Particulate Matter (PM) Adsorption and Leaf Characteristics of Ornamental Sweet Potato (Ipomoea batatas L.) Cultivars and Two Common Indoor Plants (Hedera helix L. and Epipremnum aureum Lindl. & Andre)

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Abstract: Particulate matter (PM) is a serious threat to human health, climate, and ecosystems. Furthermore, owing to the combined influence of indoor and outdoor particles, indoor PM can pose a greater threat than urban PM. Plants can help to reduce PM pollution by acting as biofilters. Plants with different leaf characteristics have varying capacities to capture PM. However, the PM mitigation effects of plants and their primary factors are unclear. In this study, we investigated the PM adsorption and leaf characteristics of five ornamental sweet potato (Ipomoea batatas L.) cultivars and two common indoor plants (Hedera helix L. and Epipremnum aureum Lindl. & Andre) exposed to approximately 300 µg m⁻³ of fly ash particles to assess the factors influencing PM adsorption on leaves and to understand the effects of PM pollution on the leaf characteristics of plants. We analyzed the correlation between PM adsorption and photosynthetic rate (Pn), stomatal conductance (gs), transpiration rate (Tr), leaf area (LA), leaf width/length ratio (W/L), stomatal density (SD), and stomatal pore size (SP). A Pearson’s correlation analysis and a principal component analysis (PCA) were used to evaluate the effects of different leaf characteristics on PM adsorption. The analysis indicated that leaf gas exchange factors, such as Pn and Tr, and morphological factors, such as W/L and LA, were the primary parameters influencing PM adsorption in all cultivars and species tested. Pn, Tr, and W/L showed a positive correlation with PM accumulation, whereas LA was negatively correlated.

Keywords: Ipomoea batatas L.; ornamental plant; morphological characteristics; particulate matter; physiological characteristics; PM mitigation

1. Introduction

In recent years, air pollution has become a serious environmental problem in several Asian cities that have experienced rapid economic and industrial development [1]. Air pollutants are composed of a complex combination of gases and particulate matter (PM). In particular, PM poses severe threats to human health, weather, and ecosystems [2]. Particle characteristics, such as concentration, size, and chemical composition, are mostly responsible for these PM impacts. The PM is either discharged directly into the atmosphere (referred to as primary PM) or formed via gas-to-particle conversion (secondary PM). Therefore, PM particles are mixed pollutants, and the mechanism controlling their formation is highly uncertain [3]. Our lack of understanding of PM formation and its chemical constituents makes it difficult to develop effective mediation approaches to reduce its effects [4].
Since PM from the outside might enter buildings via natural ventilation including doors and windows, indoor PM concentrations have risen as a result of the transfer of increasingly large amounts of outdoor-generated particles to indoor environments and the emission of indoor-originated particles [5]. In many cases, indoor PM concentrations strongly coincide with the trends of PM concentration in urban areas [6,7]. Indoor-generated PM, which is caused by building materials, such as flooring, paint, and plastics, and human activities, including cooking and cleaning, is also a critical human health concern because individuals spend around 80–90% of their time indoors [5,8]. Indoor PM concentrations can be higher than outside concentrations because of the combined effects of indoor and outdoor particles [6]. The components of indoor particles are determined by the particles generated in both indoor and outdoor environments [9]. Plants are a sustainable yet underexploited way to improve indoor air quality. They can enhance indoor air quality by concurrently absorbing CO$_2$ and emitting O$_2$ via their light-dependent photosynthetic apparatus and by increasing air humidity through water vapor from stomata [10]. Several studies have reported that indoor plants can significantly reduce indoor PM pollution [11,12].

Plants act as biofilters and bioindicators that can mitigate PM pollution due to their large surface distribution, response to particles, and leaf characteristics [13,14]. Plants directly and indirectly reduce the damage caused by PM. They intercept PM particles directly via their branches and leaves [15]. Furthermore, different types of plant leaves have various physiochemical traits, which means that their capacity to absorb PM particles significantly varies. Therefore, several studies have been conducted on the effects of physiological characteristics and leaf morphology on PM removal efficiency [16–19]. At the leaf scale, the accumulation ability is highly correlated to leaf morphology and microstructure, such as leaf and waxy cuticle shape, leaf roughness, leaf pubescence, and leaf surface wettability [20–22]. Plants can lower PM concentrations through evapotranspiration and by changing the air humidity and temperature [20,23–25]. The interaction between PM particles and the leaf surface is mostly determined by hygroscopicity because air humidity plays a key role in changing the physiochemical traits and dispersion state of particles [26].

Plants can function as biofilters, but they are susceptible to PM pollution because of several factors that make plant growth and physiological processes difficult [27–29]. Accumulated PM on leaves can reduce photosynthetically active radiation (PAR) by absorbing and scattering light rays [30]. Fine particles can block the stomata, leading to reduced gas exchange and plant growth because stomatal movement is highly linked to primary metabolism [31,32]. Particulate matter stress may induce leaf loss and tissue death, decrease chlorophyll levels, and increase leaf temperature, all of which results in physical and chemical changes caused by PM constituents, such as nitrate, sulfate, organic pollutants, and trace elements [33]. Particulate matter pollution also alters soil pH and chemistry. It may allow toxic metals to penetrate plant tissues and induce secondary stresses, including pathogen stress and drought stress. Under PM conditions, several morpho-physio-biochemical changes have been identified in different species. As a result, certain species are more tolerant to PM pollution than others [34].

To this end, this study examined PM adsorption and the leaf characteristics of ornamental sweet potato (Ipomoea batatas L.) cultivars and compared them to common indoor plants, such as Hedera helix L. and Epipremnum aureum Lindl. & Andre, in Korea. Sweet potato is an important industrial and edible crop. Ornamental sweet potato cultivars are spring-time ornamental crops that are widely grown in greenhouses. With the introduction of numerous new cultivars in recent years, it has become a popular species because of its striking foliage colors and trailing habit [35]. The foliage form of sweet potatoes varies dramatically across approximately 6000 cultivars that have been identified [36]. Different ornamental sweet potato cultivars have different leaf morpho-physiological traits, which result in individual variations in their capacity to adsorb particulate matter. However, few studies have investigated the correlation between PM adsorption and the leaf characteristics of different ornamental sweet potato cultivars that have different leaf morphological traits. The main aim of this study was to examine (1) the effects of leaf gas exchange,
leaf morphology, and stomatal characteristics on PM adsorption in different sweet potato cultivars compared to common indoor plants, and (2) determine which leaf characteristics influence the capacity of plants to adsorb PM.

2. Materials and Methods

2.1. Plant Materials and the PM Fumigation Chamber

In this study, five sweet potato (Ipomoea batatas L.) cultivars, ‘Beni Haruka’ (B), ‘Black Heart’ (BH), ‘Sweet Caroline Purple’ (CP), ‘Goldfinger’ (GF), and ‘Margarita’ (M), and two common indoor ornamental plants in Korea (Hedera helix L. and Epipremnum aureum Lindl. & Andre) were selected as test plants. Sweet potato cultivars, excluding Beni Haruka, are commonly planted as ornamental plants. Beni Haruka is one of the most common edible cultivars in East Asia [37]. The stems of the 5 sweet potato cultivars were used for callus induction and were cultivated in MS medium for 5 weeks [38]. The plantlets were placed in a greenhouse at the University of Seoul, Seoul, Korea (37°34’57.5’’ N, 127°03’39.1’’ E) for a month after being transplanted into 1 L plastic pots containing a commercial substrate (Green partner, Nongwoo Bio, Suwon, Korea). H. helix and E. aureum were purchased from an ornamental plant shop in Seoul, Korea. Before beginning the fumigation, all test plants were acclimated for a week in glass-enclosed chambers under sunlight.

This study was carried out under controlled conditions in growth chambers (Growth chamber, YTK Co., Uiwang, Korea) equipped with a solid aerosol generator (SAG 410, Topas GmbH, Dresden, Germany) at the beginning of July 2020 (Figure 1). Fly ash, which is a source of anthropogenic particulate matter (PM) which occurs in both indoor and outdoor conditions [39], was generated using a solid particle generator to simulate PM pollution conditions in plants. Fly ash test powder (JIS test powder class 5, APPIE, Kyoto, Japan), which is typically under 10 µm in diameter, was used in this experiment. The PM concentration in the chamber (1.5 m × 1.5 m × 2.0 m) was measured and regulated by a PM detector (CEL-712 Microdust Pro, Casella CEL Inc., Sterling, MA, USA). The uniformity of the PM distribution in the chamber was tested before the experiment began. Furthermore, before the experiments, the chamber’s interior surface was carefully cleaned by wet and dry mopping so as to remove pre-existing dust. The temperature and relative humidity in the chamber were precisely regulated. A total of 10 plants of each cultivar and species with similar growth conditions were placed in a chamber with a PM fumigater and also arranged in such a way that they would not be unaffected by particles on the chamber’s walls. Throughout the experiment, all test plants were well watered and randomly placed to prevent drought stress and positional effects.

![Figure 1. Schematic diagram of the PM-fumigated growth chamber.](image-url)
The test plants in the chamber were exposed to fly ash particles at $307 \pm 46 \mu g m^{-3}$ (target concentration, $300 \mu g m^{-3}$) for 9 h between 09.00 and 18.00. The PM concentration was based on the PM$_{10}$ warning level for air quality standards in Korea [40]. The day/night temperature was maintained at 27/22 °C and the relative humidity was maintained at 40–45% for 24 h. Figure 2 shows the daily variation in the PM-fumigated chamber.

2.2. Gas Exchange Measurements

Measurements of leaf gas exchange parameters, including photosynthetic rate ($P_n$), stomatal conductance ($g_s$), and transpiration rate (Tr), were measured at 0, 2, 5, and 7 days after the beginning of exposure (DAE) between 09.00 and 12.00. The second to fourth fully expanded leaves of 5 test plants per cultivar and species were measured using a portable gas exchange measurement system (Li-6400 XT, LI-COR Inc., Lincoln, NE, USA) with a leaf chamber fluorometer (6400-40, LI-COR Inc., Lincoln, NE, USA) that enclosed a 2 cm$^2$ leaf area [41]. During the measurements, the CO$_2$ concentration was 400 µmol mol$^{-1}$, the temperature was 27 °C, and the relative humidity was 40–50%. Photosynthetically active radiation (PAR) was maintained at 1000 µmol photons m$^{-2}$s$^{-1}$.

2.3. Morphological and Stomatal Characteristics

Leaf sampling was conducted at 7 DAE between 09.00 h and 12.00 h. Leaf area and the width/length ratio were measured on the fully expanded leaves of five test plants per cultivar and species using winFolia (Regent Instruments Inc., Sainte-Foy, QC, Canada). The samples were freeze-dried using a lyophilizer (FD 8508, ilShinbiobase CO. Ltd., Dongducheon, Korea) to study the stomatal characteristics. Stomatal density and stomatal pore size per leaf were determined using field emission scanning electron microscopy (FESEM; SU8010, Hitachi, Tokyo, Japan). Stomatal density was quantified based on the number of stomata obtained using FESEM.

2.4. Measurement of PM Adsorption on the Leaf Surfaces

The PM adsorption on leaves was measured using a modified method adopted from Liu et al. and Kwak et al. [42,43]. The surfaces of the leaves from each cultivar and species were randomly sampled. The sampled leaves were cleaned successively using the following steps. First, the sampled leaves of each cultivar and species were cleaned by immersing them in a separate beaker filled with 270 mL of deionized water and stirring for 10 min in a shaker. Second, the beaker containing the deionized water-cleaned leaves was immediately placed in an ultrasonic cleaner (Powersonic 610, Hwashin Instrument, Seoul, Korea) and
then washed with an ultrasonic wave of 500 W for 1 min. The obtained eluent was poured into 3 small beakers (90 mL) after the leaves had been ultrasonically washed. All test small beakers were weighed prior to pouring ($W_1$). After cleaning, the area of the washed leaves was measured using winFolia (Regent Instruments Inc., Sainte-Foy, QC, Canada). Each beaker containing the eluent was covered with clean filter paper to exclude external dust particles. All the beakers were dried for 5 days at 80 °C using an oven dryer until the eluent had completely evaporated, and then the beakers were placed in a balance chamber to equilibrate to a constant weight. They were then immediately weighed again using an electronic balance ($W_2$). The total mass of particles on the leaves were determined using a high precision balance with an accuracy of 0.0001 g (PX124, Ohaus, Parsipanny, NJ, USA). It was high enough to accurately measure total PM weight on several leaves per species. The mass of the PM eluted by the cleaning steps was calculated as $W = W_2 - W_1$, and the PM adsorption was represented as the mass of particulates per leaf area. In this method, ultrasonic cleaning is critical to assess the PM adsorption capacity of plants accurately and quantitatively [42].

2.5. Statistical Analysis

Tukey’s HSD ($p < 0.05$) and one-way analysis of variance (ANOVA) were used to compare the leaf characteristics and PM adsorption among cultivars and species. Both the Shapiro–Wilk normality test and the Barlett test of homogeneity of variance were used to check the assumptions of normality and homogeneity of variance. The significant differences in parameters for each day compared to 0 DAE were determined using an independent $t$-test. Pearson’s correlation was used to test the relationship between PM adsorption and leaf characteristics, and a principal component analysis (PCA) was conducted to determine the dominant factors that could affect PM adsorption. All analyses were conducted using SPSS Statistics 26 (SPSS Inc., Chicago, IL, USA). The values in the figures and tables are the mean ± SD. Microsoft Excel (Excel 16.0, Microsoft Corporation, Redmond, Washington, DC, USA) and R studio (R version 4.0.5., R studio Inc., Boston, MA, USA) were used to process the data.

3. Results

3.1. Gas Exchange Characteristics

All parameters for the gas exchange characteristics showed significant differences between the 5 sweet potato cultivars and the 2 common indoor plants (Hedera helix L. and Epipremnum aureum Lindl. & Andre) at 0 DAE (Figure 3). Significant differences in photosynthesis rates ($P_n$) were observed between the 2 groups at 0, 5, and 7 DAE. There was no significant difference between GF and H. helix at 2 DAE. Among sweet potato cultivars, the $P_n$ of black heart (BH) was higher at 0 and 2 DAE compared to that of GF. However, there were no significant differences between the $P_n$ of BH and GF at 7 DAE. The $P_n$ of Beni Haruka (B) and Sweet Caroline Purple (CP) had significantly increased compared to those of GF at 7 DAE. In contrast, the $P_n$ decreased in BH and Margarita (M) at 7 DAE compared to 0 DAE. The other sweet potato cultivars showed no significant differences between 0 and 7 DAE. Unlike the sweet potato cultivars, the $P_n$ for H. helix significantly increased at 7 DAE compared to that at 0 DAE. At 0 and 2 DAE, stomatal conductance ($g_s$) and the transpiration rate (Tr) of the five sweet potato cultivars were significantly higher than those of H. helix and E. aureum. Furthermore, B and CP also had significantly higher $g_s$ and Tr values at 7 DAE than H. helix and E. aureum. There were also significant differences in $g_s$ and Tr among the sweet potato cultivars. The $g_s$ of M was much higher than those of B and GF at 0 DAE, and CP and M had higher Tr than B and GF at 0 DAE. However, at 7 DAE, B had a significantly greater $g_s$ than GF and M. In addition, the Trs for B and CP were significantly higher than that of GF at 7 DAE. Significant differences in the $g_s$ and Tr for the sweet potato cultivars were observed between 0 and 7 DAE (Figure 3). The $g_s$ and Tr were significantly reduced in GF and M at 7 DAE compared to 0 DAE. The $g_s$ of B significantly increased at 7 DAE compared to 0 DAE, unlike GF and M.
Beni Haruka (B) and Sweet Caroline Purple (CP) had significantly increased compared to those of GF at 7 DAE. In contrast, the Pn decreased in BH and Margarita (M) at 7 DAE compared to 0 DAE. The other sweet potato cultivars showed no significant differences between 0 and 7 DAE. Unlike the sweet potato cultivars, the Pn for *H. helix* significantly increased at 7 DAE compared to that at 0 DAE. At 0 and 2 DAE, stomatal conductance (gs) and the transpiration rate (Tr) of the five sweet potato cultivars were significantly higher than those of *H. helix* and *E. aureum*. Furthermore, B and CP also had significantly higher gs and Tr values at 7 DAE than *H. helix* and *E. aureum*. There were also significant differences in gs and Tr among the sweet potato cultivars. The gs of M was much higher than those of B and GF at 0 DAE, and CP and M had higher Tr than B and GF at 0 DAE. However, at 7 DAE, B had a significantly greater gs than GF and M. In addition, the Trs for B and CP were significantly higher than that of GF at 7 DAE. Significant differences in the gs and Tr for the sweet potato cultivars were observed between 0 and 7 DAE (Figure 3). The gs and Tr were significantly reduced in GF and M at 7 DAE compared to 0 DAE. The gs of B significantly increased at 7 DAE compared to 0 DAE, unlike GF and M.

Figure 3. Net photosynthetic rate (A), stomatal conductance (gs), and transpiration rate (Tr) of five *Ipomoea batatas* L. cultivars (‘Beni Haruka’ (B), ‘Black Heart’ (BH), ‘Sweet Caroline Purple’ (CP), ‘Goldfinger’ (GF), and ‘Margarita’ (M)), *Hedera helix* L. and *Epipremnum aureum* Lindl. & Andre exposed to 300 µg m⁻³ of fly ash particles from 0 to 7 days after the beginning of exposure (DAE). Data are plotted as mean ± SD (n = 5). Different letters indicate significant differences among cultivars and species at p < 0.05 according to Tukey’s HSD test. The asterisk signs denote significant differences for each day compared to 0 DAE. Significant levels: *p < 0.05, **p < 0.01.

3.2. Morphological and Stomatal Characteristics

The different leaf shapes of the five sweet potato cultivars, *H. helix*, and *E. aureum* are shown in Figure 4A. The leaf shape of all the sweet potato cultivars tested varied from broadly cordate to lobed. The leaves of B and BH were broadly cordate in shape (Figure 4A(a,b)), whereas CP, GF, and M had a lobed leaf shape (Figure 4A(c–e)). The leaves of *H. helix* were also lobed (Figure 4A(f)). *E. aureum* had ovate-shaped leaves (Figure 4A(g)). The leaf sizes of *E. aureum* and M were the largest of all the plants studied (Table 1). *H. helix* had the smallest leaves. Significant differences in leaf size were observed among the sweet potato cultivars. The width/length ratio for CP was the highest, while that of *E. aureum* was the lowest. The stomatal characteristics of the cultivar and species leaf surfaces were studied using FESEM (Figure 4B). Stomata were found on both the adaxial and abaxial surfaces of the five sweet potatoes and *E. aureum* (Figure 4B(a–e,g)). Although their leaves were amphistomatous, stomatal densities on the abaxial surfaces were significantly higher, with the exception of B leaves (Table 1). The stomatal density on the abaxial surfaces of B, BH,
CP, and GF did not vary significantly, whereas there was a significant difference between them and *H. helix* and *E. aureum*. There were no significant differences in stomatal pore size among the cultivars and species tested. Peltate glandular trichomes were observed on the adaxial and abaxial surfaces of the five sweet potato cultivars (Figure 4B(a–e)). Furthermore, the leaf surfaces of the five sweet potato cultivars were highly structured with ridges and valleys, and ash particles were observed in the grooves between the ridges and valleys. In addition, particles generally accumulated around the trichomes and stomata of the adaxial sides of the leaves.

**Figure 4.** (A) Selected leaf images and (B) field emission scanning electron micrographs of five *Ipomoea batatas* L. cultivars (‘Beni Haruka’ (B), ‘Black Heart’ (BH), ‘Sweet Caroline Purple’ (CP), ‘Goldfinger’ (GF), and ‘Margarita’ (M)), *Hedera helix* L. and *Epipremnum aureum* Lindl. & Andre exposed to 300 $\mu$g m$^{-3}$ of fly ash particles at 7 days after the beginning of exposure (DAE). Leaf images of Beni Haruka (A(a)); Black Heart (A(b)); Sweet Caroline Purple (A(c)); Goldfinger (A(d)); Margarita (A(e)); *Hedera helix* L. (A(f)); and *Epipremnum aureum* Lindl. & Andre (A(g)), respectively. Micrographs of adaxial (above) and abaxial (below) surfaces of Beni Haruka (B(a)); Black Heart (B(b)); Sweet Caroline Purple (B(c)); Goldfinger (B(d)); Margarita (B(e)); *Hedera helix* L. (B(f)); and *Epipremnum aureum* Lindl. & Andre (B(g)) at 500× magnification, respectively. (A(a–g)) Scale bar = 3 cm, (B(a–g)) Scale bar = 100 $\mu$m. White arrow indicates stomata. Asterisk sign indicates a peltate glandular trichome. White dash circle indicates fly ash particles on the leaves.
Table 1. Leaf area, width/length ratio, stomatal density, and stomatal pore sizes of five *Ipomoea batatas* L. cultivars (‘Beni Haruka’ (B), ‘Black Heart’ (BH), ‘Sweet Caroline Purple’ (CP), ‘Goldfinger’ (GF), and ‘Margarita’ (M)), *Hedera helix* L., and *Epipremnum aureum* Lindl. & Andre exposed to 300 μg m⁻³ of fly ash particles at 7 days after the beginning of exposure (DAE).

| Leaf Characteristics | Ipomoea batatas | Hedera helix | Epipremnum aureum |
|----------------------|-----------------|--------------|------------------|
|                      | B               | BH           | CP               | GF   | M     | H. helix | E. aureum |
| Leaf area (cm²)      | 49.5 ± 14.6 ab  | 30.3 ± 5.0 bc| 29.2 ± 1.9 cd    | 55.6 ± 6.7 a | 9.4 ± 1.6 d | 67.1 ± 6.8 a |
| Width/Length ratio   | 0.91 ± 0.08 abc | 0.86 ± 0.09 abc| 0.84 ± 0.05 bc  | 0.97 ± 0.03 ab | 0.97 ± 0.03 ab | 0.60 ± 0.09 d |
| (mm⁻²)               | Adaxial 356 ± 13 a | 364 ± 60 a | 212 ± 13 b | 53 ± 13 bc | 46.6 ± 7.1 a | 68 ± 23 c |
|                      | Abaxial 417 ± 13 a | 394 ± 57 a | 364 ± 60 a | 212 ± 13 b | 144 ± 47 bc |           |
| Stomatal density     | 85.7 ± 6.4 a     | 99.1 ± 22.9 a| 93.1 ± 32.7 a  | 66.1 ± 20.7 a | 12.4 ± 4 cd | 68 ± 23 c |
| Stomatal pore size (μm²) | 45.0 ± 2.3 a | 91.2 ± 23 b | 84 ± 13 b | 61 ± 13 b |            |           |

Values are mean ± SD (n = 5). Different letters indicate significant differences among cultivars and species at p < 0.05, according to Tukey’s HSD test.

3.3. PM Adsorption on the Leaf Surfaces

Figure 5 shows the variation in PM adsorption on the leaves from five different sweet potato cultivars and two common ornamental plants (*H. helix* and *E. aureum*) at 2, 5, and 7 DAE. There were also significant differences in PM adsorption. In terms of PM adsorption capacity per unit of leaf area, CP had the highest adsorption capacity (24.8 ± 2.4 and 64.3 ± 3.1 μg cm⁻²), while *E. aureum* had the lowest (3.8 ± 0.5 and 5.3 ± 0.9) at 2 and 7 DAE, respectively. The PM adsorption per unit of leaf area by CP was 12.09 times greater than that of *E. aureum* at 7 DAE. Significant differences in PM adsorption capacities were observed between the sweet potato cultivars. At 7 DAE, the order was as follows: CP > BH = M > B = GF. At 2 and 5 DAE, CP had a significantly greater PM adsorption capacity than the other cultivars.

![PM adsorption graph](image)

**Figure 5.** PM adsorption of five *Ipomoea batatas* L. cultivars (‘Beni Haruka’ (B), ‘Black Heart’ (BH), ‘Sweet Caroline Purple’ (CP), ‘Goldfinger’ (GF), and ‘Margarita’ (M)), *Hedera helix* L., and *Epipremnum aureum* Lindl. & Andre exposed to 300 μg m⁻³ of fly ash particles at 2, 5, and 7 days after the beginning of exposure (DAE). Data are the mean ± SD (n = 5). Different letters indicate significant differences among cultivars and species at p ≤ 0.05 according to Tukey’s HSD test.

3.4. Factors Influencing PM Adsorption on the Leaves

A correlation coefficient matrix was constructed for PM adsorption, Pₙ, gₛ, Tr, LA (leaf area), W/L (width/length ratio), the stomatal density of the adaxial surfaces (SD(ad)), stomatal density of the abaxial surfaces (SD(ab)), and the stomatal pore size (SP) (Figure 6). The PM adsorption was significantly positively correlated with Pₙ (p < 0.01), Tr (p < 0.01), W/L (p < 0.01), and SD(ab) (p < 0.05), whereas PM adsorption was significantly negatively correlated with LA (p < 0.01). Given that a number of factors were observed to be associated with each other, the impact of a single factor could not provide a complete explanation for the effect of leaf characteristics on PM adsorption. Strong positive correlations were found
among \( P_n, g_s, \) Tr, and SD(ab). However, there was a strong negative correlation between the LA and W/L.

**Figure 6.** Factor correlation analysis matrix for five *Ipomoea batatas* L. cultivars (‘Beni Haruka’ (B), ‘Black Heart’ (BH), ‘Sweet Caroline Purple’ (CP), ‘Goldfinger’ (GF), and ‘Margarita’ (M)), *Hedera helix* L., and *Epipremnum aureum* Lindl. & Andre. Significance levels: * \( p < 0.05 \), ** \( p < 0.01 \), *** \( p < 0.001 \). Abbreviations: PM = PM adsorption on leaf surfaces; \( P_n \) = net photosynthetic rate; \( g_s \) = stomatal conductance; Tr = transpiration rate; LA = leaf area; W/L = leaf width/length ratio; SD(ad) = adaxial stomatal density; SD(ab) = abaxial stomatal density; SP = stomatal pore size. Red letter indicates significant positive associations and blue letter indicates significant negative associations.

The contribution made by leaf characteristics to PM adsorption on the leaf surface was clarified using a PCA (Figure 7). There were three principal components with a cumulative contribution rate of 77.71%. The first principal component (PC 1), mainly based on \( P_n, g_s, \) and Tr, explained 46.78% of all the characteristic factors. This component represents the leaf gas exchange characteristics. The second principal component (PC 2) explained 18% of all characteristic factors. PC 2 was dominated by leaf area and W/L, which reflect leaf morphological characteristics. The third principal component (PC 3) accounted for 12.59% of the total variance and was dominated by stomatal pore size. These three components were unrelated to one another and could be used to explain different aspects of the original variables.
components were unrelated to one another and could be used to explain different aspects of the original variables.

Figure 7. Biplot of the principal component analysis (PCA) showing the performance of five Ipomoea batatas L. cultivars ('Beni Haruka' (B), 'Black Heart' (BH), 'Sweet Caroline Purple' (CP), 'Goldfinger' (GF), and 'Margarita' (M)), Hedera helix L., and Epipremnum aureum Lindl. & Andre with regards to gas exchange, leaf morphological, stomatal characteristics, and PM adsorption on leaves. Abbreviations: PM = PM adsorption on leaf surfaces; Pn = net photosynthetic rate; gs = stomatal conductance; Tr = transpiration rate; LA = leaf area; W/L = leaf width/length ratio; SD(ad) = adaxial stomatal density; SD(ab) = abaxial stomatal density; SS = stomatal pore size.

4. Discussion

The physiological responses of plants, the changes in potential PM capture capacities to PM pollution, and the variations in photosynthetic rate (Pn), stomatal conductance (gs), and transpiration rate (Tr) of all tested plants were investigated (Figure 3). Under 300 μg m⁻³ of fly ash at 7 DAE, the Pn of 2 sweet potato cultivars (BH and M) were significantly (p < 0.05) lower than that at 0 DAE. Particulate matter has been previously shown to have a detrimental impact on the photosynthetic apparatus in plants dusted with various compounds [30,33,44]. There can be several reasons why an increase in the amount of retained PM leads to a reduction in the effective photosynthesis of plants. First, PM hinders gas exchange ability by blocking the stomata [45]. Second, PM that has accumulated on the leaves covers the surface and thus prevents the leaves from absorbing light [46]. Lastly, PM adsorption and stomatal blockage by various particles reduce the transpiration rate and inhibit gas exchange in the leaves, resulting in higher leaf temperatures and impaired photosynthesis [47]. The capacity of plants to accumulate PM is also considered to be associated with a decrease in the photosynthesis rate [48].
accumulation of air contaminants in leaves is also influenced by leaf gas exchange traits, such as the transpiration rate [49]. The $g_s$ parameter is used to determine gas exchange capability. Particulate matter can enter leaves via the stomata and aggregate around it, resulting in stomatal blockage and a decrease in stomatal conductance [50]. Our results are consistent with the abovementioned effects of PM on stomatal conductance [50,51]. At 7 DAE, $g_s$ and Tr in GF and M were significantly lower than at 0 DAE (Figure 3). According to the correlation analysis, $g_s$ was highly correlated with Tr for all tested plants, with a correlation coefficient of 0.927 ($p < 0.001$) (Figure 6). Our findings showed that stomatal blockage caused by the accumulation of PM in leaves ultimately reduces transpiration. Plant characteristics, such as transpiration rate, can influence the reduction of airborne particles [52–54]. Ryu et al. [55] reported that the PM removal efficiencies of E. aureum are higher under light conditions than under dark conditions because light stimulates the opening of stomata, which leads to a higher transpiration rate. As a result, the variation in the transpiration rates of the test plants can affect their PM adsorption capacity.

In our study, the differences in leaf morphology, including leaf size and leaf W/L, were studied in all the plants. Furthermore, SEM observations of leaves from the five sweet potato cultivars, H. helix, and E. aureum, indicated differences in microstructure, stomatal density, and stomatal pore size among cultivars and species, and between abaxial and adaxial surfaces (Figure 4). A larger leaf size can lead to an increased boundary layer around leaf surfaces, which may result in a negative correlation with PM adsorption [56,57]. The resistance to particle deposition is increased by the boundary layer [57]. Our results also indicate that LA was a highly significant factor ($p < 0.01$) and negatively correlated with PM adsorption (Figure 6). Leaf W/L was another significant factor affecting the accumulation of PM in leaves ($p < 0.01$) (Figure 6). A lower W/L indicates that the leaf margins were closer to the main vein, causing the leaves to flutter less, thereby reducing the opportunity to capture PM [58]. Among all tested plants, E. aureum, which had the highest LA and the lowest W/L ratio, showed the lowest capacity for PM adsorption (Table 1, Figure 5). In contrast, the CP leaves, which had the greatest W/L ratio, accumulated the most PM (Table 1, Figure 5). The accumulation of PM per unit leaf area is highly influenced by leaf microstructure, including grooves, trichomes, and stomata [59]. The PM removal potential is higher in plants with pubescent and rougher leaf surfaces [60]. Peltate glandular trichomes were found on the leaves of the five sweet potato cultivars (Figure 4B(a–e)). Compared to E. aureum, they had a greater impact on PM adsorption (Figure 5). Stomatal density is related to leaf roughness, and it is well known that PM deposition is greater on leaves with rougher surfaces [61]. The adaxial surface stomatal density (SD(ad)) of all plants tested had no significant relationship with PM adsorption (Figure 6). In contrast, on the abaxial surface, stomatal density was significantly related to PM on the leaf surface ($p < 0.05$) (Figure 6). However, because the abaxial surface stomatal density (SD(ab)) was highly correlated with gas exchange characteristics, it is difficult to assume that it is only related to the retention of PM on the leaves due to leaf roughness (Figure 6). Stomatal conductance, which is a gas exchange characteristic, depends on stomatal pore size and density [62]. In this study, no relationship was observed between stomatal pore size (SP) and $g_s$ (Figure 6). Stomatal pore size also showed no relationship with PM adsorption, which is consistent with previous research [18,56].

A Pearson correlation matrix was constructed, and a principal component analysis (PCA) was carried out to evaluate the relationship between different parameters (Figures 6 and 7). The PM adsorption on leaves was strongly affected by leaf gas exchange and morphological characteristics. Furthermore, $P_n$, Tr, W/L, and SD(ab) were all positively correlated with PM adsorption, while LA was negatively correlated (Figure 6). The combined grouping of these parameters in the PCA also validated this result (Figure 7). We observed that PM adsorption on the leaves was significantly influenced by PC 1, which was mainly based on leaf gas exchange characteristics. The PCA also showed that PM adsorption was positively correlated with $P_n$, $g_s$, and Tr. Leaf gas exchange is not typically considered to be an important factor affecting PM adsorption. It focuses primarily on the
deleterious effects of PM on the rate of the photosynthetic apparatus [30,33,44]. However, because the deposition of PM particles increases with hygroscopic growth and particle coagulation, the removal efficiencies of particles with hygroscopic and wetting properties are strongly correlated to changes in the relative humidity (RH) caused by the leaf gas exchange traits [63]. In the atmosphere, PM functions as a condensation nucleus. It absorbs moisture in the same way on leaf surfaces when the water vapor source is plant transpiration [26,64,65]. The PM accumulation process due to plant transpiration is dependent on the particle concentrations, the physical and chemical characteristics, morphology, the history of the leaves, and atmospheric conditions, particularly rainfall, season, and wettability [26]. Previous studies have reported a negative correlation between accumulated PM and photosynthetic processes after longer and more severe PM exposure [30,49,66,67], whereas ambient PM concentrations can be easily reduced via leaf gas exchanges by intact plants [17]. PC 2, which was dominated by morphological characteristics, also significantly influenced PM adsorption on the leaves of all tested plants (Figure 7). Recent research on the PM removal efficiency of vegetation has usually focused on the correlation between leaf morphology, microstructure, and accumulation [42,47,57,61]. In this study, the leaf W/L ratio was positively correlated with particle deposition, whereas there was a negative relationship between LA and PM adsorption (Figures 6 and 7). Our analysis showed that leaf shape had a strong correlation with PM removal efficiency. In contrast, adaxial stomatal density and stomatal pore size, which reflect leaf microstructure traits, had no significant relationship with PM adsorption (Figure 6). However, it is well known that the microstructure of the leaf surface has a strong influence on its ability to retain PM. On the surface, there are dense, narrow, and deep grooves that provide enough space for the particles to be retained [19]. According to several studies, the presence of stomata helps retain PM [58,69]. Weerakkody et al. [57] reported that the amount of PM deposited was related to stomatal density. We observed trichomes on the leaves of sweet potato cultivars in this study (Figure 4B(a–e)). We did not quantify the trichome density on the leaves of the tested plants but observed that the leaves with trichomes had significantly rougher leaves. The presence of trichomes may increase the surface area of the leaves on which PM can accumulate. Furthermore, when compared to leaves without trichomes, the boundary layer resistance of leaves with trichomes is lower, which will enhance PM uptake [22,70]. Particulate matter adsorption is significantly affected by epicuticular waxes [71,72]. Their chemical composition and structure may influence PM accumulation and immobilization [16]. The presence of trichomes and epicuticular wax is highly correlated to the wettability of leaves. A low wettability reduces the amount of PM that becomes attached to the leaf surface and increases the amount in water droplets, which allows them to be removed when the droplets roll off the leaves [73]. The outcomes of our research can explain the effects of leaf gas exchange traits and morphology on plant PM capture ability. However, further investigations, including on wettability and epicuticular traits, are needed to fully understand the impacts that the leaf microstructures of the tested cultivars and species have on PM adsorption.

5. Conclusions

Significant PM adsorption differences were observed between the leaf characteristics of different cultivars and species after studying the PM adsorption and leaf characteristics of ornamental sweet potato (*Ipomoea batatas* L.) cultivars and two common indoor plants (*H. helix* and *E. aureum*). Among the sweet potato cultivars, CP, which had the highest leaf W/L ratio, had the greatest PM adsorption capacity per unit of leaf area. The leaves of *E. aureum*, which had the largest leaf area, had the lowest PM adsorption capacity among all the plants tested. The effects of PM stress on the physiological characteristics of ornamental sweet potato cultivars were also investigated. When compared to those before exposure, the photosynthetic rate (*Pn*) of BH and M decreased at 7 DAE. Stomatal conductance (*gs*) and transpiration (*Tr*) were significantly reduced in GF and M 7 days after treatment began. The Pearson correlation matrix and the PCA showed that the factors influencing PM adsorption

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can be divided into three main components. The leaf gas exchange characteristics of leaves, including \( P_n \), Tr, and SD(ab), which are highly related to transpiration, had more significant effects on PM adsorption than the other factors. We also found that PM adsorption on leaves was significantly affected by morphological characteristics, such as LA and leaf W/L. The \( P_n \), Tr, W/L, and SD(ab) values were positively correlated with PM adsorption, whereas LA was negatively correlated. This study contributes to the understanding of PM mitigation via plants by investigating the correlation between leaf characteristics and the amount of PM on leaves. In the future, we would like to broaden the scope of our research to include the density of trichomes, wettability, and epicuticular traits, which are features of the leaf microstructures of all the plants we studied.

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