Effect of trichome structure of *Tillandsia usneoides* on deposition of particulate matter under flow conditions

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**A R T I C L E I N F O**

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**A B S T R A C T**

The removal of particulate matters (PM) has emerged as one of the most significant issues in public health and environment worldwide. Environmentalists have proposed the use of indoor air-purifying plants as an eco-friendly strategy to resolve PM-related problems and effectively remove fine particulate matter (PM\textsubscript{2.5}). Among air-purifying plants, *Tillandsia usneoides* (L.) L. (*T. usneoides*) has been used as a biomonitor for heavy metals and air pollutants. However, the PM removal effect of *T. usneoides* and its primary mechanism remain unclear. Here, we investigated the PM removal performance of *T. usneoides* in a closed chamber under flow conditions, the effects of trichomes, and the array density according to the different types of PM. The chamber with bulk *T. usneoides* under flow conditions exhibited 16.5 % and 9.2 % higher removal efficiency in PM\textsubscript{2.5} *T. usneoides* for incense and A1 rigid PM, respectively, than that without *T. usneoides*. *T. usneoides* with trichome structure exhibited larger removal efficiencies of 7% and 2% in PM\textsubscript{2.5} and PM\textsubscript{10}, respectively, than without trichome for incense particles. In addition, the increase in total effective surface was effective for the deposition of both PM types. The increase in effective surface area by trichome structure and array density of *T. usneoides* is a crucial factor for the deposition of PM.

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1. Introduction

Air pollution induced by particulate matter (PM) has put human health and the environment at risk in many countries (Di et al., 2017; Dominici et al., 2014). Recently, the hazard of air pollution including PM has been warned (Goldman and Dominici, 2019). The relation between the exposure to fine PM (PM$_{2.5}$) and mortality and cardiovascular morbidity was rigorously explored by American Heart Association (Brook et al., 2010). As a result, the potential effect of PM$_{2.5}$ on several chronic cardiovascular diseases, including hypertension, heart failure, and diabetes was recently reported (Lelieveld et al., 2019). Furthermore, epidemiological analysis revealed that long-term exposure to air pollution has adverse effects on pulmonary health, especially for individuals with chronic lung diseases (Baeza-Squiban et al., 1999; Hoek et al., 2013). Hence, various technologies have been introduced for effective removal of PM$_{2.5}$. High efficiency particulate air (HEPA) filter is one of the most popular filters used for air purification (Payet et al., 1992). Many research groups tried to improve the filter used in air purifying devices (Chen et al., 2017a, 2017b, 2017c; Gu et al., 2017; Han et al., 2015; Liu et al., 2015a, 2015b; Zhang et al., 2016). In addition, electrostatic precipitator (ESP) has been widely employed to remove PM from flue gases in various industrial processes, including boilers, incinerators, coal-fired power plants, metallurgical industries (Parker, 1997).

Phytoremediation was introduced as a bioremediation process that utilized various types of plants to remove, transfer, and settle down contaminants in the atmosphere, soil, and underground water (Salt et al., 1998). City vegetation can sustainably reduce air pollution and improve human health by utilizing the ability of plants to remove atmospheric PM (Willis and Petrokofsky, 2017). The effects of canopy vegetation have been examined through laboratory- and field-based experiments (Maher et al., 2013; Nowak et al., 2006; Pugh et al., 2012) in different tree species (Beckett et al., 2000; Chen et al., 2017a; Sabo et al., 2012) and varying canopy densities (Chen et al., 2016; Liu et al., 2015b).

The effects of leaf morphology (Liu et al., 2012) and surface property (Sabo et al., 2012) of plants on PM deposition were investigated. The relationship between foliar PM$_{2.5}$ accumulation and trichome density and groove area ratio was also reported (Chen et al., 2017b). The stem and leaves of Tillandsia species, e.g., *Tillandsia velutina Ehlers* (T. velutina) and *Tillandsia usneoides* (L.) L. (T. usneoides), are covered with dense, overlapping, and multicellular trichomes named foliar trichomes. The most excellent feature of the trichomes of *Tillandsia* is its highly elongated wing cells (Benz and Martin, 2006; Liu et al., 2017). In relation to indoor atmospheric pollutants, Li et al. (2015) investigated if *T. velutina* can absorb formaldehyde efficiently and if the leaf trichomes can improve formaldehyde uptake (Techato et al., 2014). Furthermore, the Spanish moss, *T. usneoides*, has been used as an atmospheric bio-monitor for Hg contamination. Energy-dispersive X-ray analysis of *T. usneoides* revealed that Hg was highly absorbed by foliar trichomes, less absorbed by epidermal cells, and not absorbed by mesophyll parenchyma (Amado Filho et al., 2002). However, the relationship between *T. usneoides* and foliar PM deposition was not fully investigated.

The effect of the trichome structure of *T. usneoides* on PM deposition under flow conditions was examined through experiment. Based on the results of the correlation between foliar PM$_{2.5}$ accumulation and trichome density and groove area ratio (Chen et al., 2017b), trichome structure affects the PM deposition of *T. usneoides* under flow conditions. Main parameters influencing PM deposition such as the PM removal efficiency and deposition constant were quantitatively analyzed in a test chamber for the following variants: flow conditions, presence of trichome structure, and different densities of *T. usneoides*. The results of this study would provide fundamental information for understanding the underlying PM removal mechanism of *T. usneoides* and for developing a new bio-inspired device for PM removal.

2. Experimental apparatus and methods

2.1. PM measurement and flow-inducing system

The experiments for PM measurement were conducted using two test chambers with volumes of 0.125 m$^3$ each. The test chambers were made of a stainless-steel frame and glass to reduce the electrostatic effect of PM deposition on the chamber surfaces (Fig. 1a). Two different types of PM were examined in this study, as follows: (1) Arizona dust (A1 ultrafine test dust, Powder Technology, Inc.), which was used as a test PM to evaluate filter performance (ISO 12103-1); and (2) PM generated by burning incense. Arizona dust and incense smoke had nominal sizes ranging from 0 μm to 10 μm. The PM contained SiO$_2$, Al$_2$O$_3$, and trace amounts of Fe$_2$O$_3$, Na$_2$O, CaO, MgO, TiO$_2$, and K$_2$O.
The exhaust smoke generated by burning incense was composed of PM2.5, base substances, including CO, CO2, NOx, and SOx, and volatile organic compounds (VOCs), such as benzene, toluene, xylenes, aldehydes, and polycyclic aromatic hydrocarbons (Lin et al., 2008). PMs were injected into the test chamber and dispersed in the air by aldehydes, and polycyclic aromatic hydrocarbons (Lin et al., 2008). Latent organic compounds (VOCs), such as benzene, toluene, xylenes, were used as tracer particles for PIV experiment. A high-speed camera (MINI UX, Photron, USA) with 1024 × 1024 pixels at 1000 frames per second (fps) was employed to capture flow images. A laser light sheet was made using a 2 W diode-pumped solid state (DPSS) continuous laser (Changchun New Industries Optoelectronics Technology Co., China) with a wavelength of 532 nm. Flow images were consecutively recorded at 1000 fps and the captured images were processed with PIVview (PIVview, PIVTEC, Germany). A multigrid interrogation window scheme was adopted to extract instantaneous velocity fields with an interrogation window size of 32 × 32 pixels with 50 % overlapping.

4. Field emission scanning electron microscope (FE-SEM) imaging

T. usneoides was exposed to high PM concentration for 1 h and was observed with a field emission scanning electron microscope (FE-SEM). Mid-leaf section of T. usneoides was coated with platinum (SC7640 model, Quorum Technology, UK) for 30 s. Sample images were captured using a FE-SEM (XL30S FEG) operating at an acceleration voltage of 5 kV.

3. Result and discussion

3.1. Effect of bulk T. Usneoides on PM removal under flow conditions

Temporal variations of PM10 and PM2.5 concentrations of burning incense in the test containing a bulk T. usneoides with and without flow conditions are compared in Fig. 2. In the absence of flow conditions, there is minimal difference in the concentrations of both types of PM between the chambers with and without T. Usneoides for 1 h. The concentrations of PM10 and PM2.5 showed different tendencies. PM10 concentration rapidly decreased within a short time period because it was mainly governed by gravitational sedimentation (Lai, 2002; Thatcher et al., 2002). This result is supported by the increase of deposition constant as particle diameter increases from 10−1 to 10 μm (Riley et al., 2002).

The removal efficiencies and deposition constants of incense particles PM10 and PM2.5 in the test chambers with and without bulk T. usneoides under the presence or absence of flow are illustrated in Fig. 2c,d. The effect of internal flow on PM deposition in the chamber was examined by comparing the test chambers with an empty chamber (reference) under flow conditions. The internal flow enhanced the number of collisions between PM and chamber surfaces, increasing the deposition rate of PM (Lai, 2002), thereby reducing 59.5 % and 27.8 % of PM10 and PM2.5, respectively. These findings are consistent with those obtained in a previous study showing that PM deposition on the chamber surface induced by internal flow was enhanced as flow velocity increased (Byrne et al., 1995). The presence of T. usneoides in the chamber gave rise to a large difference in the removal rates under flow conditions. When T. usneoides is exposed to flow, PM removal rates were increased to 73.8 % and 44.3 % for PM10 and PM2.5, respectively.

The deposition constant (λ) was defined to compare the reduction rates of different PM concentrations. Considering the lack of air exchange, the deposition constant (λ) was obtained by exponential fitting of PM concentration curves using the following equation:

$$C(t) = C_0(t) \times \exp(-\lambda t) \quad (2)$$

Under flow conditions, the λ values of PM2.5 and PM10 on T. usneoides samples were 0.53 and 1.53, respectively. This indicated that the λ values were increased by 76 % and 29 % for PM2.5 and PM10, respectively, compared with the reference. Thus, the PM removal effect of T. usneoides existed when flow is applied.

The PM deposition experiment was repeated using A1 rigid particles under the same experimental conditions used for incense PM to determine the effect of particle type on the deposition of PM. Temporal...
variations of PM$_{10}$ and PM$_{2.5}$ concentrations of A1 rigid PM in the chamber containing _T. usneoides_ with and without flow conditions are compared in Fig. 3a,b. Similar with the results for incense PM, the PM removal effect of _T. usneoides_ for A1 rigid PM was not observed in the absence of flow conditions.

The removal efficiency and deposition constant of A1 PM$_{10}$ and PM$_{2.5}$ in the chamber with and without _T. usneoides_ under the presence or absence of flow conditions were compared in Fig. 3c-d. The overall decrease in PM concentration of A1 particles was greater than that of the incense particles. This finding was attributed to the size and weight difference between A1 and incense particles. In the case of PM$_{10}$ under flow conditions, the removal efficiency was found to be over 98 % after 1 h. Therefore, the deposition constants 4.28 and 4.9, were increased by 15 %. The effect of _T. usneoides_ was more pronounced for PM$_{2.5}$ than in PM$_{10}$. The removal efficiencies of A1 in the chamber with and without _T. usneoides_ were 86.1 % and 76.9 %, respectively, which had a gap of
about 10% under flow conditions. Based on the PM concentration results, the differences in the removal efficiencies and deposition constants were attributed to the deposition of PM on the surface of *T. usneoides*.

### 3.2. Effect of trichome structure of *T. Usneoides* on PM removal

*T. usneoides* stem and leaves are covered with dense, overlapping, and multicellular trichomes named foliar trichomes, as illustrated in Fig. 4a (Liu et al., 2017). Moreover, the most prominent feature of trichomes is its highly elongated wing cells (Fig. 4b). Each elongated wing cell of trichome has microscale grooves of 5–10 μm (Fig. 4c). We assumed that trichome structure plays a key role on the PM deposition of *T. usneoides* under flow conditions. As shown in Fig. 5a and c, most PMs were deposited on the trichome structure after 1 h of exposure under high concentration of both types of PM. A1 rigid particles were trapped in the microscale grooves of trichome (Fig. 5b), whereas incense particles were not clearly observed at low magnification ranges (500x). However, as shown in Fig. 5d, the particles were adsorbed on the trichome structure in a net pattern at high magnification (6500×). Therefore, the trichome surface structures of *T. usneoides* were helpful in enhancing the effective surface area for PM adsorption.

Experiments on *T. usneoides* arrays that have the same the length and weight of each stem were conducted to examine the effect of the presence of trichome on PM removal. The deposition constant and removal efficiency were compared for cases with and without trichome structure. Fig. 6a and b are SEM images of *T. usneoides* with and without trichome structure, respectively. For incense particles, the removal efficiencies for PM$_{2.5}$ and PM$_{10}$ of *T. usneoides* with trichome structure were 36.6% and 63.0%, respectively (Fig. 6c). For the *T. usneoides* array without trichome structure, the corresponding removal efficiencies for PM$_{2.5}$ and PM$_{10}$ were 29.7% and 60.9%, respectively. The difference between the removal efficiencies of *T. usneoides* with and without trichome structure was approximately 7% in PM$_{2.5}$ and 2% in PM$_{10}$. Therefore, the effect of trichome structure is notable for PM$_{2.5}$. The deposition constant for incense particle exhibited similar tendency with removal efficiency. The deposition constant of PM$_{2.5}$ of *T. usneoides* with trichome structure is 0.45 (± 0.01), which is 30% larger than that of *T. usneoides* without trichome structure (0.35 ± 0.11).
For A1 rigid particles, the removal efficiencies of T. usneoides with and without trichome structure had a small difference (Fig. 6e). This result is attributed to the fact that most of A1 PM were deposited after 1 h and exhibited minimal difference in the final PM concentration. As shown in Fig. 6f, the deposition constants for PM$_{2.5}$ and PM$_{10}$ of T. usneoides with trichome were 2.51 and 7.27, respectively, which were 20 % and 13 % greater than those of T. usneoides without trichome.

### 3.3. Effect of T. Usneoides density on PM removal

Next, we conducted an experiment using two different types of T. usneoides arrays (Arrays A and B) to investigate the effect of total effective surface area under the same flow conditions. For the case of incense particle, the removal efficiencies of PM$_{2.5}$ and PM$_{10}$ with Array A were 35.8 % and 62.9 %, respectively (Fig. 7a). For Array B, the removal efficiencies of PM$_{2.5}$ and PM$_{10}$ were 38.1 % and 65.8 %, respectively. Furthermore, the deposition constants of PM$_{10}$ and PM$_{2.5}$ of Array B were 0.46 and 1.23, which were 7.5 % and 8.8 % larger than those of Array A (Fig. 7b).

For A1 rigid PM, the removal efficiencies of PM$_{2.5}$ and PM$_{10}$ with Array A were 90.5 % and 98.7 %, respectively (Fig. 7c), whereas the removal efficiencies of PM$_{2.5}$ and PM$_{10}$ for Array B were 91.5 % and 98.9 %, respectively. The deposition constants of PM$_{10}$ and PM$_{2.5}$ for Array B were 2.44 and 7.25, which were 7.6 % and 6.4 % greater than those of Array A (Fig. 7d). The difference in removal efficiencies between Array A and B was very small, and the difference in deposition constants was approximately 6%–7% for A1 rigid PM. Therefore, the increase of total effective surface area is advantageous for the deposition of both types of PM.

However, although the density of T. usneoides is about threefold different between Array A and B, the removal efficiencies and deposition constants for both types of particles are not significantly different. For better understanding on this phenomenon, we compared the outlet velocity profiles of flow passing through the T. usneoides arrays (Fig. 8). As the array density of T. usneoides increased, the average outlet velocity decreased to 0.87 and 0.64 m/s. The number of collisions between T. usneoides surface and PM may decrease because of the increase in flow resistance due to the blockage induced by increased array density. Therefore, this finding indicated that reduced velocity due to increased array density has less influence on PM deposition (Lai and Nazaroff, 2000).
4. Conclusion

The effects of _T. usneoides_ and its trichome structure on the removal of different PM types in the closed chamber under flow conditions were experimentally investigated. The removal efficiencies of PM$_{2.5}$ at different concentrations in the chamber with bulk _T. usneoides_ were 16.5 % and 9.2 % larger than those without _T. usneoides_ for incense and A1 rigid PM, respectively. This difference is attributed to the PM deposition on the surface of _T. usneoides_. Both types of PM were adsorbed on the trichome structure of _T. usneoides_. To verify the PM removal effect of trichome structure, the deposition constants and removal efficiencies were compared for _T. usneoides_ with and without trichome structure. The _T. usneoides_ with trichome exhibited greater removal efficiencies of 7% in PM$_{2.5}$ and 2% in PM$_{10}$ compared to those of _T. usneoides_ without trichome. The deposition constants of PM$_{2.5}$ and PM$_{10}$ for _T. usneoides_ with trichome were 2.51 and 7.27, which were 20 % and 13 % greater than those of _T. usneoides_ without trichome. Finally, the experiment was conducted using two _T. usneoides_ arrays (Arrays A and B) to investigate the effect of different total effective surface areas of _T. usneoides_ under flow conditions. The increase of total effective surface was effective for the deposition of both types of PM. However, although the array density of Array B was about three times larger than Array A, the removal efficiencies and deposition constants for both particles were only slightly increased. This finding is attributed to the increased flow resistance due to the flow blockage induced by larger array density. The results of this study would help elucidate the PM removal mechanism of _T. usneoides._

CRediT authorship contribution statement

**Jeong Jae Kim:** Conceptualization, Methodology, Investigation, Writing - original draft. **Jaehyun Park:** Writing - original draft, Data curation, Methodology, Investigation. **Sung Yong Jung:** Writing - original draft, Writing - review & editing, Investigation. **Sang Joon Lee:** Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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