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Seasonal Variations of Particulate Matter Capture and the Air Pollution Tolerance Index of Five Roadside Plant Species

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Abstract: Particulate matter (PM) is the most dangerous type of air pollutant and is harmful to human health. Plants can be used as a biofilter to remove PM from the atmosphere and improve air quality. In this study, we used the air pollution tolerance index and four leaf traits of five different plant species commonly used in landscaping in Korea to determine which plants are best suited to remove PM from the atmosphere in roadside areas in spring, summer, and autumn. We found that the PM concentrations in the atmosphere impacted the amount of PM accumulated in the plants, with increased PM accumulation during periods of increased environmental PM levels on the roadside. Euonymus japonicus, and Euonymus alatus accumulated the highest amount of PM and had the highest tolerance levels to air pollution. Thus, these species could be suitable for use in areas with high PM concentrations to improve air quality. We also found that shrubs were more effective in accumulating PM than trees and recommend that shrubs and trees be used together to further increase the amount of PM removed from the atmosphere in urban areas.

Keywords: air quality; air pollution; biofilter; shrubs; urban area

1. Introduction

Particulate matter (PM) refers to very small solid and liquid particles found in the atmosphere that originate from human activity and natural sources [1]. PM is considered the most dangerous type of air pollution, due to its effects on human health, especially in children and older adults. For example, PM with a small diameter can have a negative effect on respiration and has been linked to respiratory diseases and lung cancer [2]. PM is classified into three categories based on diameter: PM10 (diameter less than 10 µm), PM2.5 or fine particles (diameter less than 2.5 µm), and ultrafine particles (diameter less than 0.1 µm).

Increases in air pollution caused by rapid urbanization have made the control of PM in these areas especially difficult due to the difficulty of controlling PM sources in densely populated areas. Increasing traffic was among the main source of PM in these areas. Road traffic frequently has a significant contribution (5–80% depending on size and location) to concentrations of PM in the air. The particles are released from the engine exhaust, abrasion of tires, for example road surface and brake components, as well as from resuspension from the road surface [3]. One cheap and effective solution to improve the air quality in these areas has been plants. In the city center of Beijing, trees removed 772 tons of PM10 per year [4]. In the United States, urban trees and shrubs removed approximately 215,000 tons per year [5]. Despite their important role in reducing PM, limits remain on the amount of PM each plant can accumulate that are based on a variety of factors, such as plant type, leaf structure, and PM concentration [6]. For example, needleleaf plants with high wax contents accumulate more PM than broadleaf plants [7,8], and broadleaf plants with rough leaves accumulates more PM than broadleaf plants with smooth leaves [9]. The environment also
impacts the amount of PM accumulation that occurs in plant leaves. For example, rain and wind can wash PM from leaves, although this too depends on a variety of factors, such as leaf structure, leaf shape, petiole structure, and leaf concentration [10].

PM impacts the survival, growth, and reproduction of plants [11]. High PM concentrations can increase PM accumulation in leaves, thus reducing light absorption and causing a decrease in photosynthesis [12]. Plant response to air pollution stress differs based on the tolerance level of each plant to air pollution, which can include changes to leaf traits [13]. The four leaf traits impacted the most by air pollution are the leaf extract pH, the relative water content (RWC), total chlorophyll (TChl), and ascorbic acid [14]. These traits can be changed to different degrees depending on each plant’s tolerance to air pollutants. The air pollution tolerance index (APTI) was created by Singh et al. [15], using these four leaf traits. Plants with a high APTI are more tolerant to air pollutants and can continue to grow while acting as a sink for air pollution. In contrast, plants with a low APTI are commonly used as an indicator of air pollution since they are more sensitive to it and may suffer death under high air pollution conditions [14].

Green areas in urban settings, such as where plants grow along roadsides, can be an effective means to reduce PM concentration levels and improve air quality by reducing air pollutants and controlling humidity and noise [16]. Since the amount of PM that can be accumulated by plants is limited by various environmental conditions (e.g., rain, wind, and temperature [17]) that also affect survival, it is vitally important to understand how PM accumulation in plant leaves differs over long periods of time under different environmental conditions. Such knowledge can aid in the selection of plants for roadside areas that can effectively reduce PM in the long term. The aim of this study was to determine the PM accumulation abilities of different types of plants (i.e., shrubs and trees) and their associated air pollution tolerance levels to identify which plants are best suited to improve air quality in high-pollution areas. To do this, we determined the amount of PM accumulation on the leaf surface of five different common plant species in Korea during three seasons (spring, summer, and autumn) and measured the four leaf traits most impacted by air pollution to analyze the impact that PM has on the plants. We also calculated the APTI for each plant to determine their tolerance levels to air pollution.

2. Materials and Methods

2.1. Study Area and Sampling Collection

We selected a roadside area with heavy traffic in the Cheongju city, South Korea (36° 38' 0" N, 127° 29' 0" E) for this study. The sampling area was a busy road next to densely populated areas near the multi-apartment complex. The road led to the Cheongju bus terminal and the highway going to another city (Figure 1). The air pollution concentrations of PM10 in the sampling area were 38.40, 22.52, 34.90 µg·m⁻³ and the concentrations of PM2.5 were 22.03, 11.35, and 18.52 µg·m⁻³ on June, August, and October, respectively [18].

We selected five plant species with different types and heights to determine the ability of PM accumulation of plants with different types. The five common roadside plant species used included three shrubs (Abelia mosanensis T. H. Chung; Euonymus japonicus Thunb.; Euonymus alatus (Thunb.) Siebold) and two trees (Zelkova serrata (Thunb.) Makino; Prunus × yedoensis Matsum.; (Table 1). In this study, chosen plants are often used for urban greening in South Korea and easy to find on the roads in the studying area [19,20]. For each plant species, we chose five different plants which have the same age to collect leaf samples (five replicates). Each plant was tagged at the start of the experiment to ensure that the leaf samples were collected from the same plants during each sampling event. Leaves free from pests and diseases, i.e., in a good condition, were collected for analysis. Based on the leaf area of each plant species, leaf samples were cut to approximately 300 to 400 cm² and placed into a paper bag. Subsequently, all samples were immediately conveyed to the laboratory for analysis. To reduce the impacting of environment factors on the leaf samples, all samples were collected on the same day after 7 days of no rain.
Figure 1. Sampling site. Cheongju city, South Korea (36°38′0″ N, 127°29′0″ E).

Table 1. List of five plants analyzed in this study.

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Family</th>
<th>Foliage</th>
<th>Habit</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Abelia mosanensis</em> T.H.Chung</td>
<td>Caprifoliaceae</td>
<td>Deciduous shrub</td>
<td>Shrub</td>
<td>1 m</td>
</tr>
<tr>
<td><em>Zelkova serrata</em> (Thunb.) Makino</td>
<td>Ulmaceae</td>
<td>Deciduous broad leaved</td>
<td>Tree</td>
<td>10 m</td>
</tr>
<tr>
<td><em>Euonymus japonicus</em> Thunb.</td>
<td>Celastraceae</td>
<td>Evergreen broad leaved</td>
<td>Shrub</td>
<td>1 m</td>
</tr>
<tr>
<td><em>Euonymus alatus</em> (Thunb.) Siebold</td>
<td>Celastraceae</td>
<td>Deciduous shrub</td>
<td>Shrub</td>
<td>1 m</td>
</tr>
<tr>
<td><em>Prunus × yedoensis</em> Matsum.</td>
<td>Rosaceae</td>
<td>Deciduous broad leaved</td>
<td>Tree</td>
<td>10 m</td>
</tr>
</tbody>
</table>

2.2. Accumulation of Surface PM, In-Wax PM, and Epicuticular Waxes on Leaves

The leaf samples were washed with distilled water and chloroform to collect the PM that had already accumulated on the leaf surface (sPM) and in the wax layer (wPM), respectively. Following the methods of Dzierzanowski et al. [21], the samples were washed with 250 mL distilled water for 60 s, then ultrasonic cleaners (WUC-A22H, Daihan Scientific, Wonju, Korea) were used to wash the leaf samples again. The leaf washing solutions were collected in a beaker and particles greater than 100 µm in size were removed using a metal sieve (pore diameter 100 µm). Next, the solution was filtered using two types of paper filters (types 91 and 42; Whatman, UK) with pore diameters of 100 and 2.5 µm, respectively. The paper filter was placed in an auto-desiccator cabinet (SLDeBG1K, SciLab, Seoul, Korea) for 48 h, then weighed. The difference in filter paper weight before and after filtration was used to determine the amount of large (100–10 µm) and coarse (10–2.5 µm) PM that had accumulated on the leaves. Finally, the leaf samples were washed with chloroform to collect the PM that had accumulated in the wax layer using the same filtration methods. After filtration, the collected solution was placed in a pre-weighed beaker to collect the epicuticular wax from the leaf samples after chloroform evaporation.

2.3. Leaves Traits

2.3.1. Leaf Extract pH (pH)

The leaf extract pH was determined using the method from Singh et al. [15]. The leaf extract pH was determined for each sample using a pH meter (HI 8424, Hana Instruments, Woonsocket, RI, USA) after 1 g of fresh leaf sample was homogenized with 10 mL distilled water at 2700 rpm for 3 min.
2.3.2. The Relative Leaf Water Content (RWC)

The fresh, turgid and dry weights were determined for each leaf sample to calculate their RWCs following the method published by Turner [22]. The leaf samples were weighed upon collection to determine the fresh weight (FW). The turgid weight (TW) was determined after soaking the leaf samples in distilled water at 4 °C in darkness for 24 h. The dry weight (DW) was determined by weighing the leaf samples after they had been dried in an oven at 80 °C for 24 h. Using these values, the RWC was determined with the following Equation (1):

\[
RWC (\%) = \left( \frac{FW - DW}{TW - DW} \right) \times 100
\]

where FW = fresh weight, TW = turgid weight, and DW = dry weight.

2.3.3. Chlorophyll Contents

The chlorophyll a (Chl a), chlorophyll b (Chl b), and total chlorophyll (TChl) contents were analyzed using Lichtenthaler [23] method. Chlorophyll a (Chl a), chlorophyll b (Chl b), and total chlorophyll (TChl) were calculated using Equation (2):

\[
\begin{align*}
\text{Chlorophyll a} &= (11.24 \times A_{616.6}) - (2.04 \times A_{644.8}) \\
\text{Chlorophyll b} &= (20.13 - A_{644.8}) - (4.19 \times A_{616.6}) \\
\text{Chlorophyll a} + b &= (7.05 \times A_{616.6}) + (18.09 \times A_{644.8})
\end{align*}
\]

where \(A_{616.6}\), \(A_{644.8}\), and \(A_{470}\) are absorbance values at corresponding wavelengths.

2.3.4. Ascorbic Acid (AA)

Ascorbic acid was determined based on the method described by Dinesh et al. [24] using the formula:

\[
\text{Amount of ascorbic acid content (mg/100 g)} = \frac{500 \times V_2 \times 25 \times 100}{V_1 \times 5 \times 5}
\]

where 500: \(\mu g\) of standard ascorbic acid taken for titration, \(V_1\): value of dye consumed by 500 \(\mu g\) of standard ascorbic acid, \(V_2\): value of dye consumed by 5 mL of test sample, 25: corresponds to total volume of the extract, 100: ascorbic acid content/100 g of the sample, 5: weight of sample taken for extraction, and 5: value of the test sample taken for titration

2.4. The Air Pollution Tolerance Index (APTI)

The APTI was measured using the method described by Singh et al. [15] and the following formula:

\[
\text{APTI} = \frac{A \times (T + P) + R}{10}
\]

where A is the ascorbic acid (mg g\(^{-1}\) FW); T is the total chlorophyll (mg g\(^{-1}\) FW); P is the leaf extract pH; and R is the RWC of the leaf (%).

The APTI of each plant was classified into four tolerance levels (tolerant, moderately tolerant, intermediate, and sensitive; Table 2) per Ghafari et al. [25].

Table 2. The tolerance levels of plants based on the APTI.

<table>
<thead>
<tr>
<th>Tolerance Level</th>
<th>Calculated Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerant (T)</td>
<td>APTI &gt; mean APTI + SD</td>
</tr>
<tr>
<td>Moderately tolerant (MT)</td>
<td>Mean APTI &lt; APTI &lt; mean APTI + SD</td>
</tr>
<tr>
<td>Intermediate (T)</td>
<td>Mean APTI − SD &lt; APTI &lt; mean APTI</td>
</tr>
<tr>
<td>Sensitive (S)</td>
<td>APTI &lt; mean APTI − SD</td>
</tr>
</tbody>
</table>

3. Statistical Analysis

All the data were analyzed using SAS software 9.4 version (SAS Institute, Cary, NC, USA) for Duncan’s multiple range test (DMRT) and \(p\) values of 0.05 were considered
significant. Pearson’s correlation analysis was used to identify the relationship between the amount of PM accumulation and the plant biochemical characteristics and the APTI.

4. Results and Discussion

4.1. PM accumulation of Plants

The PM accumulation amounts on the leaf samples differed by species and season. The total PM accumulation in the leaves of the five plant species ranged from 41.15 to 124.78 μg·cm⁻² in spring (June), 25.50 to 63.29 μg·cm⁻² in summer (August), and 24.54 to 66.69 μg·cm⁻² in autumn (October). The PM accumulation was highest for all species in the spring, with no difference found between summer and autumn. In the spring and summer, *E. japonicus* had the highest PM accumulation, followed by *E. alatus*, and *A. mosanensis*, whereas *P. × yedoensis* and *Z. serrata* had the lowest PM accumulations. In the autumn, *E. alatus* had the highest PM accumulation, followed by *E. japonicus*. Overall, *A. mosanensis* had the lowest PM accumulation in its leaves.

The total PM accumulation on the leaf surface of the shrubs was higher than that of the trees and the PM accumulation on the leaf surfaces was higher than that of the wax layer for all species and all seasons. *E. japonicus* had the highest sPM accumulation levels in the spring, whereas *E. alatus* had the highest levels in summer and autumn. Furthermore, the plant with the highest wPM accumulation in all seasons was *E. japonicus*. Additionally, the amount of large PM was higher than course PM for all plants and seasons. The amount of epicuticular wax for all seasons was highest in *E. japonicus*. *Z. serrata* had the lowest amount of epicuticular wax (Figures 2 and 3).

In this study, leaf PM accumulation was highest in the spring, which was also the season with the highest PM concentrations. This result agrees with those of previous studies that have shown that higher PM concentrations in the environment result in plants that accumulate greater amounts of PM [26,27]. This could also partially explain the lower PM concentrations found on the leaves during the summer and spring in this study, since these seasons have lower environmental PM concentrations. The lower PM concentrations in summer could have also been due to the removal of PM from the plant leaves by rain. We also determined that the amount of sPM was higher than wPM in all species, which agrees with the findings of Popek et al. [28]. Furthermore, we found that the shrubs accumulated more PM on their leaf surfaces than the trees, which agrees with Sæbø et al. [9], who showed that shrubs growing lower to the ground accumulated more large-sized PM in...
their leaves than trees did. These findings indicate that shrubs should be utilized more in roadside green areas to increase the amount of PM removed from the atmosphere in these urbanized environments.

Figure 3. The amount of epicuticular wax of five plant species in three seasons (spring, summer, and autumn).

The PM accumulation measured in this study differed by species. Many previous studies have shown that evergreens accumulate more PM than deciduous plants [29–31]. Other studies have shown that trees with greater leaf area were more effective at PM accumulation [32] and that leaf structure, including leaf shape, area, and wax, impacts the PM accumulation abilities of plants [33]. Taken together, these findings could explain why E. japonicus accumulated the greatest amount of leaf PM in this study, since it is an evergreen plant that has smooth leaves with curled leaf edges that keep PM on the leaf apices despite rainfall. Moreover, the glands and secretions of the leaves and their high amount of wax (the highest of all studied species) also aided in its PM accumulation [34–37]. In this study, the rainfall and the PM concentration can be the main factors that impact the amount of PM accumulation on the leaves of the five plant species. That can explain the decreasing PM accumulation in the summer (the season with the highest rainfall) and increasing PM in the spring (the season with the highest PM concentration in the air). Further study needs to consider the PM source in the area study, which can influence the PM accumulation of plants.

4.2. Leaf Traits

The leaf trait values determined in this study are listed in Table 3. The TChl differed by plant and season and ranged from 0.13 to 0.34 mg·g$^{-1}$ in spring, 0.12 to 0.17 mg·g$^{-1}$ in summer, and 0.11 to 0.23 mg·g$^{-1}$ in autumn. We did not find any trends when the TChl was compared between the three seasons. The TChl of Z. serrata and P. × yedoensis was significantly higher in spring and decreased in summer and autumn. No significant differences were found between the three seasons in the remaining three species. In both spring and autumn, Z. serrata had the highest TChl levels. In summer, P. × yedoensis had the highest TChl levels. The plants with the lowest TChl were E. alatus and E. japonicus, respectively. The RWC ranged from 51.66% to 74.13% in spring, 69.44% to 78.04% in summer, and 65.16% to 78.12% in autumn. The RWC of Z. serrata did not significantly differ between the three seasons, but all other species had a significantly lower RWC in the spring.
compared to summer and autumn. No significant differences were found in the leaf extract pH in either the species or season studied except for *A. mosanensis*. The pH of *A. mosanensis* was highest in the summer (6.01) and lower in spring (5.82) and autumn (5.71). *E. japonicus* had the highest leaf extract pH in the spring, while *E. alatus* had the highest leaf extract pH in summer and autumn. The AA of the five species ranged from 0.15 to 0.60 mg-g⁻¹ in spring, 0.35 to 0.67 mg-g⁻¹ in summer, and 0.36 to 0.55 mg-g⁻¹ in autumn. *E. alatus* had the highest AA levels in the spring, while *E. japonicus* had the highest in summer and autumn. Conversely, *A. mosanensis* had the lowest AA levels in all three seasons. Overall, the AA levels were significantly reduced in the spring. Table 4 shows the correlations between the leaf traits, the APTI, and the PM accumulation in the leaves of the five studied species. We found that the PM accumulation in the leaves was negatively correlated with TChl and the RWC and positively correlation with AA. No correlation was found between PM and pH in the spring, but a positive correlation between the two was found in the summer and autumn.

Table 3. Average leaf trait parameter values of five plant species in three seasons (spring, summer and autumn).

<table>
<thead>
<tr>
<th>Leaf Traits</th>
<th>Seasons</th>
<th><em>A. mosanensis</em></th>
<th><em>Z. serrata</em></th>
<th><em>E. japonicus</em></th>
<th><em>E. alatus</em></th>
<th><em>P. × yedoensis</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>AA (mg-g⁻¹)</td>
<td>Spring</td>
<td>0.15 ± 0.01 b</td>
<td>0.22 ± 0.06 b</td>
<td>0.47 ± 0.09 b</td>
<td>0.60 ± 0.07 a</td>
<td>0.23 ± 0.02 b</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.35 ± 0.05 a</td>
<td>0.49 ± 0.09 a</td>
<td>0.67 ± 0.09 a</td>
<td>0.48 ± 0.09 b</td>
<td>0.45 ± 0.08 a</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>0.36 ± 0.04 a</td>
<td>0.43 ± 0.04 a</td>
<td>0.55 ± 0.20 ab</td>
<td>0.42 ± 0.05 b</td>
<td>0.44 ± 0.05 a</td>
</tr>
<tr>
<td>pH</td>
<td>Spring</td>
<td>5.82 ± 0.05 b</td>
<td>5.69 ± 0.19 a</td>
<td>5.92 ± 0.14 a</td>
<td>5.87 ± 0.17 b</td>
<td>5.62 ± 0.14 a</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>6.01 ± 0.08 a</td>
<td>5.87 ± 0.13 a</td>
<td>5.82 ± 0.10 a</td>
<td>6.12 ± 0.18 a</td>
<td>5.82 ± 0.16 a</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>5.71 ± 0.04 c</td>
<td>5.69 ± 0.13 a</td>
<td>5.83 ± 0.12 a</td>
<td>5.92 ± 0.08 ab</td>
<td>5.60 ± 0.28 a</td>
</tr>
<tr>
<td>RWC (%)</td>
<td>Spring</td>
<td>51.66 ± 3.56 c</td>
<td>74.13 ± 7.41 a</td>
<td>66.83 ± 4.82 b</td>
<td>55.29 ± 2.70 b</td>
<td>61.15 ± 2.55 b</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>75.13 ± 3.17 a</td>
<td>69.44 ± 2.68 a</td>
<td>74.56 ± 2.82 a</td>
<td>77.65 ± 2.72 a</td>
<td>78.04 ± 3.17 a</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>65.96 ± 2.22 b</td>
<td>65.16 ± 8.03 a</td>
<td>77.45 ± 4.20 a</td>
<td>76.30 ± 3.09 a</td>
<td>78.12 ± 1.86 a</td>
</tr>
<tr>
<td>TChl (mg-g⁻¹)</td>
<td>Spring</td>
<td>0.17 ± 0.02 a</td>
<td>0.34 ± 0.07 a</td>
<td>0.16 ± 0.02 a</td>
<td>0.13 ± 0.03 a</td>
<td>0.21 ± 0.03 a</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.16 ± 0.02 a</td>
<td>0.16 ± 0.07 b</td>
<td>0.13 ± 0.04 ab</td>
<td>0.12 ± 0.01 a</td>
<td>0.17 ± 0.04 ab</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>0.16 ± 0.02 a</td>
<td>0.23 ± 0.04 b</td>
<td>0.11 ± 0.04 b</td>
<td>0.11 ± 0.02 a</td>
<td>0.14 ± 0.00 b</td>
</tr>
</tbody>
</table>

* ANOVA was used to analyze the significance of the difference in leaf traits between difference seasons. AA: ascorbic acid, pH: leaf extract pH, RWC: relative leaf water content, and TChl: total chlorophyll concentration. Levels of significance: ns, *, **, and ***: nonsignificant, and significant at p < 0.05, p < 0.01, and p < 0.001, respectively.

Measures of TChl indicate the effectiveness of photosynthesis and can be used to determine the impact of air pollution on plants, since the reduction in TChl leads to decreased growth. In this study, the TChl of the shrubs (*A. mosanensis, E. japonicus*, and *E. alatus*) was lower than the trees (*Z. serrata* and *P. × yedoensis*). This could be due to the high amount of large-sized PM (10–100 μm) accumulated on the shrub leaves, which decreased the light absorbance of the plants. The negative correlation between PM and TChl could also explain the lower TChl levels in the shrubs. In another study, PM accumulation on the leaf was blocked on the stomata due to the reduced TChl contents of the plants. The increased TChl contents in *Z. serrata* and *P. × yedoensis* in the summer and autumn may explain the decreasing amount of PM accumulation in the leaves during these seasons.
Table 4. The correlation between PM accumulation on leaves, leaf traits, and the APTI of five plant species.

<table>
<thead>
<tr>
<th></th>
<th>AA</th>
<th>pH</th>
<th>RWC</th>
<th>TChl</th>
<th>APTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>sPM (10–100 µm)</td>
<td>0.390 *</td>
<td>0.448</td>
<td>0.107</td>
<td>−0.344 *</td>
</tr>
<tr>
<td></td>
<td>sPM (2.5–10 µm)</td>
<td>0.546 *</td>
<td>0.268</td>
<td>−0.475</td>
<td>−0.344</td>
</tr>
<tr>
<td></td>
<td>wPM (10–100 µm)</td>
<td>0.539 *</td>
<td>0.452</td>
<td>0.087 *</td>
<td>−0.411 **</td>
</tr>
<tr>
<td></td>
<td>wPM (2.5–10 µm)</td>
<td>0.322</td>
<td>0.122</td>
<td>−0.074</td>
<td>−0.435 **</td>
</tr>
<tr>
<td>Summer</td>
<td>sPM (10–100 µm)</td>
<td>0.450 *</td>
<td>0.330</td>
<td>0.256 *</td>
<td>−0.475 *</td>
</tr>
<tr>
<td></td>
<td>sPM (2.5–10 µm)</td>
<td>0.444 *</td>
<td>0.109</td>
<td>0.377</td>
<td>−0.379</td>
</tr>
<tr>
<td></td>
<td>wPM (10–100 µm)</td>
<td>0.427 *</td>
<td>0.255 *</td>
<td>0.286 *</td>
<td>−0.445 *</td>
</tr>
<tr>
<td></td>
<td>wPM (2.5–10 µm)</td>
<td>0.029</td>
<td>0.108</td>
<td>−0.167 *</td>
<td>−0.518 **</td>
</tr>
<tr>
<td>Autumn</td>
<td>sPM (10–100 µm)</td>
<td>0.329</td>
<td>0.553 **</td>
<td>0.385</td>
<td>−0.563 **</td>
</tr>
<tr>
<td></td>
<td>sPM (2.5–10 µm)</td>
<td>0.244</td>
<td>0.054</td>
<td>0.266</td>
<td>−0.153</td>
</tr>
<tr>
<td></td>
<td>wPM (10–100 µm)</td>
<td>0.298</td>
<td>0.410 *</td>
<td>0.497 *</td>
<td>−0.532 **</td>
</tr>
<tr>
<td></td>
<td>wPM (2.5–10 µm)</td>
<td>0.510 **</td>
<td>−0.226</td>
<td>0.522</td>
<td>−0.414 *</td>
</tr>
</tbody>
</table>

AA: ascorbic acid, pH: leaf extract pH, RWC: relative leaf water content, TChl: total chlorophyll concentration, and APTI: air pollutant tolerance index. Levels of significance: ns, *, and **: nonsignificant, and significant at \( p < 0.05 \), and \( p < 0.01 \), respectively.

The RWC is an expression of the water transpiration rate of plants and plays an important role in plants [38], since plants with a high RWC are better able to maintain their physiological functions under environmental stress [39]. A high RWC may increase plant tolerance to air pollutants, but plants grown under high PM conditions have a lower RWC than those grown under lower PM concentrations. Many previous studies have indicated that PM accumulated on leaves leads to the loss of water and dissolved nutrients [40]. In this study, the RWC was lowest in summer, corresponding with the highest PM concentration season.

The leaf extract pH of plants impacts their chlorophyll and AA contents [31] and is known to be a sensitive indicator of air pollution [39], since changes in leaf extract pH may lead to increasingly sensitive stomata. Additionally, reductions in pH reduce photosynthesis rates and lead to a decreasing conversion rate of hexose sugar to AA, which directly relates to the tolerance level of plants to air pollution [41]. Thus, plants with a high leaf extract pH level are more tolerant to air pollution. In this study, *E. japonicus* and *E. alatus* were more tolerant to air pollution than the other species.

AA is a natural plant antioxidant that plays a primary role in plant tolerance to pollutants [42]. Additionally, AA plays an important role in maintaining cell division and protecting plant tissues from the influence of environmental stress, such as air pollution [43]. Plants with high AA are more tolerant to air pollution. The AA of plants in the pre-moon season with higher PM concentrations was higher than those in the post-moon season with lower PM concentrations. The same tendency was found in this study, with the highest AA levels found in the season with the highest PM concentrations (spring).

4.3. The APTI

The APTI of the five species was lowest in the summer. We did not find any significant differences between the APTI of the five species between summer and autumn, except for *Z. serrata*. The tolerance levels to air pollution based on the APTI are provided in Table 5. In the spring, the plants were classified into four tolerance levels: tolerant (*Z. serrata*), moderately tolerant (*E. japonicus*), intermediate (*E. alatus* and *P. × yedoensis*), and sensitive (*A. mosanensis*). In summer, three tolerance levels were determined: moderately tolerant (*E. japonicus*, *E. alatus*, and *P. × yedoensis*), intermediate (*A. mosanensis*), and sensitive (*Z. serrata*). In autumn, all species were similarly tolerant to air pollution as in the summer except for *A. mosanensis*, which was considered sensitive in the autumn.
Table 5. The APTI and tolerance levels of five plant species in three seasons (spring, summer and autumn).

<table>
<thead>
<tr>
<th>Species</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>APTI</td>
<td>Tolerant Level</td>
<td>APTI</td>
</tr>
<tr>
<td>A. mosanensis</td>
<td>5.26</td>
<td>Sensitive</td>
<td>7.73</td>
</tr>
<tr>
<td>Z. serrata</td>
<td>7.54</td>
<td>Tolerant</td>
<td>7.24</td>
</tr>
<tr>
<td>E. japonicus</td>
<td>6.97</td>
<td>Moderately tolerant</td>
<td>7.86</td>
</tr>
<tr>
<td>E. alatus</td>
<td>5.89</td>
<td>Intermediate</td>
<td>8.06</td>
</tr>
<tr>
<td>P. × yedoensis</td>
<td>6.25</td>
<td>Intermediate</td>
<td>8.08</td>
</tr>
</tbody>
</table>

Plants with a high APTI are more tolerant to air pollution compared to plants with a low APTI [44], which makes high-APTI plants ideal for use as biofilters in areas with high PM concentrations and low-APTI plants ideal indicators for air pollution. The tolerance levels to air pollution differ by species and environmental condition [45]. In this study, E. japonicus, E. alatus, and P. × yedoensis showed the same tolerance levels in all three seasons, indicating that these plants may be tolerant to different PM concentrations and environmental conditions. Thus, these plants could be planted in areas of high PM concentrations to improve air quality. In contrast, Z. serrata was tolerant to high PM concentrations in the spring but was sensitive in the summer and autumn. This could be due to differences in environmental conditions between the seasons, such as temperature and humidity, and indicates that Z. serrata would be less ideal for use in areas with high PM concentrations. There was a significant correlation between environmental PM and the APTI.

5. Conclusions

In this study, leaf PM accumulation differed by species and season, with the greatest amount of PM accumulation occurring in the spring. The APTI also differed between plant species and showed the same tendency under different seasons. Furthermore, PM was significantly correlated with leaf traits and the APTI. We also found that the studied shrubs accumulated much more large-sized PM in their leaves and were more effective at accumulating PM than the studied tree species. Of the five plants, E. japonicus, and E. alatus were the most effective at accumulating PM and were found to be the most tolerant to air pollution under the different seasons. Thus, we conclude that these species should be considered for additional planting in roadside green areas to increase PM reduction. Plants with a high APTI and PM accumulation capabilities could be a criterion for selecting plant species to improve air quality in areas such as roadside areas with severe air pollution. In addition, the combined use of trees and shrubs could further help to increase the PM accumulation of green areas in urbanized regions. In further studies, the heavy metals released from traffic need to be analyzed to determine how to improve air quality and the impact of air pollutants on plants that grow in these areas.

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