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Removal of fine particulate matter ($PM_{2.5}$) via atmospheric humidity caused by evapotranspiration☆

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ABSTRACT

Reduction of particulate matter (PM) has emerged as one of the most significant challenges in public health and environment protection worldwide. To address PM-related problems and effectively remove fine particulate matter ($PM_{2.5}$), environmentalists proposed tree planting and afforestation as eco-friendly strategies. However, the PM removal effect of plants and its primary mechanism remains uncertain. In this study, we experimentally investigated the PM removal performance of five plant species in a closed chamber and the effects of relative humidity (RH) caused by plant evapotranspiration, as a governing parameter. On the basis of the PM removal test for various plant species, we selected *Epipremnum aureum* (*Scindapsus*) as a representative plant to identify the PM removal efficiency depending on evapotranspiration and particle type. Results showed that *Scindapsus* yielded a high PM removal efficiency for smoke type $PM_{2.5}$ under active transpiration. We examined the correlation of PM removal and relative humidity (RH) and evaluated the increased effect of RH on $PM_{2.5}$ removal by using a plant-inspired in vitro model. Based on the present results, the increase of RH due to evapotranspiration is crucial to the reduction of $PM_{2.5}$ using plants.

1. Introduction

Air pollution caused by airborne particulate matter (PM) poses a serious threat to public health, climate, and environment in many countries (Dominici et al., 2014). This phenomenon also entails considerable socioeconomic cost related to respiratory diseases and cleaning appliances for traffic, industry, and power plants. The improvement of indoor environmental quality has been continuously recommended because indoor environmental factors directly affect public health through long-term exposure to PM in a closed space for various indoor activities.

PM is a highly complex mixture of small particles and liquid droplets from various sources suspended in air (Seinfeld, 2005; Zhang et al., 2017b). The PM particles of various sizes are categorized into PM_{10} and $PM_{2.5}$ based on their particle diameters below 10 and 2.5 μm, respectively. In particular, $PM_{2.5}$ particles are harmful to public health because they, along with various toxic compounds, accumulate in human bronchi and lungs due to their small size (Baeza-Squiban et al., 1999). Long-term exposure to $PM_{2.5}$ particles, which can remain suspended in air for several weeks, may trigger cardiovascular diseases (Brook et al., 2010), and the portion containing the secondary PM of $PM_{2.5}$ particles is much greater than that of PM_{10} particles. Thus, various dust removal technologies have been developed to mitigate and remove $PM_{2.5}$ particles effectively (Chen et al., 2017c; Gu et al., 2017; Han et al., 2015; Liu et al., 2015a; Zhang et al., 2017a; Zhang et al., 2016).

With concerns on eco-friendly and sustainable control measures, the ability of plants to capture and remove atmospheric PM particles has been extensively investigated (Willis and Petrokofsky, 2017). The effects of canopy vegetation have been investigated through laboratory- and field-based experiments (Maher et al., 2013; Nowak et al., 2006; Pugh et al., 2012) according to tree species (Beckett et al., 2000; Chen et al., 2017a; Sabo et al., 2012) and canopy density (Chen et al., 2016; Liu et al., 2015b). However, in spite of the rapidly growing interest, most studies on the effect of plants on PM reduction have only focused on leaf morphologies (Burkhardt et al., 1995; Liu et al., 2012; Blanusa et al., 2015; Chen et al., 2017b) and surface properties (Sabo et al., 2012). To understand the mechanism of PM reduction using plants, it is necessary

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to systematically investigate the effect of evapotranspiration on PM reduction.

In this study, we quantitatively investigated the dust removal performance of several air-purifying plants which reported to reduce indoor air pollutants (Wolverton et al., 1989) in a closed chamber and selected *Scindapsus* as a representative test plant species. To understand the parameters affecting the PM removal by plants, we examined the PM removal efficiency according to the transpiration rate and particle type. During the experiments, the environmental factors influenced by plants were simultaneously monitored. A plant-inspired model system was also proposed on the basis of our experimental results to systematically verify the effect of critical parameters on the PM removal performance.

2. Materials and methods

2.1. Plants and a transpiring-leaf inspired model

We tested seedlings of five representative test species that have been known for air purification and dust removal capacity: *Epipremnum aureum* (*Scindapsus*), *Sansevieria hyacinthoides*, *Ficus banghalensis* (rubber tree), *Hedera helix* (ivy), and *Viburnum odoratissimum* (coral tree). These seedlings purchased from a local shop were domesticated for two weeks with one watering per week. Each seedling was planted in a small pot of 0.1 m in diameter and its height in the pot was approximately 0.25 m. The soil surface occupying the cross-sectional area of the pot was exposed to the atmosphere. The volume of each seedling planted in the pot was approximately 7% of the whole volume of the test chamber. Each seedling was then placed inside the test chamber, and the illumination level was modulated to regulate its transpiration rate. The test chamber was covered with a dark curtain to create a dark environment. To produce the light condition, we illuminated the chamber in a 3:3:6 ratio of 430 nm:470 nm:660 nm by using light-emitting diode (LED) lamps (PARUS) with a photon flux density of 2000 μmol/m^{2}s. This illumination level corresponded to that on a sunny day in summer at noon. To exclude the possible influences of different surface area, leaf arrangement, and leaf orientation, we conducted each experiment using the same *Scindapsus* seedling sample under the light/dark conditions. The total leaf area of *Scindapsus* was measured as 421 cm^2. To mimic leaf transpiration, especially on RH change and to investigate the effect of PM removal, we used 7 cm × 14 cm paper towels (SCOTT Multi-fold towel 47222, Kimberly-Clark Professional). Three pieces of papers wet with distilled water or dry were hung on the ceiling of the test chamber. In the case of paper experiment, the paper model was only utilized to verify only the effect of RH under controlled experimental condition to exclude possible factors including total leaf area, leaf surface property, and plant condition in seedling experiment.

2.2. PM generation and efficiency measurement

The PM generation and efficiency measurement were conducted in a 2.7×10^{-2} m^3 test chamber composed of glass and a stainless-steel frame to minimize the electrostatic accumulation of fine particles on the wall (Figure S1). Two different types of PM particles were examined in this study: (1) Arizona dust (A1 Ultrafine Test Dust, Powder Technology Inc.) used as a test dust to evaluate the filter performance (ISO 12103-1) and (2) dust generated by burning incense (Figure S2). Arizona dust and incense smoke measured a nominal size of 0 μm–10 μm and contained SiO_2, Al_2O_3, and trace amounts of Fe_2O_3, Na_2O, CaO, MgO, TiO_2, and K_2O. The exhaust smoke generated by burning incense is composed of $PM_{2.5}$ particles, many gaseous substances, including CO, CO_2, NO_2, and SO_2, and volatile organic compounds, such as benzene, toluene, xylenes, aldehydes, and polycyclic aromatic hydrocarbons (Lin et al., 2008). The PM particles were injected into the test chamber and dispersed in air by repetitively opening and closing the chamber. The differences in PM concentrations in the test chamber at the same time were measured less than 5% for PM_{10} and 1% for $PM_{2.5}$. The initial concentration was set to a hazardous pollution level, which was equivalent to the TSP index ranging from 1000 μg/m^3 to 1500 μg/m^3. A hand-held particle counter (TES-5200, TES Electrical Electronic Corp.) was used to monitor the particle concentration for 3–5 h after the particles were injected into the chamber. Each sampling process was carried out for 1 min at a fixed air-suction flow rate of 2.84 L/min. In this study, the removal efficiency was calculated by comparing the concentrations between the initial particle concentration in the closed chamber and the temporal changes after 3 h. Variations in temperature and relative humidity (RH) in the chamber were also examined. Before each measurement was conducted, the chamber was rinsed with DI water, wiped with dust-free papers, and flushed with filtered air to secure a particle-free environment. In addition, leaves of seedlings were also rinsed with DI water, wiped with dust-free papers, and flushed with filtered air for repeated experiment.

3. Results and discussion

3.1. PM removal of various plants

To compare the dust removal capabilities of five plants, we monitored their mass concentrations of PM_{10} and $PM_{2.5}$ particles in the test chamber (Fig. 1a and b). The mass concentrations of PM_{10} particles in the chamber with the test plant species exhibit a trend similar to those in the empty chamber. Independent of plants species, PM_{10} particle concentration is influenced by gravitational sedimentation (Lai, 2002; Thatcher et al., 2002). In this study, we excluded the effect of electrostatic force by making the test chamber with glass panels and stainless-steel frames. In addition, we minimized the effect of aerodynamic force with blocking external flow or circulating flow in the test chamber during PM concentration measurement. We assumed that the PM_{10} and $PM_{2.5}$ particles have spherical shape with mean size of 10 μm and 2.5 μm, respectively. In this case, the settling time of the PM_{10} particles can be speculated to be 1/16 of that of the $PM_{2.5}$ particles due to gravitational sedimentation. Thus, the removal rates of PM_{10} particles are much higher than those of $PM_{2.5}$ particles.

The change in the mass concentrations of $PM_{2.5}$ particles in each experiment for the five plant species is considerably different. Among the obtained concentrations, the PM concentration in the ivy chamber is the lowest, whereas the PM concentration in the *Sansevieria* chamber is the highest. The concentrations of dust particles in the *Scindapsus*, ivy, and coral tree chambers are significantly lower than those in the other chambers. The five plant species are also classified into two groups: group A shows the same trend as the empty chamber, and group B exhibits a significantly decreased $PM_{2.5}$ concentration. The mass concentration of $PM_{2.5}$ in group A (Sansevieria and rubber tree) is reduced by 50%–60%, whereas the mass concentration of $PM_{2.5}$ in group B (*Scindapsus*, ivy, and coral tree) is decreased to approximately 90%.

Although the volume proportions of the five plant species to the test chamber volume are in a similar range, RH in the group B chambers increases to approximately 60% and remains unchanged during the whole measurements (Fig. 1c). The RHs in group A and empty chambers are maintained in the range of 15%–25%. Plants exhibit different transpiration rates according to morphological factors, such as root-to-shoot ratio, leaf area, and leaf structure even under the same ambient environmental conditions, such as light, water, and wind (Devlin, 1975). The differences in transpiration

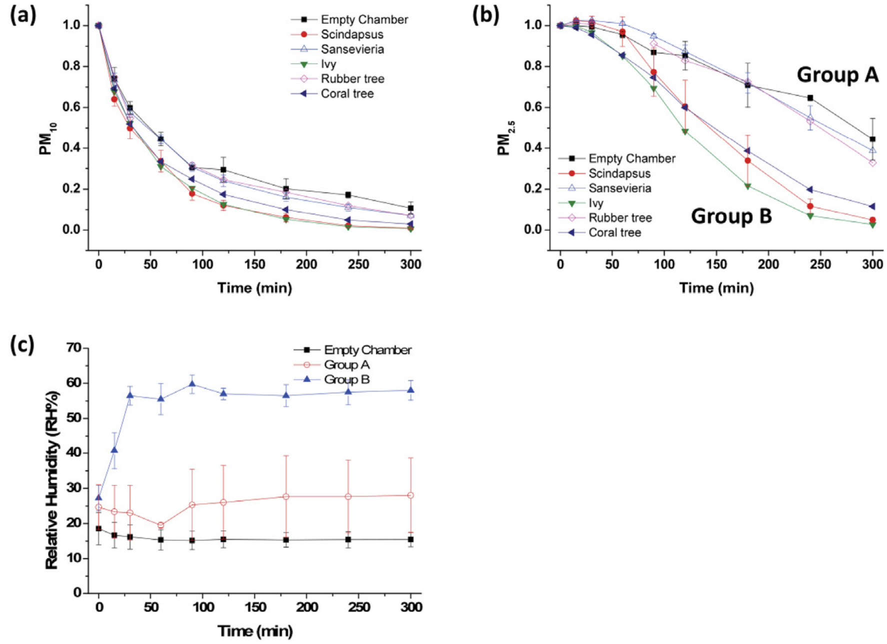

Fig. 1. Temporal variations in (a) PM_{10} and (b) $PM_{2.5}$ particle concentrations of the test chambers with and without plant species: *Epipremnum aureum* (Scindapsus), *Sansevieria hyacinthoides* (Sansevieria), *Hedera helix* (ivy), *Ficus banghalensis* (rubber tree), and *Viburnum odoratissimum* (coral tree). The y-axes represent PM_{10} and $PM_{2.5}$ concentrations relative to their initial concentrations, respectively. Test plant species were grouped into 'Group A' and 'Group B' based on the decreasing trend of $PM_{2.5}$ concentration. (c) Variations of relative humidity (RH) in the test chamber during PM monitoring.

rates may change RH in the test chambers. The increased RH seems to affect $PM_{2.5}$ removal in group B chambers. On the basis of the PM removal performance of various plants, we selected *Scindapsus* as the representative plant in the group B to investigate the dust removal mechanism of plants with varying transpiration rates and particle types.

3.2. Effect of evapotranspiration on PM removal

Variations in the PM concentration and removal efficiency in the chambers with and without *Scindapsus* were compared under the light/dark condition (Fig. 2). The PM concentration in the chamber with *Scindapsus* distinctly decreases compared with that in the empty chamber regardless of light condition. This result is attributed to the presence of plants occupying a certain volume in the chamber, thereby shortening the effective distance between PM particles and collectible surfaces. This phenomenon then leads to a rapid sedimentation of PM particles under gravitational potential.

For the PM_{10} particles, the concentration decreases rapidly within a short period due to the effect of gravitational sedimentation. Although the decreasing trends of PM_{10} and $PM_{2.5}$ particles are relatively different, the concentrations of both PM particles in the chamber with *Scindapsus* under light condition significantly decrease after 90 min (Fig. 2a and b). After 180 min, the removal efficiencies of *Scindapsus* for PM_{10} and of $PM_{2.5}$ particles under light condition are 4.0% and 21.4% higher than those under dark condition (Fig. 2c).

Plants usually transpire more rapidly under light condition than under dark condition because light stimulates the opening of stomata. When *Scindapsus* transpires actively under light condition, stomata are opened to uptake liquid and emit water vapor into air. In addition, RH in the chamber under light condition increases compared with that under dark condition (Fig. 2d).

In addition, to distinguish the effect of evaporation on the soil surface from the evapotranspiration, temporal variations in PM concentrations and RH conditions were continuously monitored in the test chamber with a pot containing the damp soil as a supplementary experiment. The effects of the damp soil on PM removal (Figures S3a–b) and RH condition (Figure S3c) were comparable to the case of empty chamber. Compared to the initial conditions, the PM_{10} concentration is decreased to 18.8%, while the $PM_{2.5}$ concentrations decreased to 64.9% after 3 h. The RH level in the chamber containing a pot with the damp soil was maintained to be approximately 25% RH on average after 3 h. Based on these experimental results, we concluded that the evaporation on the damp soil is negligible to the change in RH conditions and PM concentrations. Therefore, the increase in RH is mainly attributed to plant transpiration and eventually to the removal of $PM_{2.5}$ particles.

3.3. PM removal efficiency according to particle type

The $PM_{2.5}$ removal efficiencies of *Scindapsus* under dark and light conditions were compared according to the type of particles (Fig. 3): solid PM particles A1 and smoke PM particles generated by burning incense. The $PM_{2.5}$ and PM_{10} removal efficiencies in the chambers with *Scindapsus* are higher than those in the empty chamber. The removal efficiencies of *Scindapsus* for solid PM particles under light and dark conditions exhibit a slightly significant difference (Figure S4). By comparison, the removal efficiency of *Scindapsus* for smoke PM particles under light condition is higher than that under dark condition.

Differences in $PM_{2.5}$ removal efficiencies according to the type of particles may be attributed to various absorption rates of particles through the plant leaf stomata. Under active transpiration, continuous and thin liquid water films are formed on stomatal walls (Burkhardt, 2010). The wetted stomata allow the transport of water and bidirectional dissolution or dispersal of substances as humidity increases (Burkhardt, 2010; Burkhardt et al., 2012; Burkhardt and Eiden, 1994). Although the entering frequency of $PM_{2.5}$ particles through the stomata remains unknown (Chen et al., 2017b), studies have shown that particles occasionally enter the stomatal opening during gas exchange (Farmer, 1993). However,

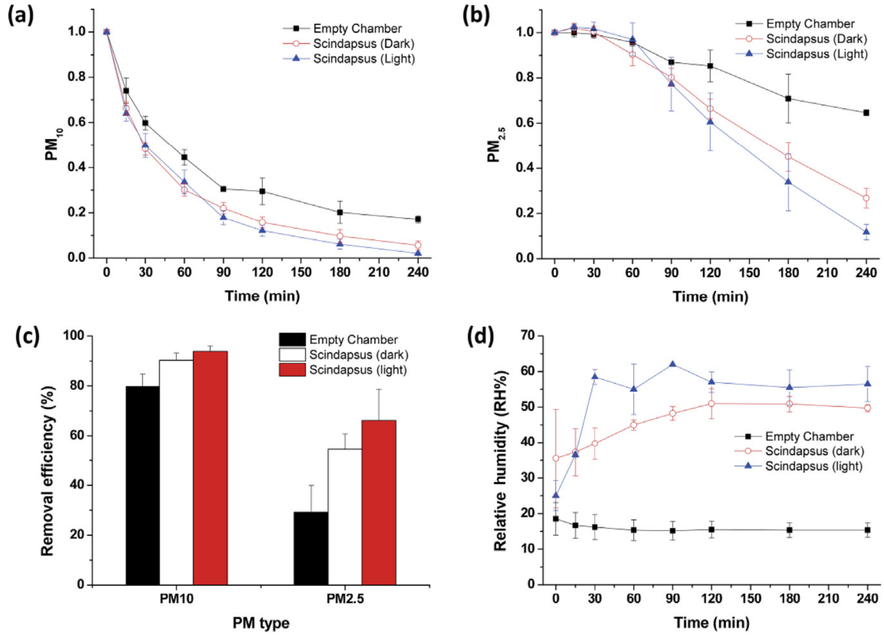

Fig. 2. Temporal variations in (a) PM_{10} and (b) $PM_{2.5}$ concentrations in burning incense in the chamber with *Scindapsus* under dark and light conditions. The y-axes represent PM_{10} and $PM_{2.5}$ concentrations relative to their initial concentrations, respectively. (c) Comparison of PM_{10} and $PM_{2.5}$ removal efficiencies in the chamber with *Scindapsus* under dark and light conditions. The removal efficiency was calculated by comparing the concentrations between the initial particle concentration in the closed chamber and the temporal changes after 3 h. (d) Temporal variations in RH for *Scindapsus* under dark and light conditions.

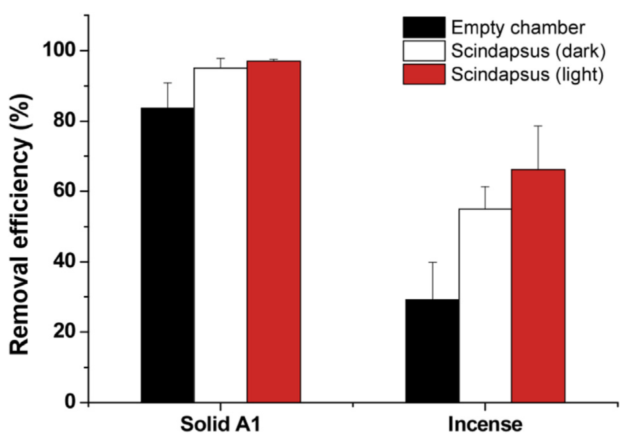

Fig. 3. Comparison of the $PM_{2.5}$ removal efficiencies from solid and burning incense particles in the chamber with *Scindapsus* under dark and light conditions. The removal efficiency was calculated by comparing the concentrations between the initial particle concentration in the closed chamber and the temporal changes after 3 h.

there is a technical difficulty in experimentally proving or observing the movement of PM particles through the stomata.

The other possible scenario for the $PM_{2.5}$ removal characteristics depending on particle type in response to humidity is closely related to the hygroscopic and wetting properties of particles. Smoke particles generated by burning incense are composed of aerosols agglomerated with oxidized chemical products, such as CO, CO_2, NO_2, and SO_2, and most of them are hydrophilic. Hydrophilic smoke particles can be easily reconstructed with water molecules with a high intermolecular force. With this agglomeration, the size of smoke particles increases. In addition, volatile organic compounds generated from burning incense enhance the hygroscopic properties. For incense smoke particles measuring 100–700 nm, the average growth factor (GF), or the ratio of the mean diameter of humidified particles to that of dry particles, is 1.67 (Li and Hopke, 1993). In general, GF increases as particle diameter increases. Thus, the deposition and removal rate of PM particles increase with hygroscopic growth of aerosol and particle coagulation (Wang et al., 2017).

On the other hand, solid particles are slightly affected by humid condition because their hydrophilicity is smaller than that of smoke particles (Mikhailov et al., 2006). Arizona test dust particles are wettable, but they have limited hygroscopicity when they are dry (Herich et al., 2009). Their GF is smaller than 1 at RH ranging from 50% to 80% (Koehler et al., 2009), indicating that the solid particles are nearly unchanged or slightly reconstructed to shrink when they are exposed to high RH. Thus, solid $PM_{2.5}$ particles do not show noticeable difference in particle depositions under humid conditions.

3.4. Effect of RH on PM removal

The change in RH caused by actively transpiring plants is closely related to the removal efficiency of smoke $PM_{2.5}$ (Figs. 2 and 3). This result implies that transpiring plants increase the RH of the surrounding ambient air, and a RH gradient is formed around the transpiring plant leaves (Ramsay et al., 1938). To understand the effect of increased RH on PM removal, we used wet papers as a transpiring leaf model (Fig. 4a). We eradicated the effect of geometrical shape by using the same type and size of papers and then compared the PM removal effect of wet papers with that of dry papers, which constituted the control group. Afterward, we injected the solid and smoke PM particles into the test chambers with dry and wet papers and maintained each RH condition inside the chamber, which was induced by test papers, during the measurement (Fig. 4b).

The reduction in the concentrations of PM_{10} and $PM_{2.5}$ burning incense particles in the test chamber containing wet papers is higher than that in the empty chamber and the chamber with dry papers after 90 min (Fig. 4c and d). The concentrations of PM_{10} and $PM_{2.5}$ solid particles rapidly decrease with time, but their

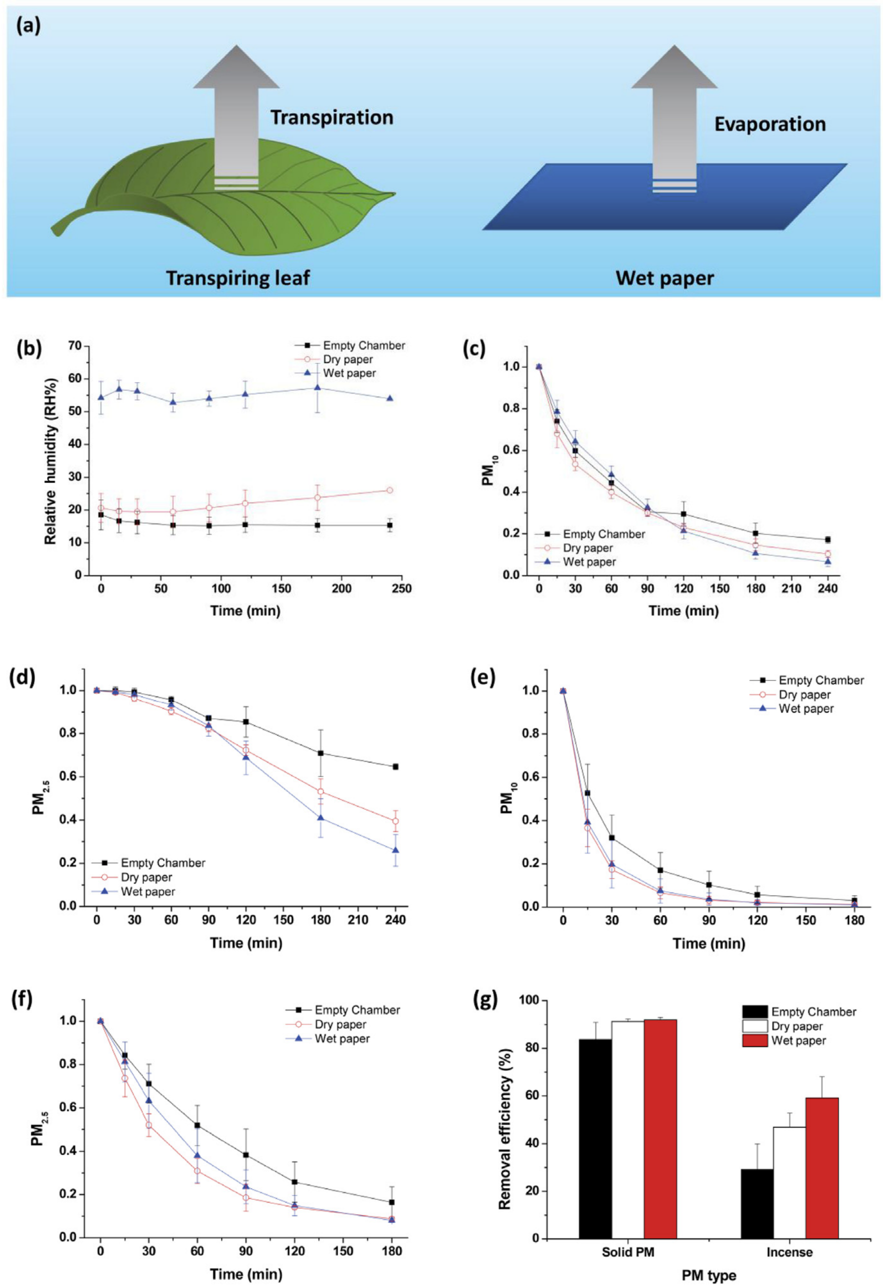

Fig. 4. (a) Schematics of a paper-based humidity-inducing device to mimic a transpiring plant leaf. (b) Temporal variation in RH in the chamber with dry and wet papers. Temporal variations in (c) PM_{10} and (d) $PM_{2.5}$ concentrations in burning incense in the chamber with dry and wet papers. Temporal variations in (e) PM_{10} and (f) $PM_{2.5}$ concentrations in solid particles in the chamber with dry and wet papers. The y-axes represent PM_{10} and $PM_{2.5}$ concentrations relative to their initial concentrations, respectively. (g) Comparison of $PM_{2.5}$ removal efficiencies in burning incense and solid particles in the chamber with dry and wet papers. The removal efficiency was calculated by comparing the concentrations between the initial particle concentration in the closed chamber and the temporal changes after 3 h.

concentrations in the dry paper do not significantly differ from those in the wet paper (Fig. 4e and f). Most solid particles are settled down in the chamber after 3 h. This result indicates that gravitational sedimentation is more effective than RH condition in decreasing the concentration of solid particles. By comparison, the PM removal of the smoke particles is enhanced by the increased RH because of the presence of wet papers in the chamber. Both transpiring plant leaves and wet papers increase RH conditions in the test chambers, thereby increasing the deposition velocity of particles (Mohan, 2016). The removal efficiencies of smoke $PM_{2.5}$ in the chambers with dry and wet papers are 46.8% and 59.1%, respectively (Fig. 4g). This difference in the effect of RH on the removal of different types of particles may be mainly attributed to the hygroscopic and wetting properties of particles (Gaston et al., 2017; Han et al., 2011; Hwang et al., 2011; Leung et al., 2017; Mikhailov et al., 2006; Montgomery et al., 2015; Wang et al., 2017), rather than the effect of particle absorption through stomatal opening.

4. Conclusions

We measured mass concentrations of PM_{10} and $PM_{2.5}$ particles in a test chamber to investigate the dust removal effect of five plant species. The mass concentration of $PM_{2.5}$ in group A (*Sansevieria* and rubber tree) is reduced by 50%–60%, whereas that of group B (*Scindapsus*, ivy, and coral tree) is decreased approximately 90%. We selected *Scindapsus* in the group B as the test plant to examine its dust removal mechanism with varying transpiration rate and particle type.

Temporal variations of PM concentration and removal efficiency in the chamber with and without *Scindapsus* were compared under light and dark conditions. The removal efficiencies of *Scindapsus* for PM_{10} and of $PM_{2.5}$ smoke particles under light condition are 4.0% and 21.4% higher than those under dark condition after 180 min. This result confirms that the increase in RH caused by plant leaf transpiration enhances the removal of smoke PM particles. On the other hand, solid $PM_{2.5}$ particles do not exhibit noticeable difference in response to humidity.

The wet paper model inspired by transpiring plant leaves increases RH in the test chamber, thereby increasing the particle deposition rate. The removal efficiencies of smoke $PM_{2.5}$ in the chambers with dry and wet papers are 46.8% and 59.1%, respectively. Thus, the PM removal effect of RH is affected by the size and hygroscopic property of particles. This study was conducted using a small-scale experimental set-up model which might have influence on the relative strength of the PM deposition process. However, the experimental results help elucidate the effects of dominant parameters on plant-inspired PM removal and serves as a reference for the design of eco-friendly and nature-inspired PM removal devices for indoor environments.

Notes

The authors declare no competing financial interest.

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Appendix A. Supplementary data

Additional information about methods and results. This material is available free of charge via the Internet.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2018.11.004.

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