

Article

Particulate Matter Removal of Three Woody Plant Species, *Ardisia crenata*, *Ardisia japonica*, and *Maesa japonica*

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Abstract: In this study, we investigated the physiological responses and particulate matter (PM) abatement and adsorption of three plants: *Ardisia crenata*, *Ardisia japonica*, and *Maesa japonica*, to determine their effectiveness as indoor air purification. When compared to control (without plants), PM was significantly and rapidly decreased by all three plants. The reduction in PM varied by species, with *A. crenata* being the most effective, followed closely by *A. japonica*, and finally *M. japonica*. *M. japonica* showed the highest rate of photosynthesis and transpiration, generating the greatest decrease in CO₂ and a large increase in relative humidity. We hypothesize that the increased relative humidity in the chamber acted in a manner similar to a chemical flocculant, increasing the weight of PM via combination with airborne water particles and the creation of larger PM aggregates, resulting in a faster sedimentation rate. *A. crenata* had a stomatal size of ~20 μm or larger, suggesting that the PM reduction observed in this species was the result of direct absorption. In the continuous fine dust exposure experiments, chlorophyll fluorescence values of all three species were in the normal range. In conclusion, all three species were found to be suitable indoor landscaping plants, effective at reducing indoor PM.

Keywords: indoor air purification; indoor landscaping; PM10; PM2.5; PM1



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1. Introduction

Particulate matter (PM) is a first-degree carcinogen as defined by the International Agency for Research on Cancer under the World Health Organization (WHO) [1]. PM is generated by a variety of sources including eolian dust, automobile emissions, factories, and homes, as well as from a large number of other artificial factors [2,3]. PM can cause significant health issues via its ability to enter the human body through the airways, and due to the large particle sizes, this makes normal biological elimination difficult. The buildup of both particles and the results of attempted elimination thus cause respiratory problems such as arteriosclerosis or dementia, and serious diseases such as lung cancer [4]. Fine dust is generally classified according to the size of the particle, i.e., as PM10, PM2.5, and PM1 if the particle size is <10 μm, <2.5 μm, and <1 μm, respectively. The United States of America and many other countries, including those in the European Union, have set environmental standards for PM10 and PM2.5. Recently, there has been increased focus on PM of smaller diameters, especially as more current research has shown that the inhalation of smaller PM can result in serious negative health effects [5].

Methods used to reduce fine dust include managing dust sources and managing indoor air quality using air conditioners or air purifiers. With the current state of global climate patterns and pollution, there has been increased interest in researching eco-friendly and sustainable methods to reduce PM, e.g., using plants [6–8]. Popek et al. [9] found that the amount of fine dust adsorbed on the leaves of woody plants or accumulated into

the wax layer was much higher on samples collected from plants near cities than that on leaves collected from the country side, where far less fine dust is produced. Plants with dense leaf hairs are effective at capturing 10–100 µm dust particles, although research has shown that dust captured in this manner is easily detached during rainfall. On the other hand, plants that form thick epicuticular wax accumulate fine dust in said wax and are effective at capturing ultra-fine dust particles (PM1, PM2.5) [10]. Leaf shape and the presence or absence of leaf hairs have been shown to have a significant effect on the accumulation of PM, but traits such as leaf morphology and leaf arrangement were found to have no relation to PM removal [11]. When utilizing herbaceous plants as PM filters, research has shown the use of heterogeneous species with varying structures and surface shapes to be more effective than any single species alone [12]. Numerous prior studies have been conducted, investigating the ability of different plant species to capture PM. In those studies, the properties of the leaves of different plant species were found to be closely related to their capacities to fine dust reduction.

Korea (33–43° N, 124–132° E) has four distinct seasons. As temperatures decrease in winter, the use of fossil fuels for heating increases, which results in an increase in outdoor fine dust. Unfortunately, because the deciduous trees common along Korean streets lose their leaves in winter, air purification via these plants is insufficient for the amount of dust produced. On the other hand, plants suitable for indoor environments can be grown indoors regardless of season. Bio-friendly work spaces and interactions with plants also alter human attitudes and behaviors, improving productivity and overall happiness [13–16]. In addition, the transpiration of plants can help control room temperature and humidity, improve indoor air quality, and reduce noise [17]. Therefore, the demand for aesthetically pleasing and functional indoor plants is rising. Interestingly, recent studies have assessed the implementation of active green wall biofilter systems which have evolved from simply planting plants in pots; these are air purifiers that flow through the plant module similarly to an air purifier [18].

Most indoor landscaping plants in Korea are non-native, introduced plants, and many species are unsuitable for the typical temperature and light conditions of a dry indoor environment with air-conditioning and heating. As a result, social interest in native plants has increased in recent years, and various attempts to utilize native plants for indoor landscaping have been made. Indoor space differs greatly from the natural environment of plants; however, in terms of the light environment, plants with a reasonable degree of shade tolerance are generally suitable for indoor use. Indoor temperatures are higher than outdoor temperatures in winter; therefore, broad-leaved trees of species found in the southern parts of Korea can be planted indoors for ornamental purposes. However, if light conditions, room temperature, ventilation, etc., are not suitable for the growth environment of plants, they greatly affect survival due to an increase in the respiration rate of plants and the occurrence of pests [19]. Therefore, drought-tolerant and shade-tolerant plants should be selected for use as indoor plants. *Maesa japonica* (Thunb.) Moritzi & Zoll. is a representative southern evergreen vine shrub that belongs to the family Maesaceae, and is known to be distributed throughout China, Taiwan, Japan, and the northern parts of Vietnam. *Ardisia japonica* (Thunb.) Blume and *Ardisia crenata* Sims. are major evergreen shrubs of the family Myrsinaceae, and are mainly native to East Asia, China, Japan, and Korea [20]. All of these species are native to Jeju island (33°50' N, 126°54' E), which is representative of the southern part of Korea. Indigenous plants from the genus *Ardisia* are well-suited for use as indoor plants, according to previous investigations of their growth via different propagation methods and in varying shading intensities [21]. With respect to native plants used for indoor landscaping in Korea, *Ardisia japonica* (Thunb.) Blume is commonly planted, followed closely by *Ardisia crenata* Sims. [22]. On the other hand, *M. japonica* is a relatively recently discovered native plant on Jeju island, South Korea. Therefore, in order to use *M. japonica* as an indoor landscaping plant, it was attempted to compare the level of air purification as well as aesthetic function compared to the above two plants.

This study was conducted to investigate the reduction in PM by, and the physiological reactions of, three plants native to South Korea; *M. japonica*, *A. japonica*, and *A. crenata*, in order to determine their suitability as indoor landscaping and air purification plants.

2. Materials and Methods

2.1. Plant Materials

The three species used in these experiments, *A. crenata*, *A. japonica*, and *M. japonica*, were propagated from cuttings taken at the National Institute of Biological Resources. Plants were transplanted into 15 cm plastic pots using horticultural soil and acclimatized to the indoor environment for more than 1 month prior to experimentation (Table 1).

Table 1. Plant height, leaf length, leaf width, and leaf number of three woody plants.

	Plant Height (cm)	Leaf Length (cm)	Leaf Width (cm)	No. of Leaves (/Plant)
<i>Maesa japonica</i>	20.7 ± 2.1 a ^z	9.1 ± 1.3 a	3.9 ± 0.6 a	52.4 ± 0.5 a
<i>Ardisia japonica</i>	17.4 ± 1.9 b	6.7 ± 1.1 b	3.3 ± 0.3 b	60.5 ± 1.6 a
<i>Ardisia crenata</i>	15.9 ± 1.9 b	7.0 ± 0.7 b	2.7 ± 0.5 b	57.1 ± 1.8 a
Significance	***	***	***	ns

The data indicate the means ± SD ($n = 5$). ^z Different letters in the same column indicate significant differences according to Duncan's multiple range test at $p < 0.05$. ns, and ***, nonsignificant and significant at $p < 0.001$, respectively.

2.2. PM Reduction

The PM reduction experiment was conducted in the laboratory between March and August 2018. Plants were placed inside an acrylic chamber [800 mm (Length) × 1200 mm (Width) × 1000 mm (Height)], into which the different sized PM (JIS Test Powders 1 class 11, The Association of Powder Process Industry and Engineering, Kyoto, Japan) was injected. A mass of 0.07 g of PM was instantaneously released using nitrogen gas.

A fluorescent lamp (light intensity: 60 $\mu\text{mol m}^{-2} \text{s}^{-1}$) was used as the light source, and the chamber was covered with a blackout curtain with a light blocking rate of 90% to control the photosynthesis caused by external light. The PM₁, PM_{2.5}, and PM₁₀ were measured using a particle counter (Aerocet 531S, Met One Instruments, Inc., Grants Pass, OR, USA) and the mass concentration method ($\mu\text{g m}^{-3}$). The carbon dioxide, relative humidity, and temperature in the chamber were measured simultaneously using an indoor air quality monitor (IQ-610Xtra, GrayWolf Sensing Solutions, Shelton, CT, USA). The experiments were conducted with four groups (control, *A. crenata*, *A. japonica*, and *M. japonica*) in a random order. An empty chamber without plants was used as the control. All treatments, including the three species of plant and the control, were conducted with seven repetitions, and each experiment was performed over the course of 8 h.

2.3. Plant Growth Traits

To investigate the relationship between PM and plant growth, we measured the height, leaf length, leaf width, number of leaves, chlorophyll fluorescence, photosynthetic rate, transpiration rate, and stomatal conductance. At the end of each chamber experiment, a leaf sample was collected and the chlorophyll and carotenoid contents, specific leaf area (SLA), leaf pH, number of stomata per unit, stoma size, and amount of PM on the leaf surface were determined. Chlorophyll fluorescence was measured after dark adaptation for 30 min using a chlorophyll fluorometer (OS30P+, Opti-Sciences, Hudson, NH, USA). The photosynthetic rate, transpiration rate, and stomatal conductance were measured between 10 a.m. and 1 p.m. using a photosynthesis system (LCpro+, ADC BioScientific Ltd., Hoddesdon, UK). To quantify the chlorophyll and carotenoid contents, 0.1 g leaf samples were frozen in liquid nitrogen, ground using a mortar and pestle, and then mixed with 10 mL of 80% acetone. The supernatants were separated by centrifugation (Cef-6, Daihan Scientific, Wonju, Korea) at 2700 rpm for 5 min and the chlorophyll a, chlorophyll

b, and carotenoid contents in the supernatants were measured using a spectrophotometer (UV-1800, Shimadzu Co., Tokyo, Japan) at wavelengths of 470.0, 464.8, and 663.2 nm. The measured values were then used to calculate the final concentrations using the following formulae according to the method of Lichtenthaler [23].

$$\begin{aligned} \text{Chlorophyll a} &= (12.25 \times A_{663.2} - 2.79 \times A_{646.8}) \\ \text{Chlorophyll b} &= (21.5 \times A_{646.8} - 5.1 \times A_{663.2}) \\ \text{Carotenoid} &= (1000 \times A_{470} - 1.82 \times \text{chl a} - 85.02 \times \text{chl b})/198 \end{aligned} \quad (1)$$

where $A_{646.8}$, $A_{663.2}$, and A_{470} refer to the absorbance values of the corresponding wavelengths.

To estimate the leaf pH, leaf samples (1 g) were ground and mixed with 10 mL of distilled water. The upper layer was separated via centrifugation (Cef-6, Daihan Scientific, Wonju, Korea) at 2700 rpm for 5 min and measured using a pH meter (HI8424, Hanna Instruments, Singapore). Leaf area was measured after the test chamber experiment using a leaf area meter (LI-3100, LI-COR Biosciences, Lincoln, NE, USA). To determine dry weight, leaves were dried for 48 h at 80 °C in a drying oven (HB-502M, Hanbek Science, Bucheon, Korea) before being measured with an analytical balance (AUW220D, Shimadzu Co., Tokyo, Japan). The SLA was calculated as the leaf area/dry weight ($\text{cm}^2 \text{g}^{-1}$) [24]. The number and size of the stomata were determined following the methods of Paek and Jun [25]. Briefly, colorless nail polish was applied to the bottom side of a leaf and allowed to dry completely. The dried film was then peeled off and mounted on a glass slide for microscopic investigation (BX53, Olympus Co., Tokyo, Japan). The amount of PM on the leaf surface was analyzed following the method of Dzierżanowski et al. [10]. We collected ~400 cm^2 of plant leaves exposed to the PM per pot. The samples were then washed with 250 mL of distilled water, and the PM larger than 100 μm was removed using a sieve. The water was then filtered sequentially, using 10–100 μm (Whatman No. 91), 2.5–10.0 μm (Whatman No. 42), and 0.2–2.5 μm (Whatman Membrane filters) filters. The filters were then dried at 80 °C in a drying oven (HB-502M, Hanbek Science, Bucheon, Korea), and weighed using an analytical balance (AUW220D, Shimadzu Co., Tokyo, Japan) after stabilization at 20 ± 3 °C. The leaf area of the leaves used in the filtration process was measured using a leaf area meter (LI-3100, LI-COR Biosciences, Lincoln, NE, USA). The amount of PM per unit area of each plant ($\mu\text{g cm}^{-2}$) was calculated by dividing the weight difference of the filter paper (before and after drying) by the leaf area.

2.4. Statistical Analysis

Statistical analyses were performed using one-way ANOVA tests ($p < 0.05$) and followed by Duncan's multiple range test (DMRT), using SAS software 9.4 version (SAS Institute, Cary, NC, USA); p values of 0.05 were considered significant.

3. Results

The reduction effect in PM1 and PM2.5 was measured at the same time based on the point at which the concentration of PM10 was uniformly diffused in the chamber and stabilized after dust injection (Table 2). Significant differences in PM1 were observed between the control and plant treatments after 4 h, and significant differences in PM2.5 and PM10 were observed after 2 h. After 8 h, the PM1, PM2.5, and PM10 levels in the control group were found to be ~3, ~6, and ~9 times higher than those in the *M. japonica* treatment, respectively, indicating that the plants effectively reduced the PM in the chamber. As a result of analyzing the effect of reducing fine dust by plant, there was no significant difference in PM1 and PM2.5 showed a significant difference after 8 h (Figure 1). The residual amounts of PM2.5 in the *M. japonica* and *A. crenata* treatments were lower than that of the *A. japonica* treatment, thus indicating that *M. japonica* and *A. crenata* were more effective in reducing PM of this size. Significant differences in PM10 levels were observed after 4 h, and the PM reducing efficiency of the plants was found to be as follows in decreasing order; *M. japonica*, *A. crenata*, and *A. japonica*.

Table 2. PM1, PM2.5, and PM10 reduction in three woody plants (mg, $n = 7$).

		0 h	2 h	4 h	6 h	8 h
PM1	Control	0.0121 a ^z	0.0241 a	0.0241 a	0.0196 a	0.0136 a
	<i>Maesa japonica</i>	0.0123 a	0.0273 a	0.0179 ab	0.0097 b	0.0050 b
	<i>Ardisia japonica</i>	0.0117 ab	0.0286 a	0.0206 ab	0.0121 b	0.0071 b
	<i>Ardisia crenata</i>	0.0100 b	0.0257 a	0.0157 b	0.0086 b	0.0044 b
	Significance	ns	ns	***	**	***
PM2.5	Control	0.779 a	0.631 a	0.372 a	0.199 a	0.107 a
	<i>Maesa japonica</i>	0.827 a	0.337 b	0.112 b	0.042 b	0.017 b
	<i>Ardisia japonica</i>	0.794 a	0.420 b	0.170 b	0.071 b	0.033 b
	<i>Ardisia crenata</i>	0.815 a	0.329 b	0.114 b	0.046 b	0.018 b
	Significance	ns	**	***	***	***
PM10	Control	9.999 a	2.398 a	0.889 a	0.373 a	0.173 a
	<i>Maesa japonica</i>	9.941 a	0.661 b	0.155 b	0.050 b	0.019 b
	<i>Ardisia japonica</i>	9.999 a	1.073 b	0.282 b	0.098 b	0.042 b
	<i>Ardisia crenata</i>	9.999 a	0.710 b	0.174 b	0.060 b	0.022 b
	Significance	ns	***	***	***	***

^z Different letters in the same column indicate significant difference according to Duncan's multiple range test (DMRT) at $p < 0.05$. ns, ** and ***, nonsignificant, significant at $p < 0.01$, and $p < 0.001$, respectively.

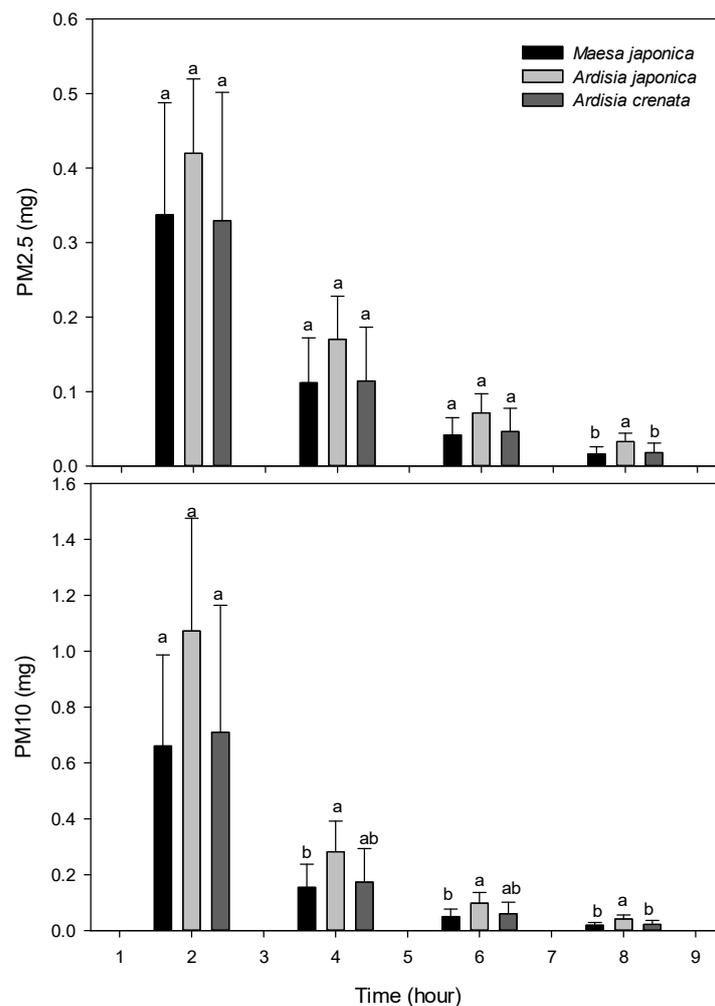


Figure 1. PM2.5 and PM10 reduction in three woody plants. The data indicate the means \pm SD ($n = 7$). The bar graph shows the amount of PM in 3 species of plants at 2 h, 4 h, 6 h, and 8 h. Different letters above bars indicate significant differences according to DMRT at $p < 0.05$.

The changes in carbon dioxide, relative humidity, and temperature in the chambers throughout the study are shown in Figure 2. Carbon dioxide in the control chamber remained at a constant concentration after stabilization, confirming that there was no inflow of air into the chambers. In the *M. japonica* treatment, the carbon dioxide concentration tended to decrease continuously for 8 h. In the *A. crenata* treatment, the carbon dioxide concentration initially remained constant and then increased, showing a tendency similar to the control. In the *A. japonica* treatment, the carbon dioxide concentration continued to increase throughout the experiment. *M. japonica* continuously absorbed carbon dioxide via photosynthesis, whereas *A. crenata* and *A. japonica* were found to have higher rates of respiration than photosynthesis after a certain period of time. This was likely because photosynthesis was not actively performed under the available light intensity supplied in this study. The relative humidity in the chambers differed significantly between the control and the plant treatments, and the relative humidity in the plant treatments varied, with *M. japonica* being the highest, followed by *A. crenata*, and *A. japonica* showed the lowest relative humidity. The temperatures in the chambers were not significantly different between the control and plant groups. There was no significant difference among plants regarding the adsorption of PM sized 0.2–2.5 μm on the leaf surface. However, *M. japonica* adsorbed the largest amount of PM sized 2.5–10.0 μm , and *A. japonica* adsorbed the largest amount of PM sized 10–100 μm (Table 3).

Table 3. Amount of PM attached to leaf surfaces according to particle size ($\mu\text{g cm}^{-2}$).

	0.2–2.5 μm	2.5–10 μm	10–100 μm
<i>Maesa japonica</i>	0.762 \pm 0.439 a ^z	1.689 \pm 0.703 a	4.867 \pm 1.692 b
<i>Ardisia japonica</i>	0.738 \pm 0.338 a	0.874 \pm 0.355 b	10.150 \pm 3.065 a
<i>Ardisia crenata</i>	0.804 \pm 0.351 a	0.907 \pm 0.450 b	6.600 \pm 1.324 b
Significance	ns	ns	**

The data indicate the means \pm SD ($n = 5$). ^z Different letters in the same column indicate significant difference according to DMRT at $p < 0.05$. ns, and **, nonsignificant and significant at $p < 0.01$, respectively.

The recorded photosynthesis and transpiration rates were highest in the *M. japonica* treatment, closely followed by *A. crenata*, with *A. japonica* displaying the lowest scores in both metrics. The stomatal conductance was highest in *M. japonica*, but did not differ significantly between *A. crenata* and *A. japonica* (Table 4). The average chlorophyll and carotenoid contents of the three plants occurred as follows in decreasing order; *M. japonica*, *A. crenata*, and *A. japonica* (Table 5). Furthermore, no significant differences were detected in the chlorophyll fluorescence values (Fv/Fm), SLA, and leaf pH among the study plants (Table 6). Significant differences were, however, detected in the number of stomata per unit and the size of stomata, whereby *A. crenata* had the largest stoma (21.1 μm) and the smallest number of stomata among the three study plants (Table 7).

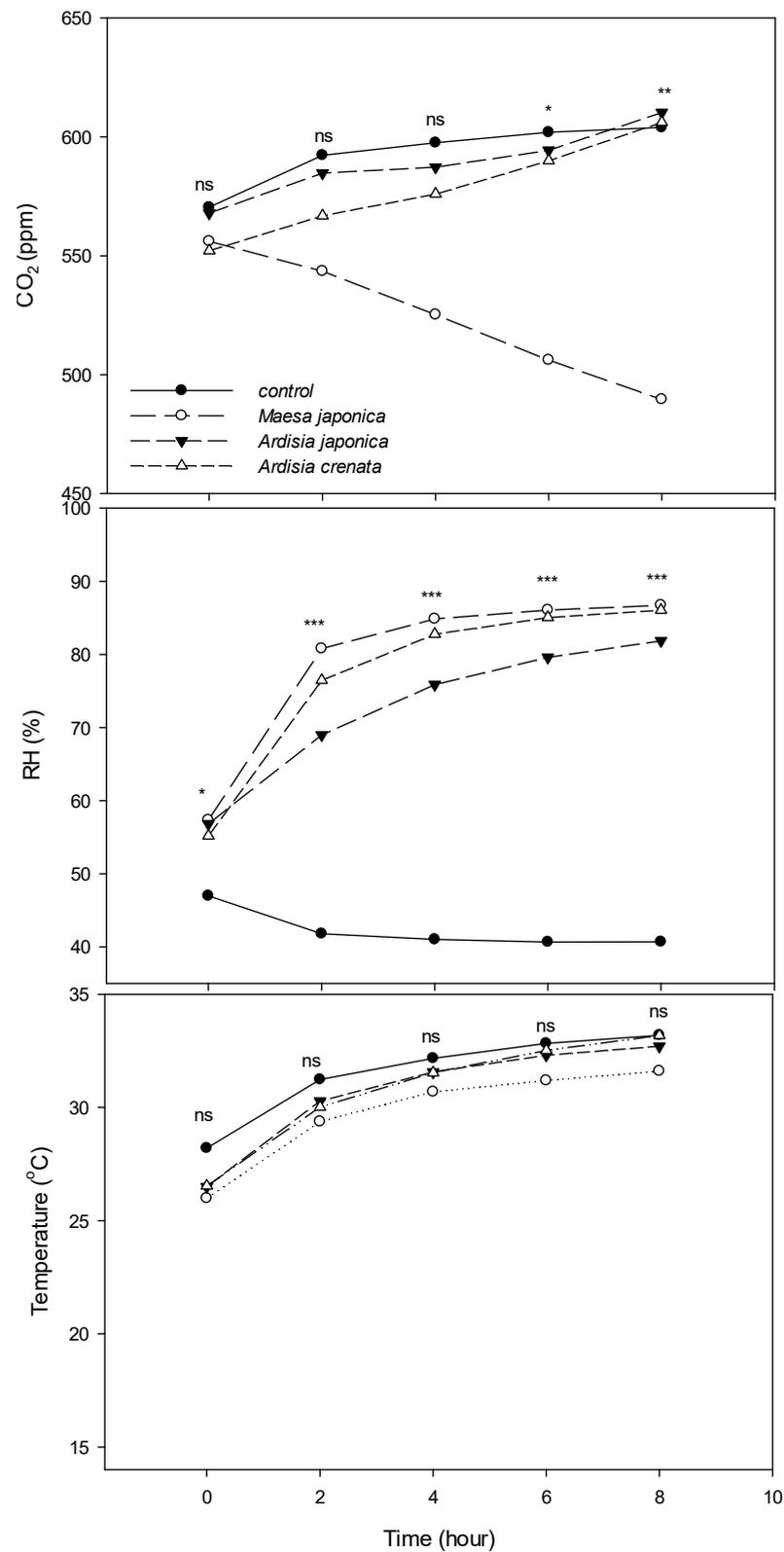


Figure 2. Changes in CO₂, temperature, and relative humidity of control and of three woody plants ($n = 7$). Measurements at start, 2 h, 4 h, 6 h, and 8 h are shown with DMRT at $p < 0.05$. ns, *, ** and ***, nonsignificant, significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

Table 4. Photosynthetic rate, transpiration rate, and stomatal conductance of three woody plants.

	Photosynthetic Rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Transpiration Rate ($\text{mol m}^{-2} \text{s}^{-1}$)	Stomatal Conductance ($\text{mol m}^{-2} \text{s}^{-1}$)
<i>Maesa japonica</i>	5.894 \pm 1.237 a ^z	1.510 \pm 0.361 a	0.060 \pm 0.019 a
<i>Ardisia japonica</i>	0.862 \pm 0.186 c	0.020 \pm 0.014 c	0.000 \pm 0.000 b
<i>Ardisia crenata</i>	2.316 \pm 1.128 b	0.436 \pm 0.306 b	0.018 \pm 0.013 b
Significance	***	***	***

The data indicate the means \pm SD ($n = 5$). ^z Different letters in the same column indicate significant differences according to DMRT at $p < 0.05$. *** Significant at $p < 0.001$.

Table 5. Chlorophyll a, chlorophyll b, and carotenoid contents of three woody plants.

	Chlorophyll Content (mg g^{-1} FW)		Carotenoid (mg g^{-1} FW)
	Chlorophyll a	Chlorophyll b	
<i>Maesa japonica</i>	1.30 \pm 0.36 a ^z	2.55 \pm 0.68 a	2.53 \pm 0.78 a
<i>Ardisia japonica</i>	0.85 \pm 0.08 b	1.69 \pm 0.16 b	1.58 \pm 0.17 b
<i>Ardisia crenata</i>	1.21 \pm 0.28 ab	2.26 \pm 0.53 ab	2.27 \pm 0.60 ab
Significance	ns	ns	ns

The data indicate the means \pm SD ($n = 5$). ^z Different letters in the same column indicate significant difference according to Duncan's multiple range test at $p < 0.05$. ns, nonsignificant.

Table 6. Fv/Fm, SLA, and leaf pH of three woody plants.

	Fv/Fm	SLA ($\text{cm}^2 \text{g}^{-1}$)	Leaf pH
<i>Maesa japonica</i>	0.791 \pm 0.016 a ^z	155.6 \pm 22.6 a	5.39 \pm 0.14 a
<i>Ardisia japonica</i>	0.791 \pm 0.010 a	163.8 \pm 24.8 a	5.40 \pm 0.19 a
<i>Ardisia crenata</i>	0.772 \pm 0.015 a	140.1 \pm 18.3 a	5.41 \pm 0.11 a
Significance	ns	ns	ns

The data indicate the means \pm SD ($n = 5$). ^z Different letters in the same column indicate significant difference according to DMRT at $p < 0.05$. ns, nonsignificant.

Table 7. Stomatal number and stomatal size of three woody plants.

	Stomatal Number ($/10^6 \mu\text{m}^{-2}$)	Stomatal Size (μm)
<i>Maesa japonica</i>	202.3 \pm 37.2 a ^z	12.3 \pm 2.1 b
<i>Ardisia japonica</i>	185.9 \pm 20.9 a	9.7 \pm 1.6 b
<i>Ardisia crenata</i>	133.0 \pm 21.8 b	21.1 \pm 2.2 a
Significance	**	***

The data indicate the means \pm SD ($n = 5$). ^z Different letters in the same column indicate significant difference according to DMRT at $p < 0.05$. **, and *** Significant at $p < 0.01$, and $p < 0.001$, respectively.

4. Discussion

In a study assessing the potential for *Chlorophytum comosum* to reduce PM, Gawrońska and Bakera [26] reported lower PM levels in chambers with plants after a certain period of time when compared to control chambers (without plants). In addition, in the comparison of PM reduction in chambers for 18 species of plants, including *A. japonica*, which can be easily obtained by consumers, PM reduction was more effective in the seedling group regardless of leaf characteristics [27]. Our study results were consistent with those of this previous study, as Table 2 clearly shows, whereby PM decreased in the presence of the study plants compared to the control treatment. In a study on the efficiency of PM removal according to the morphological characteristics of leaves (big leaf, small leaf, compound leaf, needle leaf) of 12 plants including *A. crenata*, there was no significant difference in plants except for those with needle leaves [28]. Thus, in this study, the leaf length and leaf width of the *M. japonica* were larger than that of the *A. crenata* (Table 1), but it did not seem to have a significant effect on PM removal. Lou et al. [29] suggested that the concentration of PM_{2.5}

in the air decreases as the relative humidity increases. In the present study, the relative humidity in the plant chamber was 70% after 2 h, which is likely to have increased the reduction in PM_{2.5} (Figure 2). On the other hand, in the chamber without plants, the PM_{2.5} may have accumulated on the chamber floor. In the *A. crenata* and *A. japonica* experiment, which showed little photosynthetic effect, the reason that *A. japonica* had a higher effect on reducing PM was because the relative humidity in the *A. japonica* chamber was higher, and the PM sedimentation rate was high due to the combination of fine dust and water particles. Lee et al. [30] demonstrated that when the humidification time varied from 12 to 24 h in a wall-type plant biofilter, the removal efficiency (both in the number and weight of PM₁₀) was higher after 24 h of humidification. In the present study, the indoor (i.e., chamber) relative humidity was highest in the *M. japonica* treatment, followed by *A. crenata*, and finally *A. japonica*. The data also show that the residual amount of PM₁₀ decreased in the same order after 4–6 h; therefore, the relative humidity of the room likely has a great impact on the removal of PM. The amount of PM accumulated on the leaf surface decreased as the PM size decrease, which is consistent with the findings of Gawrońska and Bakera [26] (Table 2). Furthermore, in the results of comparison by size of PM in downtown areas and suburban areas, the larger the particle, the greater the amount [10,31]. The effects of PM on human health are related to the size of the particles; therefore, *M. japonica*, which had the highest adsorption of PM_{2.5–10}, is likely the most effective plant of those examined for improving indoor air quality.

The leaf areas of *M. japonica*, *A. japonica*, and *M. crenata* were 1859.7, 1337.7, and 1079.2 cm², respectively. The amount of accumulated PM per unit leaf area of a plant decreases exponentially with increasing the distance from the pollutant source; therefore, plants should be placed as close as possible to the pollutant source and the leaf area should be as wide as possible to maximize the fixing of PM onto leaf surfaces [32,33]. In particular, *M. japonica* had the largest total leaf area due to its highly active growth in the indoor environment, which may have had a significant influence on its PM-reducing effect. Yoon et al. [34] reported that the reduction rate of cigarette smoke in both light and dark conditions was faster when *Spathiphyllum* was introduced, and that the PM removal rate was higher in species with high rates of photosynthesis. In the case of outdoor plants in areas with a lot of dust from vehicle traffic, the PM adsorbed on the surface of the leaves created a shade effect, which reduced the photosynthetic rate [35]. In a comparison of the PM removal efficiency and photosynthetic rates of five species of trees in urban areas, *Sorbaria sorbifolia* was shown to have the highest photosynthetic rate and PM removal efficiency of all five species [31]. In the present study, *M. japonica* had the highest photosynthetic rate and PM removal among the three study plants (Table 4). This effect may be attributed to the higher photosynthetic rate of *M. japonica*; PM reduction is more effective if the PM adsorbed on leaf surfaces does not inhibit photosynthesis.

In an investigation of the transpiration rate of, and relative humidity generated by, 27 indoor plants, Jeong et al. [36] found that the relative humidity in the chamber was high when the transpiration rate was also high. Przybysz et al. [31] also reported that *S. sorbifolia* had the highest transpiration rate and the highest PM removal effect among the five urban tree species studied. Our findings are consistent with those of these previous studies, whereby the relative humidity in the chambers increased in the order of increasing transpiration rates (Figure 2). Whether or not the stomata, which function to control the evaporation of water, are opened depends on the surrounding moisture state, and the opening of the stomata becomes larger under high moisture conditions. In the present study, the transpiration rate and relative humidity were highest in the *M. japonica* chamber, and the opening of the stomata due to the increase in humidity may have had an effect on the reduction in PM.

Chlorophyll b is effective at absorbing short wavelengths of light; thus, a high concentration of chlorophyll b is beneficial for growth in shaded conditions [37]. The plants used in this study had chlorophyll b contents that were about two times higher than their chlorophyll a content, indicating their suitability for indoor environments with low light.

Of the three species used in this study, *M. japonica* had the highest chlorophyll a and chlorophyll b contents, which most certainly influenced its rate of photosynthesis (Table 5). In terms of the Fv/Fm value, which indicates the stress levels of plants, no significant differences were found among the three studied plants. This may indicate that the plants were not stressed in the indoor environment, were resistant to the PM used in the present study, and are, therefore, all valuable as indoor landscaping plants (Table 6).

When plants exchange gas through stomata, they also absorb air pollutants at the same time, sequestering, reducing, and transporting them [38,39]. PM that has a diameter similar to the size of stomata can block said stomata, affecting gaseous exchange [40]. The diameters of dust particles used in this study were mainly 10 µm or less, which is larger than the average stoma size of *M. japonica* and *A. crenata* (Table 7). *A. crenata* had lower photosynthetic and transpiration rates than *M. japonica* (Table 3), but after 8 h of fine dust injection, the amount of PM was consistent with that of the *M. japonica* treatment. This result may be because *A. crenata* has stomata that are twice the size of PM10; therefore, the incidence of stoma clogging was lower than that of the other two plants. Przybysz et al. [41] measured the PM accumulated on the surface of the leaves and within the wax layer according to the degree of contamination and time in three evergreen tree species. These authors found that the amount of PM adsorbed into the wax layer in areas with low concentrations of fine dust was almost constant, but that the PM captured by the wax layer increased over time in areas with a high degree of contamination. In the *M. japonica* and *A. japonica* treatments, the PM may settle over time due to combination with water particles in the chamber, and PM which is smaller than the stomata size may be absorbed and possibly accumulated in the wax layer. These explanations may account for the findings that a residual amount of PM2.5 in treatments with *M. japonica* (with a high number of stomata) and *A. crenata* (with large stomata) reached the same level after 8 h of dust injection (Figure 2). In conclusion, the reduction in PM is not only caused by gravity, but also by the metabolic absorption of plants, which is affected by their specific traits [26].

5. Conclusions

The results of this study elucidate the indoor air purification ability of three woody plants, *M. japonica*, *A. crenata*, and *A. japonica*. All three plant treatments used in this study showed a lower residual amount of PM compared to the empty control chamber, and the effects varied by plant, with *M. japonica* being the most effective, followed by *A. crenata*, and finally, *A. japonica*. It is likely that the air purification effect was related to growth traits such as relative humidity, photosynthetic rate, transpiration rate, and stomata size. In future studies, it will be worthwhile to assess the correlations between PM reduction and other various properties of plants, such as antioxidant properties, growth rate, and leaf color, to better understand the PM abatement and adsorption capacity of different plant species.

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