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Interaction of Urban Trees and Atmospheric Fine Particulate Matter in Budapest

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1. Background and aims

Nowadays, urban areas span about 3% of the earth's land surface area, however, resides more than 4.2 billion (about 55%) of the global population, and this percentage is believed to rise to 68% in 2050. The rapid increase of urbanization is posing substantial challenges to both human well-being and environmental sustainability. Because of densely buildings, heavy traffic, and extensive excavation construction activities in metropolitan areas leads to the formation of urban heat islands (UHI), drought, and severe air pollution. Air pollution, particularly fine particulate matter (PM), poses a serious threat to human health and the environment on local, regional, and global scales not only because of its harmful health effects but also the difficulties associated with its removal. Unlike pollutants in food, soil, and water, air pollutants are extremely challenging to remove, particularly as urbanization continue to increase, exacerbating the retention of fine PM in urban areas. In Hungary, the annual $PM_{2.5}$ from 2020 to 2023 ranged between 11-13 $\mu g \bullet m^{-3}$ in Hungary, and it is more extremely pressing in Budapest, as the metropolitan region of Budapest is the spot urbanized surface in Hungary. The exceedance of PM and other precursor gases has led to infringement procedures, highlighting the challenge of controlling PM in this region.

In response to these challenges, green infrastructure has been considered as one potential urban planning solution for improving air quality as well as enhancing the sustainability of cities for growing urban populations. Urban trees are fundamental components of the urban landscape, serving aesthetic purposes while playing crucial ecological roles. These roles include mitigating environmental impacts, providing shade, improving air quality, and fostering biodiversity. Consequently, urban trees are vital in helping cities adapt to climate change through effectively trap significant quantities of PM on their leaf surfaces, making this an effective and widely implemented sustainable strategy in many cities.

The relationship between urban trees and the environment is assessed from two perspectives: trees as bio-indicators of environmental quality and the growth patterns of trees as reflections of environmental quality. The structure parameters serve as straightforward indices of growth, while photosynthesis, a fundamental physiological process, is crucial for the ontogenetic development of plants. Photosynthesis is influenced by daily and seasonal fluctuations in urban environmental conditions. It is the key factor for the growth and survival of trees, as the energy captured and stored through photosynthesis supports plant growth. Plants possess the ability to adapt stressors by photosynthetic acclimation or thermal regulation. However, how urban trees do not respond uniformly to changing environmental circumstances, as conditions in urban areas are significantly different from those in natural habitats.

Therefore, deploying advanced trees that effectively interact with atmospheric pollution will be a crucial step in urban planning. Although the benefits of urban trees are well-documented, our understanding of the underlying physiological processes, such as photosynthesis, that influence their long-term health and growth in cities remains limited. This study aims to explore the interaction between urban trees and ambient fine particulate matter in Budapest, focusing on both the impact of air pollution on the growth of urban trees and the benefits these trees provide in retaining fine PM. Our objectives are as follows:

1) Canopy volume assessment: We aim to compare two different methods for assessing canopy volume in urban trees. The tree structure will be measured by evaluating different dimensions of the above-ground canopy and using a leaf area index (LAI) system.

2) Photosynthesis activities evaluation: By comparing different photosynthetic parameters and identifying key components that contribute to changes in net photosynthesis, we aim to assess the trees' ability to adapt to the stressed conditions typical of urban environments.

3) PM retention: We intend to evaluate the ability of different woody plant species to retain fine PM on their leaf surfaces. Additionally, we analyzed the chemical properties of fine PM accumulated on the leaves and discuss the interactions between fine PM and leaf surfaces. By differentiating the chemical properties of washed-off PM, we aim to determine its sources and understand the role of urban trees in filtering harmful pollutants from the air.

4) Trace elements (TE) retention: Given that TE retention is one of the most challenging aspects of air pollution removal, we plan to investigate the translocation of TE within different woody plant species.

The results of this study will provide valuable insights into the interactions between roadside trees and ambient pollution in metropolitan areas like Budapest. The ongoing global climate change further underscores the importance of selecting plant species that can thrive in urban environments. Beyond their decorative and practical functions, it is essential to carefully assess trees' ability to withstand various abiotic pressures, including pollution, temperature extremes, and water scarcity. By prioritizing the selection of resilient tree species, cities can create healthier, more sustainable urban landscapes that will benefit current and future generations. This research will contribute to the development of urban planning strategies that integrate green infrastructure, ultimately enhancing the quality of life in densely populated areas.

2. Materials and methods

We sampled from two locations: Deák Ferenc tér (47°49' LN; 19°05' LE, 104 m above sea level) and Budai Arborétum (47°28' LN; 19°2' LE, 113-143 m above sea level) in Budapest, Hungary to represent urban street and urban park, respectively. Selected species are the *Acer platanoides* L. 'Globosum' (Norway maple), *Fraxinus excelsior* L. Westhof's Glorie (common ash), and *Tilia tomentosa* Moench (silver linden), are among the most common planted medium-sized (20-35m) roadside deciduous trees in the study area and in many East-Central European cities, with distinct leaf morphologies.

Sampling took place from May 2021 to October 2024 from Deak Ferenc tér (urban street) and Budai Arborétum (urban park). Five individuals of each species with tree heights around 10m (ranged from 9 - 11 m) were selected at each site.

On-site measurements were done from 2021 to 2024. The structural data, including diameter at breast height (dbh), tree height (h), bole length, and crown radii in four cardinal directions, were measured. LAI was measured by an AccuPAR LP-80 (PAR/LAI Ceptometer, Decagon Devices Inc., WA, USA). The probe was positioned at open position next to each tree and four positions (east, west, south, and north) under tree canopy. The net photosynthesis (A [$\mu mol \cdot m^{-2} \cdot s^{-1}$]), rate of transpiration (E [$mmol \cdot m^{-2} \cdot s^{-1}$]), intercellular CO_2 concentration (C_i [ppm]), leaf temperature (T_{leaf} [°C]), stomatal conductance (g_s [$mol \cdot m^{-2} \cdot s^{-1}$]), and photosynthetically active radiation (PAR [$mmol \cdot m^{-2} \cdot s^{-1}$]) were measured with photosynthesis systems: ADC BioScientific LCi Analyser Serial No. 32732 (ADC BioScientific Ltd.,EN, UK) in 2021. A total of 574 measurement in 2021. From 2022 to 2024, The net photosynthesis (A [$\mu mol \cdot m^{-2} \cdot s^{-1}$], rate of transpiration (E [$mmol \cdot m^{-2} \cdot s^{-1}$]) were measured by CI-340 (CID Bio-Science Inc., WA, USA). A total of 620 measurements in 2022 to 2024. Measuring was always taking places in a time scale ranging from 9:00 a.m. to 11:00 a.m. because a daily curve of photosynthetic activity shows that the difference between species begins around that time.

For PM deposition analysis, sampling took place from 2021 to 2023. A total of 432 leaf samples were collected. In the laboratory, each subsample was soaked in 250 ml distilled water for twenty-four hours and then shaken in an ultrasonic compact cleaner (UC005 AJ1, Tesla) for 10 minutes. The resulting dust suspension was filtered using filter paper with a pore size 2.0-4 μm. After filtering suspension was then separated into two parts. A 25 ml portion of the suspension was placed into a beaker and evaporated in a sand-bath till constant dry weight. The weight of the beakers was measured three times: before adding the suspension, with suspension, and after the suspension was evaporated, using an electronic scale (Adventurer, Ohaus, Parsippany-Troy Hills, NJ, USA) with a detection limit of 100 μg. The weight of PM was then calculated, in the unit of μg. The dried PM deposition was then processed for further investigation of HM contents. The second part of suspension was used to analyze their physiochemical parameters (pH, EC, salt content, NH_4^+, NO_3^-, SO_4^{2-}, and Cl^- content). The pH, EC, and salt content were measured by a Mettler Toledo™ SevenGo Duo equipment. The ion concentrations of NH_4^+, NO_3^- , SO_4^{2-} were first subjected to a chemical reaction, then followed be a spectrometer measurement, the protocol proposed by Tandon H.L.S, (2013). The concentration of Cl^- was determined by the Mohr method. After washing off, leaf samples were naturally dried, and their leaf areas were measured using an AM350 leaf area meter (ADC Bio Scientific Ltd., UK). Real-time images and measured parameters were exported to Excel files, and then the average leaf area of each species per square centimetre (cm^2) was computed.

Soil samples were dried to constant weight at room temperature, grounded. To remove plant debris and stones, all soil samples were sieved through a 2.0 mm mesh. We weighted 2g of each sample and examined the physicochemical properties (pH, EC, salt content, humus, NO_3^-, NH_4^+, K_2O, and P_2O_5). The pH was determined potentiometrically in H_2O and KCL solution, 1:2.5 of soil: solution ratio. While the EC values, salt contents, concentrations of NH_4^+ and NO_3^- were similar as to the dust suspension. To determine the humus quantity in soil samples, weigh 0.3 g of the soil sample into an Erlenmeyer flask, add 10 cm³ of 0.4 mol·dm⁻³ potassium dichromate ($K_2Cr_2O_7$) solution, cover with a funnel, and heat over a sand bath for 10 minutes. After cooling, rinse the funnel with distilled water and dilute the mixture to 200 cm³. Add at least 10 drops of phosphoric acid (H_3PO_4) and 5 drops of diphenylamine indicator. Titrate with 0.2 mol·dm⁻³ Mohr's salt ($Fe(NH_4)_2(SO_4)_2$) until the solution changes from brownish to light green. Finally, calculate the humus content based on the titration results. To determine the K_2O and P_2O_5 content in soil, weigh 5 g of air-dried soil into a shaker, add 100 cm³ of ammonium lactate in an acidic medium, and shake for 30 minutes. After shaking, filter the suspension. Measure the K_2O concentration using a flame photometer. For P_2O_5 determination, take 10 cm³ of the filtrate into a glass beaker, add 15 cm³ of ammonium molybdate in a sulfuric acid medium, followed by 1 cm³ of 1 m·m%⁻¹ ascorbic tin chloride solution, and let the mixture stand for 15 minutes. Then, measure the sample's transmittance using a spectrophotometer at 438 nm and calculate the K_2O and P_2O_5 concentration accordingly.

Four groups of samples were process for the determination of TE contents: the dried fine PM deposition (*n*= 432), leaf samples (*n*=252), branch samples (*n*=252), and soil samples (*n*=69). All samples were procedure by a wet digest method as described follow. For fine PM deposition, 5 ml of 65% HNO_3 and 1 ml of 30% of H_2O_2 were add to the sample beakers, then transfer to a burette. Leaf, branch and soil were first ground. Then, for all samples, 1g of the samples were weighted and placed into a burette, then add 10 ml 65% HNO_3 and 4 ml 30% of H_2O_2. All sample after transferred into a burette, then burette will be insert into a thermal apparatus, heat to 130°C, and maintain for 1.5 hours. Subsequently, allow it to cool and dilute with distilled water to a final volume of 10 ml for the fine PM samples and 100 ml for other samples. Finally, the solutions were then filtered for analysis. From the filtrate solution, TE elements including Cu, Fe, Ni, Pb, and Zn were determined by using atomic absorption spectrometer (AAS) AURORA AI 1200 (AURORA Instruments Ltd, Canada). The AAS equipment was operated with an ai-acetylene flame and the deuterium (D2) background correction was used. The precision of the AAS device is 0.5%. And the detection limits used in the study were Cu> 0.02 $mg \cdot L^{-1}$, Fe> 0.03 $mg \cdot L^{-1}$, Ni> 0.01 $mg \cdot L^{-1}$, Pb> 0.1 $mg \cdot L^{-1}$, Zn> 0.01 $mg \cdot L^{-1}$. The amount of TE was calculated to dry weight ($mg \cdot kg^{-1}$).

The total leaf surface area was calculated by structure parameters and leaf area index (LAI). Photosynthetic parameter water-use efficiency, and unified stomatal optimization (USO) model were computed. To access woody plants' ecological

benefits, fine PM deposit on leaf surface and pollutant indices geo-accumulation (I_{geo}) enrichment factor (EF), bio-concentration factor (BCF), and comprehensive bio-concentration index (CBCI) were calculated. In addition, the meteorological data of Budapest were obtained from the database of Hungarian Meteorological Service. The data of temperature, precipitation, and max wind speed were collected from János hegy, Újpest, and Lőrinc, whereas the ambient $PM_{2.5}$ and PM_{10} concentrations were measured from Széna tér, Erzsébet tér, and Teleki tér to analysis their impact on the fine PM deposition.
After calculation, all statistical procedures were conducted using the software IBM SPSS 27 (Armonk, NY, 2020) and Microsoft Excel. For the measured TE content, when the values are lower than the AAS detection limits, they were replaced with the detection limits for further analysis.

3. Results and discussion

Structure of urban trees

The average leaf area of *A. platanoides* was 102.82 cm^2 at urban park and 86.40 cm^2 at street site, *F. excelsior* was 123.74 cm^2 at urban park and 121.45 cm^2 at urban street site, and *T. tomentosa* was 42.51 cm^2 at urban park and 57.64 cm^2 at urban street. Among those, *A. platanoides* showed bigger leaf area in urban park, no difference was found for *F. excelsior*, while *T. tomentosa* showed bigger leaf area at urban street site. The different performance of each species indicates their different strategies to the urban environment. The leaves of *A. platanoides* are very thin which in turn makes them when excessive exposure to direct sunlight can cause browning and yellowing at the leaf edges. Furthermore, under shade leaves are larger, the position of *A. platanoides* at urban street exposure to more sunlight. Thus, led to the result of leaf size at street site of *A. platanoides* was smaller than at urban park. In contrast, the leaf size of *T. tomentosa* at urban street was larger than those at urban park. It maybe because *T. tomentosa* cope with stress environment in modifying leaf to a smaller size. In contrast, there were no differences between urban park and urban street of *F. excelsior* indicates a similar adaption and growth level at these two locations. Thus, plant adaptation to their growth circumstance is species-specific even under similar conditions.
In our study, the LAI of *A. platanoides* ranged from 1.36 to 7.09 $m^2 \cdot m^{-2}$, *F. excelsior* 0.59 to 7.20 $m^2 \cdot m^{-2}$, and *T. tomentosa* 0.95 to 7.84 $m^2 \cdot m^{-2}$. The highest was found in *T. tomentosa* in June whereas the lowest found in *F. excelsior* in July. The result of one-way ANOVA showed that *T. tomentosa* (4.67 $m^2 \cdot m^{-2}$) has significantly higher average LAI compared to *A. platanoides* (4.11 $m^2 \cdot m^{-2}$) and *F. excelsior* (3.37 $m^2 \cdot m^{-2}$).
Since LAI vary among different places and seasons, we measured their changes in one vegetation phrase. All the species show a similar fluctuating trend in one vegetation, first increasing from May to June, followed by a decrease from June to July, and then increasing from July to August, and ultimately a decline from August to September and October. The increase from May to June is attributed to the final phase of leaf expansion. Leaves attain the full expansion at the end of

May to early of June. *T. tomentosa* exhibited higher LAI than other two species over this two-month period, which we categorized as spring season. Interestingly, LAI of all species significantly decreased in July. The decline observed here may be attributed to characteristics specific to urban environments, such as summer drought and heat stress in UHI condition. In addition, in hot weather, trees also alter leaf orientation, which leads to a reduction in the LAI. This further confirms the occurrence of heat stress in Budapest during July. Whereas the reduction of LAI in autumn is attributable to leaf abscission, leading to diminished canopy density. Noteworthy, that the lack of data of *F. excelsior* in late October due to the early leaf fall, which also limited their ecological benefits. A higher LAI is often indicating a better growth in trees, as it reflects a greater surface area of leaves per unit of ground area. The increased leaf surface area enhances the tree's ability to photosynthesize, thereby promoting more vigorous growth and overall health. Thus *T. tomentosa* has adapted better than other two species and has a higher potential interaction with the ambient pollution in Budapest.
The average crown volume of *A. platanoides* (253.34 m^3) and *T. tomentosa* (269.03 m^3) were higher than those of *F. excelsior* (186.24 m^3). This phenomenon can be attributed not only to the crown morphology of the trees but also to the observed higher prevalence of stress-related symptoms in *F. excelsior*, such as powdery mildew disease, premature leaf shedding, and death. The phenological data of urban trees can reflect their biological response to climate, which indicates that *A. platanoides* and *T. tomentosa* adapt better to the urban conditions of Budapest than *F. excelsior*. The denser canopy of *T. tomentosa* and *A. platanoides* undoubtedly benefits in the decreasing of the UHI phenomenon and closer interaction with ambient pollution. Furthermore, our results of independent sample T-test analysis showed no significant differences ($p < 0.05$) between two methods to access the tree surface areas. Thus, a tree's total leaf area can be calculated by measuring its tree heights, crown height, and shade projection area, and through LAI as well. Both measurement methods can be applied to estimate tree canopy and to access their ecosystem benefits, such as CO_2 sinks.

Photosynthetic Parameters

In urban areas, plants are growing under conditions of constant readapt to the dynamic presence of various stresses in the environment. The average net photosynthesis of *T. tomentosa* (6.68 $\mu mol \cdot m^{-2} \cdot s^{-1}$) was significantly higher than *A. platanoides* (4.85 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and *F. excelsior* (4.64 $\mu mol \cdot m^{-2} \cdot s^{-1}$). In terms of transpiration and stomatal conductance, *T. tomentosa* showed the highest 2.23 $mmol \cdot m^{-2} \cdot s^{-1}$and 0.08 $\mu mol \cdot m^{-2} \cdot s^{-1}$, followed by *A. platanoides* 1.88 $mmol \cdot m^{-2} \cdot s^{-1}$ and 0.06 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and the lowest found in *F. excelsior* 1.34 $mmol \cdot m^{-2} \cdot s^{-1}$ and 0.04 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The internal CO_2 was higher in *T. tomentosa* and *A. platanoides* than in *F. excelsior*. In contrast, higher surface temperature was found in *A. platanoides* and *F. excelsior* than *T. tomentosa*. However, no significant difference was observed between WUE and PAR. Therefore, stomatal conductance and internal CO_2 positively impact the net photosynthesis rate of urban trees, whereas leaf temperature exhibits negative effects.

The overall result of photosynthesis parameters from different locations in 2021 (n=578) suggests that when under moderate stress conditions, species may exhibit varying physiological responses compared to conditions of extreme stress. Although *T. tomentosa* did not establish better photosynthetic activities at urban streets than other two species. Nevertheless, it is important to note the mortality of sampled trees from *F. excelsior* and *A. platanoides* at urban park, whereas no *T. tomentosa* trees died.

The comparison of different photosynthetic activities showed significant differences between seasons, with the highest in spring, followed by summer, and the lowest in autumn at urban park. However, at street site, the decline of photosynthesis was subjected to autumn. The significant changes of net photosynthesis in different seasons indicates that the photosynthesis activities of all species at urban park were more sensitive to environmental changes, that urban trees have a greater adaptation to maximize the photosynthesis than suburban or rural area. In comparison across species, *T. tomentosa* showed higher net photosynthesis at urban park site in spring and summer, and *F. excelsior* showed higher net photosynthesis at urban street site in spring. Thus, the better photosynthesis activities of *T. tomentosa* were only when the environmental conditions were preferable, and it is more sensitive than the other two species to environmental changes.

Their strongest Pearson correlation coefficients (0.79) was found between net photosynthesis and stomatal conductance, which indicates that the higher the stomatal conductance, the higher the net photosynthesis. Furthermore, we found a positive correlation (0.39) between stomatal conductance and transpiration. Other factors that are positively correlated with stomatal conductance, such as PAR (0.32) and internal CO_2 (0.15). In our study, WUE was positively correlated with net photosynthesis (0.38), and negatively correlated with transpiration (-0.43), internal CO_2 (-0.24), leaf surface temperature (-0.34), and PAR (-0.15). Since the WUE at the street site of all species was higher than at the urban park, the most important might be the higher transpiration of them at the urban park. The auto linear modelling (R^2=0.90) demonstrates that all the parameters (E, WUE, C_i, g_s, T_{leaf}, and PAR) can predict 90.7% of the net photosynthesis. Among all these factors, g_s takes up 75% of the importance. This result validates the correlation coefficient, indicating that drought is the primary factor influencing the growth and survival of urban trees in Budapest. Since in the case of severe or extreme drought, the reduced photosynthesis is mostly caused by a decrease in Rubisco activity. Thus, we can conclude that the drought conditions in Budapest are moderate.

The stomatal conductance of all species ranges from 0.04 to 0.10 $mol \cdot m^{-2} \cdot s^{-1}$. Among which, there was no difference in *A. platanoides* between urban park and street; *F. excelsior* showed lower conductance at urban park than street site, and *T. tomentosa* exhibited the opposite. In comparison of species, *T. tomentosa* (0.10 $mol \cdot m^{-2} \cdot s^{-1}$) had higher stomatal conductance than *A. platanoides* (0.06 $mol \cdot m^{-2} \cdot s^{-1}$) and *F. excelsior* (0.04 $mol \cdot m^{-2} \cdot s^{-1}$) at the urban park, while this difference did not show at the street site. Given that both locations are situated in an urban environment, drought could potentially be the primary factor influencing the closure of stomatal conductance. Although the performances were species-specific, however, except *T. tomentosa* at the urban park, the others exhibited similar, thus, all current species are more or less drought susceptible. However, at places like street sites, which have stronger anthropogenic interferences, *T. tomentosa* was more sensitive to the environmental changes of the urban park and urban high-traffic locations.

The Optimal stomatal conductance model (USO model) is widely used because it is straightforward to parameterize from the leaf scale to implement at large scales. In the model, g_1 has an inverse relationship with WUE. Consequently, a plant with a high g_1 loses more water for each unit of carbon absorption compared to a plant with a low g_1. In our study, the relationship between stomatal conductance and the USO model parameter was strongly corrected. However, the R^2=0.64 indicates that stomatal regulation was not the only factor. After fitting in the USO model, stomatal conductance was linear regression with R^2=0.94. The stomal conductance can better predict the net photosynthesis of urban trees. Thus, the intercept of urban trees net photosynthesis in Budapest is major regulated by their stomatal conductance. This also indicates the moderate drought level in Budapest's urban area.

In our study, the model intercepts (g_1) of *T. tomentosa* and *A. platanoides* showed a significantly higher value than in *F. excelsior*. The relationship between the USO model index was in a similar trend. *T. tomentosa* and *A. platanoides* present a better fit in the USO model, with R^2=0.50 and 0.34, respectively. The fit for *F. excelsior* was not so strong (R^2=0.10). It was also confirmed by the relationships between USO that stomatal conductance controlled the net photosynthesis of *A. platanoides* and *T. tomentsa*. *F. excelsior* might also undergo additional physiological modifications to adapt to its environment. The important part that stomatal conductance plays in photosynthesis and transpiration makes it possible to judge how well urban trees do in cities. However, low g_s (g_s <0.2 mol·m^{-2}·s^{-1}) coverage both *A. platanoides* and *F. excelsior*. Thus, under moderate drought in Budapest, *T. tomentosa* and *A. platanoides* adapt better in stomatal regulation to the urban environment and will provide more benefits to the ecosystems.

In 2022 to 2024, the net photosynthesis ranged from 0.15 to 38.75 µmol·m^{-2}·s^{-1}, 0.24 to 38.27 µmol·m^{-2}·s^{-1}, and 0.45 to 41.70 µmol·m^{-2}·s^{-1} for *A. platanoides, F. excelsior,* and *T. tomentosa*, respectively. Transpiration rate ranged from 0.08 to 4.10 mmol·m^{-2}·s^{-1}, 0.26 to 5.05 mmol·m^{-2}·s^{-1}, and 0.10 to 6.96 mmol·m^{-2}·s^{-1} for *A. platanoides, F. excelsior,* and *T. tomentosa,* respectively. Whereas WUE ranged from 0.18 to 62.07 µmol·mmol^{-1}, 0.19 to 63.69 µmol·mmol^{-1}, and 0.69 to 80.14 µmol·mmol^{-1} for *A. platanoides, F. excelsior*, and *T. tomentosa*, respectively. All parameters range widely because photosynthetic activities were significantly different in different seasons. Overall, from 2022 to 2024, there were no significant differences in photosynthetic activities across all species.

The overall net photosynthesis and transpiration rate of *T. tomentosa* was higher than *A. platanoides* and *F. excelsior* in 2023 and 2024, this was true in 2021 as well. However, 2022 did not demonstrate this, as the higher net photosynthesis and transpiration of *T. tomentosa* are typically associated with the spring season. However, the absence of spring data in 2022 obscures this phenomenon. The comparison of seasons clearly indicates a significant decline in *T. tomentosa* from spring to autumn. Thus, the environmental conditions of spring in Budapest are suitable for the *T. tomentosa*. However, when environmental circumstances change, such as with global warming, traffic density increase can lead to *T. tomentosa* losing this advantage.

The Spearman's correlation coefficient shows net photosynthesis is positively correlated (0.37) with transpiration, indicates that the level of transpiration increased or decreased simultaneously with the changes in the intensity of photosynthesis. However, no correlation was found between LAI and WUE. The changes of photosynthesis and transpiration of urban trees are shown a significant decrease in July coincided with the decrease of LAI. The decrease of LAI influenced transpiration and net photosynthesis. We can estimate tree-level or forest-level transpiration and evaluate their ecological benefits using the correlation between transpiration and LAI.

The overall comparison of physiological parameters, including leaf area, LAI, total leaf areas, as well as their photosynthetic parameters from 2021 to 2024, suggests that *T. tomentosa* copes better with the current urban stressors in Budapest, followed by *A. platanoides*, and the *F. excelsior* the least. In addition, climate change is leading to increased drought in urban areas, making WUE a more significant parameter in this context. In the investigation from 2022 to 2024, the WUE of all species did not show any significant differences among different years or seasons. This also demonstrates their ability to adapt to the drought conditions of the urban areas.

Fine Particulate Matter Reduction Potential

The wash-off of fine PM was significantly higher for *A. platanoides* and *F. excelsior* at the urban street compared to the urban park, while no significant differences were observed for *T. tomentosa* between the two locations. We might attribute the lack of difference in *T. tomentosa*'s tomentose leaf surfaces between the two sites not to its ability to accumulate PM, but rather to its wash-off rate.

The impact of sampling times on the fine PM wash-off from leaf surfaces of various urban trees from 2021 to 2023 (n=432). The fine PM accumulated on leaf surfaces ranged from 0.26 to 78.9 $\mu g \cdot cm^{-2}$, with the lowest found in *T. tomentosa* in 2021 and the highest in *F. excelsior* in 2023. In 2021, there was no difference between woody plant species, and the overall trapped fine PM was lower than in 2022 and 2023. This is because in 2021 the leaf samples were first dried and then soaked in distilled water, while in 2022 and 2023, leaf samples were soaked in distilled water when they were fresh. Therefore, the retained PM on the dry leaf is harder to wash off compared to fresh leaves. Thus, collection falling leaves can be a good phytoremediation strategy for PM reduction. In 2022, *A. platanoides*

and *F. excelsior* trapped significantly higher fine PM than *T. tomentosa*. Whereas in 2023, *F. excelsior* was significantly higher than *A. platanoides* and *T. tomentosa*. We immediately soaked the leaf samples in distilled water after delivering them to the laboratory in 2022 and 2023, allowing the results to accurately reflect the effects of precipitation wash-off. Compared the difference of *F. excelsior* in 2022 and 2023, the concentration of fine PM wash-off increased 2-fold. The reason for this is that in 2023, the number of leaves soaked in distilled water decreased to 5, indicating a relatively higher interaction between the leaves and water. This can also be applied to *A. platanoides*, since the amount of precipitation in 2023 was significantly higher than in 2022 in Budapest, leading to the lower fine PM accumulating on the leaf surface. However, the influences of precipitation were not found on *T. tomentosa* between 2022 and 2023.
The difference between each year already discussed before, we compared here between seasons in each year. In 2021, the wash-off fine PM ranged from 0.11 to 12.24 $\mu g \cdot cm^{-2}$. There were no differences among all species in all seasons. Whereas, compared between species, *A. platanoides* presents higher fine PM in spring than summer and autumn; no differences were discovered for *F. excelsior* in all seasons; and higher accumulation in spring than autumn was found in *T. tomentosa*. The leaf samples in 2021 were first displayed in the laboratory until naturally dry before soaking in distilled water, the condition was similar to an extremely dry condition or autumn leaf fall. Therefore, most healthy urban trees contribute to fine PM retention, regardless of the species. In 2022, the wash off fine PM concentration was ranged from 1.01 to 67.46 $\mu g \cdot cm^{-2}$. *A. platanoides* showed higher fine PM wash-off than T. tomentosa in spring and summer, whereas *F. excelisor* showed higher than *T. tomentosa*. For *A. platanoides*, no differences were discovered among all seasons, whereas *F. excelsior* and *T. tomentosa* both gradually increased towards autumn. The differences were subjected to the *A. platanoides* and *F. excelsior* were easier wash off to *T. tomentosa*. The leaf surface of *A. platanoides* and *F. excelsior* are smoother compared to *T. tomentosa*. Thus, leaf trait and wettability are among the important factors that influence fine PM accumulation and wash-off rate. In 2023, the contents of fine PM were ranged from 0.63 to 78.00 $\mu g \cdot cm^{-2}$. *F. excelsior* exhibited significantly higher fine PM wash-off than *A. platanoides* and *T. tomentose* in spring, summer, and autumn. However, no differences were found among all seasons in *T. tomentosa*. In comparison between species, *A. platanoides* showed lower content of fine PM spring than summer autumn, while *F. excelsior* showed higher wash-off concentration in spring and summer than autumn. And no differences were found in *T. tomentosa* between different seasons. The climate in Budapest is characterized by long periods of summer drought, thus during the summertime, fine PM accumulation circle in summer might be longer than in spring and autumn. In 2023, the total leaf area of all species was similar, and all leaf samples were collected from the urban park. Despite the reduction of F. excelsior leaves to five per subsample, there was a significant increase in the wash-off of fine PM. This significant higher fine PM wash off from *F. excelsior*

in 2023 than in 2022 and exceeded the wash-off rates of *A. platanoides* and *T. tomentosa* suggests a higher wash-off rate for *F. excelsior* by precipitation and wind interactions.

The potential of urban trees to accumulate fine PM on their leaf surfaces can vary significantly depending on environmental conditions. However, in our study, *T. tomentosa* did not exhibit such variability. This consistency in PM retention can be attributed to the species-specific characteristics of plant leaves. Washing off accumulated particles from plant surfaces into more permeable soil by rainfall is typically considered a net removal of PM from the atmosphere, especially for fine PM, where water-soluble fractions are abundant. Therefore, more attention should be paid to plant species with smooth leaves, as their higher wash-off potential enhances this removal process. The entire vegetative structure should be taken into consideration to better understand the full potential of different species in PM accumulation.

The RDA results confirms that the ambient PM_{10} and $PM_{2.5}$ were both negative correlated with temperature, precipitation and max wind speed. The higher max wind speed and temperature were more associated in summer, whereas the precipitation was associated with both spring and summer. In terms of the fine PM accumulation, it was positively correlated with ambient PM_{10} and ambient $PM_{2.5}$ concentration and negatively correlated with max wind speed, temperature, and precipitation. However, although those impact factors are influencing the accumulation of the fine PM on leaf surface, the correlation were not strong, this is further confirmed by the RDA axis explanation level were 43.8% and 45.1% only. Thus, there are other environmental factors which also crucial affecting the accumulation of fine PM on urban woody plant leaf surface.

The performance of *A. platanoides* and *T. tomentosa* were similar at urban park compared to *F. excelsior*, whereas at street site, *A. platanoides* and *F. excelsior* were more unified compared to *T. tomentosa*. Although the results suggest that the load of fine PM on leaf surface were significant influenced by average temperature, wind speed, and precipitation. And it is hard to evaluate a plant potential in trapping fine PM on the leaf surface. The RDA analysis results also shows that the selected environmental variables significantly species performances and seasonal patterns. Ambient PM_{10}, ambient $PM_{2.5}$ concentration, fine PM load on leaf surface, and max wind are highly correlated and are closely associated with the seasonal variables: summer and autumn, which suggests that these environmental conditions are most pronounced during these seasons. Precipitation appears to be negatively correlated with the summer and might have a stronger influence in other seasons like spring. Furthermore, the RDA results further confirm the correlation between LAI and transpiration, LAI and net photosynthesis.

Since the average of LAI and fine PM deposition of all trees were 5.03 and 5.56 $\mu g \cdot cm^{-2}$ respectively. We calculated the tree cover in Budapest could capture up to 38.17 tons of fine PM at a given time. However, achieving large-scale fine PM reductions in Budapest requires additional strategies. Budapest is a typical medium sized city in the temperate zone; our results might potentially apply to similar cities. As cities in other climate regions may experience different seasonal dynamics, potentially altering the effectiveness of species in particulate matter retention under varied conditions. Thus, to access their overall potential, several factors, such as the layout of the green infrastructure, local meteorological parameters, and ambient PM concentrations should also be considered. Nevertheless, their impact on urban trees at the scale of a city cannot be disregarded. The development of trees is frequently constrained by significant landscape design factors, ultimately leading to a reduction in their ecological advantages. Thus, additional research is required to establish optimal environmental conditions for trees and to maximally benefit from the advantages they offer.

Chemical Properties of Wash-off Fine Particulate Matter and Soil

The pH values of fine PM suspension ranged from 4.62 to 7.71, and the EC values ranged from 15.99 to 732.1 μs·cm^{-1}, significantly exceeding the guideline for natural rainwater (0-50 μS·cm^{-1}). Especially for *A. platanoides* and *F. excelsior*, the higher values of fine PM suspension suggest the formation and accumulation of chemicals on the leaf surfaces. NH_4^+, NO_3^- , SO_4^{2-}, and Cl^- are the dominant water-soluble ions of fine PM suspension. The average amount of NH_4^+, NO_3^- , SO_4^{2-}, and Cl^-ranged from 3.28 mg·L^{-1}, 1.97 mg·L^{-1}, 20.40 mg·L^{-1}, and 50.64 mg·L^{-1}, respectively. Whereas the percentages of NH_4^+, NO_3^- ranged from 1.59 to5.99 and 1.37 to 6.51. The concentration of NH_4^+ and NO_3^- were higher the chemical composition of $PM_{2.5}$ from Budapest.

The proportions of major ions in the fine PM suspension from 2021 to 2023 among different species (*n*=432). A similar trend $Cl^->SO_4^{2-}>NO_3^->NH_4^+$ was found in all species. The concentrations of SO_4^{2-} and Cl^- of fine PM suspension were the most abundant components, their percentage ranged from 7.6% to 54.12% and 41.01% to 87.28%, respectively. The high concentration of chloride is Budapest, a typical Central European city, is believed during winter months and related to road salt and de-icing agent. The aerosols behave of road salt is similarly to other traffic-related air pollutant with larger 2.5 μm particles, they decay to the background concentrations by 400-500 m from the roadway. We also detected high concentration of sulphate. The exceed sulphates could originate from the reaction of SO_2, a gaseous pollutant primarily emitted by anthropogenic sources such as combustion processes in power plants, industries, and traffic. Since the primary sources of SO_4^{2-} and Cl^- are anthropogenic. The concentration can be significantly different from one to another. As well as their possibility of accumulating in high concentration on the leaf surfaces of urban trees. There were no significant differences between the two locations, indicating that the chemical levels in urban park and street site were comparable. This suggests that the sources of air pollution are not confined to a specific area but rather have a regional impact. However, the comparison between different year of NO_3^-, SO_4^{2-} and Cl^- were significant. As can be concluded from the forementioned ions concentration of fine PM suspension from different woody plant species in Budapest from 2021 to 2023, species and location did not significant influenced the chemical structure of fine PM wash off. Since most of the airborne PM may store by plants temporarily on leaf surface, resuspend in air, or washed off into the soil by rainfall, the chemical proportion of fine PM wash off impacts with a series of dynamics of factors. Within a city setting like Budapest, where has moderate air pollution there is not distinct difference between an urban park and an urban street.

The overall pH values of soils were alkalized from all plantations, 8.04 and 7.46 at *A. platanoides*, 7.95 and 7.44 at *F. excelsior*, and 8.08 and 7.44 at *T. tomentosa*. The average EC values was 166.90, 180.95, and 176.67 μs·cm^{-1}, respectively. The humus contents were all in a normal range, with 4.15%, 3.22%, and 4.68% for each species, respectively. NH_4^+ and NO_3^- were all in a similar range among all species. Phytoavailable K_2O and P_2O_5 concentration were 721.89 and 550.82 mg·kg^{-1}, 496.61 and 578.41 mg·kg^{-1}, 927.45 and 620.71 mg·kg^{-1} from *A. platanoides*, *F. excelsior*, and *T. tomentosa*, respectively. The data of phytoavailable K_2O and P_2O_5 were ranged widely, this reflected in the standard deviation were very high, it is because P and K are very mobile. The pH value and EC of soil were similar at both locations. The humus content, phytoavailable K_2O and P_2O_5 were higher at the urban park. In contrast, the NH_4^+ and NO_3^- were higher at the urban street. This shows a slight better soil nutrient from the urban park than the urban street.

Translocation of Trace Elements in Urban Trees

The concentration of TE in the environment can significantly influence the translocation and accumulation of TE in urban tree. The range of Cu, Fe, Ni, Pb, and Zn from fine PM suspension was 0.43 to 191.90 mg·kg^{-1}, 1.95 to 165.06 mg·kg^{-1}, 1.50 to 135.00 mg·kg^{-1}, 0.12 to 193.85 mg·kg^{-1}, and 0.19 to 80.00 mg·kg^{-1}, respectively. In comparison of species, *A. platanoides* and *F. excelsior*, the trend of TE was similar, Fe> Ni>Cu>Zn. Pb was different, for fine PM washed off from *A. platanoides*, Pb had the second smallest concentration, whereas the concentration from *F. excelsior* was second largest. However, the trend of TE of fine PM washed off from *T. tomentosa* was significantly from other two species, it showed Cu>Ni>Fe>Pb>Zn.

While the measured Cu, Fe, Ni, Pb, and Zn content from soil were ranged between 18.67 to 19.45 mg·kg^{-1}, 1190.40 to 1552.80 mg·kg^{-1}, 71.10 to 193.45 mg·kg^{-1}, 6.10 to 82.36 mg·kg^{-1}, and 0.46 to 1120.16 mg·kg^{-1}. It follows the order of: Cu< Pb< Ni< Zn <Fe in all species. Cu and Fe contents were stable among all samples, while Ni, Pb, and Zn were ranged widely. The I_{geo} values suggest that Cu, Fe, and Zn levels in the soil were within acceptable norms. Nonetheless, Ni was at a moderate degree of contamination, whereas Pb was at a low level of contamination. The Zn level varied significantly among the samples, perhaps due to the absence of homogeneous mixing and stratification in urban soil.

The MANOVA analysis revealed significant effects for year, season, and species were significant, indicating a strong group-level influence on the dependent variables. Additionally, the effect of location was significant, though the effect size was moderate. Corresponding to the result of MANOVA, the differences between urban parks and urban street were not significant from all species. Except for Fe and Ni from *A. platanoides* wash-off. The Cu, Ni, and Zn concentrations in the fine PM suspension of *T. tomentosa* were substantially greater than those in *A. platanoides* and *F. excelsior* at both locations. The Fe content showed similar trend at the urban street location; however, no significant change was observed at the urban park. Whereas no significant differences across all species at both locations. This indicates urban trees are very good candidate for ambient pollution monitoring, all TE showed similar trends among all species. Importantly, the concentrations of fine PM washed off from *T. tomentosa* were lower than those from the other species, whereas trace TE concentrations were higher. This discrepancy might be attributed to differences in leaf surface morphology. Factors such as precipitation and wind may more easily remove fine PM from the leaves of *A. platanoides* and *F. excelsior*.

The seasonal changes in TE concentrations from fine PM wash-off were generally stable from *A. platanoides* and *F. excelsior*. In contrast, the TE concentrations in fine PM wash-off from *T. tomentosa* displayed significant fluctuations across different years and seasons. Fe consistently has the highest concentrations across all species and seasons, since Fe is a macronutrient element for plant growth. Cu and lead Pb also show substantial concentrations compared to Ni and Zn, which are lower in magnitude. The elevated ambient pollution levels were reflected in the increased Pb concentrations found in fine PM wash-off suspensions from all tree species studied. The meteorological conditions of low wind speed and low precipitation were recorded that in October 2021. In addition, ambient PM_{10} and $PM_{2.5}$ were consistently elevated. Over a span of 11 days, only day recorded PM_{10} (range: 24.00 - 98.67 $\mu g{\cdot}m^{-3}$, average: 60.32 $\mu g{\cdot}m^{-3}$) under recommended limits 25 $\mu g{\cdot}m^{-3}$, while $PM_{2.5}$ (range: 12.00 - 48.00 $\mu g{\cdot}m^{-3}$, average: 32.68 $\mu g{\cdot}m^{-3}$) were always higher than recommended value. These findings underscore the significant contribution of combustion sources and the secondary formation of fine PM, particularly during late autumn and winter when $PM_{2.5}$ concentrations tend to peak. Thus, the unpreferable meteorological conditions couple with heavy traffic resulting in elevated Pb concentration.

The contents of all measured elements have no significant differences among species in both leaf and branch. The order of measured TE follows Fe>Ni>Pb>Cu>Zn in the leaf of *F. excelsior* and *T. tomentose*, while Fe>Ni>Cu>Fb>Zn in *A. platanoides*. This highlights the high concentration of Ni in our study. Interestingly, there were no significances between the two locations in all species, which further confirms the similarities of the urban park and urban street at the medium size city like Budapest.

The average BCF for the five trace elements was ranked as follows: Cu (0.45-0.88), Fe (2.19-4.68), Ni (0.43-1.40), Pb (1.35-3.33), Zn (0.41-1.46) from dust to leaf, and Cu (0.69-0.70), Fe (0.07-0.08), Ni (0.13-0.15), Pb (0.44-0.57), Zn (0.01-0.03) from soil to branch. The interaction with leaf surface deposition differed among species and elements, whereas the translocation from soil to branch was consistent across species and all elements. Furthermore, the computed BCBI (0.11-0.31) from dust to leaf and BCBI (0.44-0.53) demonstrate the variations across species in the accumulation of trace elements from dust to leaf, as well as the translocation of trace elements from soil to branch. The concentration of TE from different parts of plants indicates that although leaves accumulate TE through both dust deposition and soil uptake, yet consistently show the lowest concentrations, is supported by studies indicating that certain elements are essential nutrients for plants and are regulated accordingly. For example, Cu and Zn are essential nutrients, and their uptake is actively regulated by plants. In contrast, Pb has no role in plant growth, leading to less active accumulation.

The Sources of Water Soluble Ions and Trace Elements

The Spearman correlation coefficients performed on pH, EC, and major ionic concentrations. All ions and EC except NH_4^+ , were significantly contributed to the changes in pH in the suspensions. The total value of EC was mainly affected by SO_4^{2-} and Cl^-. NH_4^+ was positive correlated with SO_4^{2-} at *p*=0.01 level. NH_4^+ concentration is typically correlated with the combined concentration of SO_4^{2-}, this occurs because ambient NH_3 absorbed into precipitations, which increase the pH as well as the ratio of oxidation and scavenging of dissolved SO_2 . Consequently, the SO_2 is further oxidized to SO_4^{2-}**.** It also indicates the occurrence of $(NH_4^+)_2SO_4$ in the fine PM deposit on the leaf surface.

Since we only found SO_4^{2-} and Cl^- significant accumulated on the fine PM from leaves surface wash-off suspensions, the strongest correlation of ions was also found between SO_4^{2-} and Cl^-, which indicates their similar origin. In Budapest, the primary sources of Cl^- are attributed to the use of winter de-icing salt. While the sampling phases did not include winter, it is highly probable that there is secondary production Cl^- being resuspended from the soil into the atmosphere. Thus, we can conclude that fine PM loads on urban tree surfaces are a major result of anthropogenic activities in the urban area of Budapest, such as coal-fired power plants, vehicle emissions, transport from remote sources, and secondary formation. The enrichment of Cl^- and SO_4^{2-} were extreme high due to de-icing agent and traffic emission sources, respectively.

RDA results highlight relationships between TE contents and fine PM weight, location, year, season, and species, with which, the environmental factors can predict 31.1% of the results. Among the environmental factors, year and fine PM weight appear to have a significant influence on the overall TE contents. The differences between locations have distinct impacts on the TE variables. Urban park strong positive association with Cu, and a comparatively weaker association with Zn and Ni. It reflects the source of soil or plant interactions in in the urban park. Whereas urban street strong positive association with Pb, which suggests that urban streets experience elevated levels of Pb compared to urban park, and it is possible due to urban pollution sources such as vehicular traffic or industrial emissions. Although Pb-containing petrol has been banned in Europe for twenty years, it can still be found in urban soil and dust suspension. Because the half-life period of Pb is very much long, which is about 2-300 years. Noteworthy that 155 of dust suspension samples and 128 of leaf samples, their Pb concentrations were under detective limits, which highlights the results of the Pb remediation.

4. Conclusion and recommendations

Urban trees play a crucial role in enhancing urban landscapes, providing ecological, aesthetic, and health benefits. However, plant growth in urban environments is often severely impacted by stress factors such as drought, the urban heat island effect, limited sunlight, and human activities. To ensure that urban greening efforts achieve their full potential, it is essential to understand the in-situ physiological responses of plants to these challenges.

In our study, *T. tomentosa* exhibited a more compact crown and a higher photosynthetic rate compared to *A. platanoides* and F. excelsior in an urban park setting. However, this advantage was not observed in trafficked areas. Despite the overall stressful urban conditions of Budapest, these species have demonstrated an ability to adapt. Nonetheless, *A. platanoides* and *F. excelsior* showed higher mortality rates, whereas *T. tomentosa* proved more resilient to the urban climate of Budapest. LAI is key determinant of canopy interaction, there is a direct relationship between leaf area and photosynthesis activities.

While the concentrations of fine PM washed off from *F. excelsior* and *A. platanoides* were higher than those from T. tomentosa, it is important to consider that *T. tomentosa* likely captures substantial amounts of fine PM on its leaf surfaces. The PM retention on *A. platanoides* and *F. excelsior* was found to be more susceptible to meteorological conditions such as wind and precipitation. Given that fine PM can be re-suspended into the atmosphere or settle back into the soil, the higher wash-off rates from F. excelsior may also contribute to fine PM retention. From a fine PM retention strategy perspective, *T. tomentosa* emerges as a more favorable choice for urban greening in Budapest, thanks to its higher resilience and ability to capture PM. Considering the serious health risks posed by fine PM and its persistence in the environment, coupled with the growing impacts of climate change, it is imperative for urban planners and designers to understand the critical relationship between vegetation cover and PM concentrations. *T. tomentosa* serves as an ideal candidate in this regard, but a comprehensive strategy that considers both species selection and urban design is vital for mitigating pollution and enhancing urban resilience.

The air quality of Budapest is primarily influenced by emissions from road travel, residential areas, individuals, and houses. It is important to acknowledge that strategic tree selection is an important management strategy for urban sustainable planning.

Further research is needed to deepen our understanding of how urban trees interact with pollution. This includes optimizing the spatial distribution of woody vegetation to maximize its ecological benefits. In future urban planning endeavours, it is crucial to prioritize the thorough consideration of fine PM reduction. The following aspects should be into account in future studies: 1). Species Selection and Establishment: The initial selection of tree species is crucial for survival rates. In addition, most of cities are plants most of urban trees from few genera which make it more sensitive to climate changes. However, supporting the long-term establishment of urban trees to reduce mortality rates may be even more critical for sustainable urban forestry. 2). Diversity of Species: Expanding the range of species used in urban plantings will provide more flexibility and resilience in species selection, promoting biodiversity and adaptability in varying urban conditions. 3). Spatial and Long-Term Assessment: Conducting spatially detailed and long-term studies will provide more precise insights into the impacts of tree planting on urban air quality and overall ecological health. 4). Systematic Modelling and Public Awareness: Developing systematic models to assess PM capture by different tree species will enhance our understanding of air pollution control. Additionally, public awareness campaigns should be considered to support efforts to reduce PM emissions.

5. New scientific results

For the first time, our study explored how the urban environment influences tree growth as well as how urban trees aid the urban environment in terms of fine PM removal. The new finding as follow:

1). The difference of air pollution in fine PM between urban street and urban park did not exceed the level that would impact on the photosynthetic activities of mature urban trees of investigated species.

2). The urban environment leads to decline of urban tree canopy in the summer, which is reflected in the decrease in LAI and in the accumulation of TE on leaf surface fine PM deposition.

3). The chemical properties of fine PM suspension, elevated concentration of Cl^- and SO_4^{2-} indicate a high level of anthropogenic activities in Budapest. The concentration of Pb in the fine PM suspension and in the urban trees' leaf indicates the reduction of Pb through time, while slight accumulated Ni pollution in Budapest.

4). The TE content of fine PM air pollution dissipates evenly due to the air movement and turbulence in the air of Budapest resulting in little differences between urban parks and urban streets.

5). The overall comparison of physiological parameters, including leaf area, LAI, total leaf areas, the photosynthetic parameters in 2021, and the ability to capture atmospheric PM confirmed that *T. tomentosa* copes better with the current urban stressors in Budapest, followed by *A. platanoides*, and the *F. excelsior* the least.

6. The publications of the author in the research field

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