge effects for smaller leaves leading to a higher rate of PM impaction (Weerakkody et al.

2018). However, in the current study, the smallest leaves demonstrated the least effective PM accumulation. Weerakkody et al. (2017) did note that two of their small-leaved species showed comparatively low PM deposition, suggesting that this was a result of their lower rigidity and attendant lower capacity to withstand PM contaminated air flow, thus lowering the turbulence surrounding the leaf boundary. They concluded that small-leaved species with a complex morphology were the most efficient species for reducing ambient PM. It is thus possible that the current results were due to the soft structure and simple morphology of the tested species, in line with the findings of Weerakkody et al. (2017). Specifically, *N. exaltata bostoniensis* (Boston Fern) has small, very soft leaves that may not have been able to withstand and capture the PM within turbulent air as effectively as the small, yet hard-leaved Australian native species used in the study of Leonard et al. (2016).

[Figure 5 near here]

Similar to the effect on $PM_{<5}$, *P. madagascariensis* (Variegated Mintleaf) and *N. exaltata bostoniensis* (Boston Fern) with the addition of *N. domestica* (Pink Blush) exhibited low values for $PM_{>5}$ accumulation, driving the differences observed between the small linear and other leaf groups (Fig. 5b). For both fractions, there was no significant leaf PM x ambient PM interaction when comparing species within each group ($PM_{<5}$: $\chi^2_7 = 2.2$, $P = 0.9$; Fig. 4c, $PM_{>5}$ $\chi^2_7 = 8.3$, $P = 0.3$; Fig. 6d). There was no significant leaf trait x ambient PM interaction found for $PM_{<5}$ ($\chi^2_3 = 2.1$, $P = 0.6$; Fig. 6c), in contrast to $PM_{>5}$ ($\chi^2_3 = 15.0$, $P = 0.002$; Fig. 6d). This finding was driven by the small linear, and medium rosette groups showing a positive relationship between ambient PM and accumulated $PM_{>5}$, while the medium linear and large rosette groups showed no relationships. Similar to the results obtained, linear leaved or ‘grass like’ species have displayed an overall low PM accumulation ability in literature (e.g. Weerakkody et al. 2017, 2018; Currie and Bass 2008; Dochinger 1980; Leonard et al. 2016). This is likely due to the tendency for linear leaves to bend easily with wind flow due to their narrow bases or petioles (Weerakkody et al. 2018). Furthermore, Weerakkody et al. (2017) suggested that species that have simple leaf arrangements with larger gaps between their leaves may produce lower turbulence surrounding the foliage, resulting in lower impaction levels.

[Figure 6 near here]

The presence of leaf hairs has been shown to increase PM accumulation in multiple previous studies (Beckett et al. 2000; Ram et al. 2014; Sæbo et al. 2012; Räsänen et al. 2013; Leonard et al. 2016; Chen et al. 2017). Leaf hairs are thought to increase PM retention by preventing the resuspension of deposited PM, and by increasing the leaf surface area for the collision of particles (Prusty et al. 2005; Qiu et al. 2009). In the current study, only one of the tested species had leaf hairs, *P. madagascariensis* (Variegated Mintleaf), which showed one of the lowest PM accumulation values. Whilst this finding was not in line with the majority of previous studies, it aligned with the findings of Perini et al. (2017), who found that hairy leaves were negatively related to PM deposition. Similarly, epicuticular wax presence has been shown to result in a higher PM deposition (i.e. Sæbo et al. 2012; Popek et al. 2013; Räsänen et al. 2013; Barima et al. 2014; Perini et al. 2017; Weerakkody et al. 2017), due to its hydrophobic nature (Sawidis et al. 2011). However, in the current study the species containing high wax content did not necessarily have the highest PM accumulation. For example, only one of the three high wax content species, *N. glabra* (Goldfish Plant), was found to be within the highest accumulating species for both > 5 mg cm^{-2} and < 5 mg cm^{-2} (Table 2, see above ***Statistical Analysis***). The other two high wax content species (*P. glabella*: Small Leaf Peperomia) and *P. obtusifolia* (Baby Rubber Plant) varied in their capacity to accumulate PM; with low wax content species *P. Xanadu* (Xanadu), *S. wallisii* (Peace Lily), and *C. comosum variegatum* (Variegated Spider Plant) consistently having the highest PM accumulation across both PM > 5 mg cm^{-2} and < 5 mg cm^{-2}.

The results from the current study demonstrate that many plants used in green walls are capable of accumulating airborne PM, but that this property varies amongst plant species. In particular, *P. madagascariensis* (Variegated Mintleaf) and *N. exaltata bostoniensis* (Boston Fern) were not effective PM accumulators, indicating that plants of this structural form may be ineffective for passive PM accumulation.

The methods used to determine the PM filtering capacity of different plant species has varied across techniques and investigations (i.e. Beckett et al., 2000; Dover, 2015; Freer-Smith et al., 2005; Lenoard et al., 2016; Maher et al., 2013; McDonald et al., 2007; Ottelé et al., 2010; Sternberg et al., 2010; Terzaghi et al., 2013; Zhang et al., 2017), likely resulting in the inconsistencies observed in the literature. Common methods used include Scanning Electron Microscope (SEM) and imaging, filtration and gravimetric assessment, however, with no standard, universal method of PM determination, it makes authors comparisons difficult to interpret. Furthermore, Weerakkody et al. 2017 noted limitations across these methods including: the limiting capacity of water to remove PM from leaf and wax structures; chloroforms capacity to dissolve non-polar constitutes of PM and the SEM scanning area being much smaller than the leaf surface area, requiring a large sample size of micrographs to be representative of the overall PM deposition. SEM and other microscopic analysis, additionally is unable to provide the total mass of deposited PM, instead providing a count for each PM size fraction. Thus, the current study aimed to provide both a total deposited PM mass and PM size fraction counts via the two methodologies used. The authors suggest that a comparative assessment of previously conducted methodologies used to determine leaf deposited PM be conducted in order to determine which method is the most accurate for standardised use in future studies.

Conclusion

This study assessed a representative sample of common living wall plant species, representing a range of different morphologies and their impact on PM deposition. All species were shown to accumulate ambient PM, however, their capacities to do so varied. In the current study, no specific leaf traits were found to be strongly influential for PM deposition, in contrast with some previous studies. Whilst it is important to determine the plant characteristics that are influential on PM deposition so as to maximise the PM removal performance of green walls, it remains difficult to do so. Plant species possess many different characteristics, making it difficult to attribute their PM accumulation capacity to a specific trait. Nonetheless, all species tested in the current study showed a capacity to entrap PM; with the species *C. comosum variegatum*: Variegated Spider Plant, *N. glabra*: Goldfish Plant, *P. xanadu*: Xanadu , and *S. wallisii*: Peace Lily demonstrating more effective PM accumulation; and thus being appropriate for use in high PM pollution environments.

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