Hungarian University of Agriculture and Life Sciences

Interaction of Urban Trees and Atmospheric Fine Particulate Matter in Budapest

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Table of Contents

LIST OF ABBREVIATIONS

A: Net photosynthesis

AAS: Atomic absorption spectrometer

AC: Accumulation coefficient

AQG: Annual quality guideline

BCBI: Comprehensive bio-concentration index

BCF: Bio-concertation factor

C_i: Internal CO_2 concentration

DW: Dry weight

E: Transpiration

EEA: European Environmental Agency

EF: Enrichment factor

Eq: Equation

EU: European Union

g_s: Stomatal conductance

LAI: Leaf area index

PAR: Photosynthetically Active Radiation

PCA: Principal component analysis

PM: Particulate matter

RDA: Redundancy analysis

ROS: Reactive oxygen species

SEM: Scanning electron microscope

SD: Standard deviation

TE: Trace elements

T_{leaf}: Leaf surface temperature

UHI: Urban Heat Island

USO: Unified stomatal optimization

WHO: World Health Organization

WSIIs: Water-soluble inorganic ions

WUE: Water use efficiency

1. INTRODUCTION

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 (Esperon-Rodriguez et al., 2022; United Nations et al., 2019). The rapid increase of urbanization is posing substantial challenges to both human well-being and environmental sustainability, such as the raised global mean surface temperature. 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 (Czaja et al., 2020; Matsumoto et al., 2022).

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 (Huang et al., 2023; Song et al., 2022). High concentration of fine PM can persist even when the coarse PM is remain within health limits (Füri et al., 2020). 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. According to a report of European Environmental Agency (EEA), air pollution remains the top threat to human health in European Union (EU), with 96% of the urban population exposed to $PM_{2.5}$ concentration exceeding the World Health Organization's (WHO) recommended limit of 5 $\mu g \cdot m^{-3}$ (EEA, 2024; WHO, 2022). In Hungary, the annual $PM_{2.5}$ from 2020 to 2023 ranged between 11-13 $\mu g \cdot m^{-3}$ in Hungary, indicating a moderate pollution level (MMSZ, 2024). This issue is more extremely pressing in Budapest, as the metropolitan region of Budapest is the spot urbanized surface in Hungary (Lennert et al., 2020). The exceedance of PM and other precursor gases has led to infringement procedures, highlighting the challenge of controlling PM in this region (Perrone et al., 2018).

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 (Abhijith et al., 2017). 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 (Zhang et al., 2019). 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 (Baldacchini et al., 2019; Kwon et al., 2021; Tyrväinen et al., 2005). Variations in canopy structures, leaf morphological traits, and physiological characteristics can profoundly influence the interactions between urban trees and their urban environment. Certain tree species may exhibit greater resilience to urban stressors, while others may struggle to cope with the challenges imposed by urbanization.

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 (Uhrin et al., 2018). 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 (Lahr et al., 2018). It is the key factor for the growth and survival of trees, as the energy captured and stored through photosynthesis supports plant growth (Cernusak, 2020). Carter and Cavaleri, (2018) also discovered that 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. Thus, a comprehensive study of the interaction between urban trees and the ambient pollution is essential.

2. OBJECTIVES

In the future, trees in urban settings will face increasingly dynamic environmental challenges. 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. Moreover, the current state of research in Hungary concerning the retention of fine PM is insufficient, emphasizing the need for a comprehensive strategy to address this issue. 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: Urban trees respond to environmental changes in various ways. 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. The results of this comparison will be applicable not only in future assessments of individual tree canopies but also in evaluating a city's overall forest cover. Understanding canopy volume is critical for urban forestry management as it directly relates to a tree's capacity for air purification, carbon sequestration, and microclimate regulation.

2) Photosynthesis activities evaluation: As photosynthesis is the fundamental process driving the growth and survival of urban trees, we will evaluate the photosynthetic activities of various tree species in Budapest. 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. This evaluation will provide insights into the resilience of different species and their potential to thrive under urban stressors such as pollution, heat, and limited water availability.

3) PM retention: We intend to evaluate the ability of different woody plant species to retain fine PM on their leaf surfaces. Additionally, we will analyze 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. This knowledge will be crucial in selecting tree species that are most effective in improving air quality.

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. This analysis will help determine the potential of various trees to remove TE from the air. Understanding the mechanisms of TE uptake and retention by urban trees will be essential for developing strategies to mitigate air pollution and protect public health.

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.

3. LITERATURE REVIEW

3.1 Overview of Urban Ambient Environments

3.1.1 Air Pollution

Rapid urbanization and population growth over the past few decades have significantly intensified human activities in cities (Dervishi et al., 2022; Roy et al., 2012). As urban areas grow, their role in shaping a sustainable future becomes increasingly vital due to their concentrated social, economic, and environmental attributes (Buzási, 2022). However, this rapid growth has brought a lot of environmental challenges, with one of the most prominent being the UHI effect, where cities experience significantly higher temperatures than their rural surroundings (Masson et al., 2020; Schwaab et al., 2021; Soltani and Sharifi, 2017). his phenomenon intensifies the already rising global temperatures, especially in densely populated and rapidly expanding cities. Regions such as the Carpathian Basin, where cities like Budapest are highly vulnerable to the impacts of climate change, are also affected by this situation. According to Buzási, (2022), these cities are experiencing intensified heatwaves and shifting seasonal rainfall patterns. The combined effects of heat waves and the increased frequency of floods represent critical climate-related risks in Budapest. Additionally, other pressing urban environmental challenge, include limited green spaces, increased noise and light pollution, and deteriorating air quality (Abhijith et al., 2017). These issues underscore the growing vulnerability of urban environments to climate change, making sustainable urban planning more essential than ever.

PM, also known as atmospheric aerosol, is a complex and heterogeneous mixture consisting of fine particles suspended in the atmosphere with diameters ranging from a few nanometers to tens of micrometers (AQEG, 2005; Dzierżanowski et al., 2011). These particles represent a non-specific pollutant, emerging from a wide array of emission sources, both natural and anthropogenic, and exhibiting diverse chemical compositions (Samek et al., 2020; S. Wang et al., 2019). PM can be categorized into two primary types: primary PM and secondary PM. Primary PM is emitted directly from natural and human-made sources, while secondary PM forms in the atmosphere through complex chemical reactions involving precursor compounds emitted from primary sources (Al-Thani et al., 2018; Dzierżanowski et al., 2011; Juda-Rezler et al., 2020). Natural sources of PM include volcanic activity, sea spray, wildfires, desert dust, soil erosion, and biological processes. In contrast, anthropogenic sources encompass vehicle emissions, road dust, coal combustion, industrial activities, and the production of materials such as cement and fertilizers. The intricate composition of PM, together with the wide variability of its sources and the chemical transformations it undergoes in the atmosphere, makes it a particularly challenging pollutant to manage and mitigate (S. Wang et al., 2019).

Several global assessments of urban environments estimate that vehicle traffic accounts for 25% of PM emissions, industrial activities contribute 15%, the burning of home fuels adds 20%, and 22% originates from unspecified sources (Bui et al., 2023; Huang et al., 2023). According to a report of EEA, from 2000 to 2022, the five most significant sources of $PM_{2.5}$ emissions in the EU were open burning of waste, road transport, public electricity and heat production, residential activities, and other waste management processes (EEA, 2024). In a typical European city, residential combustion and traffic emissions are the primary contributors to PM levels, underscoring the significant role of these sources in urban air pollution (EEA, 2024; Ferenczi et al., 2021).

PM consists of a diverse array of airborne substances, including carbonaceous aerosols, water-soluble inorganic ions (WSIIs), TE, polycyclic aromatic hydrocarbons (PAHs), and even biological entities such as bacteria (S. Wang et al., 2019). These particles are frequently classified by size as coarse (2.5 -10 μm), fine (0.1 - 2.5 μm), and ultrafine (0.1 μm) (AQEG, 2005). The most abundant components of fine PM mass are crustal elements (Na^+, K^+, Mg^{2+}, and Ca^{2+}), followed by secondary inorganic ions (NH_4^+ , NO_3^- and SO_4^{2-}) (Perrone et al., 2018; Samek et al., 2020). The chemical composition of PM and other characteristics can differ widely across different regions due to different sources, climate conditions and seasons (Al-Thani et al., 2018; Juda-Rezler et al., 2020). Despite this variability, it is generally recognized that the chemical components of PM can provide valuable insights into its sources and characteristics (S. Wang et al., 2019). For instance, specific components of PM can be traced back to particular events or environmental conditions, allowing researchers and policymakers to identify and target the most significant sources of pollution.

The impact of PM on human health is not solely dependent on its concentration but is also strongly influenced by its size, shape, and chemical composition (Alwadei et al., 2022). The lifespan of PM in the atmosphere varies with particle size; PM_{10} particles typically remain airborne for two to three days, while $PM_{2.5}$ particles can stay suspended for five to seven days (Ferenczi et al., 2021). Because $PM_{2.5}$ particles remain in the air longer, they have a higher potential for long-distance transport and a greater likelihood of being inhaled by humans, making them more hazardous to health compared to larger particles. This is particularly concerning because fine and ultrafine particles can penetrate deep into the respiratory system and even enter the bloodstream, leading to more serious health effects.

TE in atmospheric PM, though constituting only a small fraction of the total elements, pose significant risks to human health due to their toxicological properties (Antisari et al., 2015; S.

Wang et al., 2019). Some TE are carcinogenic, mutagenic, teratogenic, and endocrine disruptors while others cause neurological and behavioral changes, especially in children (Ali et al., 2013). It has been reported that in the EU, annual airborne emissions of Pb, Cd were 2400 tons and 105 tons, respectively and the tire wear and tear lead to an annual release of 7500 tons of Zn and 2500 tons of Cu (Kończak et al., 2021). Thus, the contamination of the environment with TE is therefore recognized as a critical issue.

However, direct monitoring methods of TE in the ambient is high cost and their unreliable information about the impact of atmospheric pollutants on the ecosystems are the two main problems we are facing now (Alahabadi et al., 2017). Moreover, the size distribution of elemental components varies significantly between different regions, influenced by local pollution sources and human activities (Cui et al., 2020; Zhou et al., 2020). TE, being persistent and irreversible in nature, disperse through air, water, and soil, leading to their migration and accumulation in the environment. This diffusion process results in significant harm to plants, animals, and human health, making TE contamination a severe and covert environmental threat. In recent decades, a considerable interest has been given to reduce air pollution in the European region (Aksu, 2015). Researchers have employed various quantitative assessment methods to evaluate the extent of TE pollution, acknowledging that the types and levels of TE contamination vary widely across different cities (Zhou et al., 2020). This variability is largely due to the diverse pollution sources and human activities prevalent in each region, highlighting the need for localized strategies to address TE pollution effectively.

3.1.2 Air Pollution Around the World and in Hungary

As over half of the world's population now resides in urban areas, air pollution has emerged as one of the most critical challenges facing cities globally, with traffic emissions often being the primary source (Roy et al., 2012; United Nations et al., 2019). The quality of air in urban areas is a major public health concern, particularly because the vast majority of the global population inhabits these regions (Abhijith et al., 2017). According to a report of the WHO, 99% of the world population breaths polluted air (WHO, 2022). In 2019 alone, air pollution contributed to over 4.2 million deaths worldwide, with 89% of these deaths occurring in low- and middle-income countries (WHO, 2022). The impact of air pollution is particularly severe in regions such as East Asia, which accounts for 35% of the global mortality attributed to air pollution, and South Asia, responsible for 32% of related deaths, followed by Africa (11%) and Europe (9%) (Lelieveld et al., 2020). In regions where dust storms occur frequently, the level of airborne PM usually higher (Al-Thani et al., 2018). China's urban air quality illustrates the global challenge: in 2019, 53.4% of the 337 cities assessed exceeded the national air quality standards, with $PM_{2.5}$ being the dominant pollutant in 78.8% of incidents, while PM_{10} accounted for 19.8% of pollution episodes (Huang et al., 2023; Yin et al., 2021). (Shaddick et al., 2020) studied the global $PM_{2.5}$ concentration in 2016, and highlighted the unequal burden of air pollution, with low- and middle-income countries in Central, Eastern, Southern, and Southeastern Asia particularly affected. These data underscore the urgent need for comprehensive strategies to combat air pollution, especially in vulnerable regions.

Europe has made significantly greater efforts to reduce air pollution, leading to notable improvements in air quality over recent decades. Despite these efforts, air pollution remains the leading environmental threat to health (Füri et al., 2020). To address this, the EU has established national reduction commitments for five major pollutants - NOx, NH_3, SOx, NMVOC, and $PM_{2.5}$ - due to their detrimental impacts on both human health and the environment (EEA, 2024). Even with these measures, 2% of air quality monitoring stations across the EU exceeded the annual limit for $PM_{2.5}$, with urban areas accounting for 70% of these exceedances and suburban areas 30% (Targa et al., 2022). Additionally, 94% of stations surpassed the WHO air quality guideline of 5 $\mu g \cdot m^{-3}$ annually for $PM_{2.5}$, with this figure rising to 98% for short-term exposure standards (WHO, 2024). Therefore, $PM_{2.5}$ pollution, particularly in urban areas, remains a pressing concern. In 2022, the emission of $PM_{2.5}$ in Hungary was ranking 10^{th} among the 27 EU countries, accounting for 2.8% of the total. Considering the fact that cross-border transportation of $PM_{2.5}$ and Hungarian hasn't reached the reduction commitment of $PM_{2.5}$ according to the Gothenburg Protocol (EEA, 2024).

In Hungary, some sources of pollution, such as biomass burning, residential heating, and agricultural activities, have shown limited progress in reduction efforts (Ferenczi et al., 2021). Residential heating and traffic-related emissions, in particular, have been identified as the main contributors to elevated PM levels in urban areas (Huang et al., 2023). In Budapest, the annual mean concentration of $PM_{2.5}$ was recorded at 12-15 $\mu g \cdot m^{-3}$ between 2020 and 2024, surpassing the maximum recommended threshold set by the WHO and marked as moderate level of pollution (Neckel et al., 2023). The city's air quality is further compromised by uncontrolled sources like road traffic, which alone accounts for 19% of total $PM_{2.5}$ emissions in Hungary, with this figure rising to 30% in Veszprém (Ferenczi et al., 2021). As one of the most densely populated cities in Central Europe, Budapest faces unique challenges in meeting both EU and WHO air quality standards. Its high levels of vehicular traffic and industrial activity make it difficult to reach acceptable pollution levels. Therefore, further research into the interaction between fine particulate matter and urban greenery, particularly woody plants, could yield critical insights for improving air quality. Such studies could play a pivotal role in future urban planning and public health initiatives, positioning vegetation as a key element in mitigating PM pollution in Budapest and similar urban centers across Europe.

3.1.3 Climate Changes

Climate change is expected to increase the frequency and intensity of extreme weather events, including heatwaves, droughts, and floods, which will significantly affect urban living conditions (Esperon-Rodriguez et al., 2022; Masson et al., 2020). Heatwaves, for example, lead to increased energy consumption for air conditioning, which not only drives up demand but also places immense strain on urban infrastructure, particularly power grids. Overburdened power grids during heatwaves can result in outages, further exacerbating the risks posed to urban populations. Moreover, the health impacts of heatwaves, such as heat stress and related illnesses, are projected to rise, especially for vulnerable groups like the elderly, children, and individuals with pre-existing conditions. In addition to temperature extremes, shifting precipitation patterns are expected to cause severe urban challenges. Increased heavy rainfall and flooding events may overwhelm drainage systems, leading to waterlogging, property damage, and significant disruption of daily activities. These risks highlight the vulnerability of urban infrastructure to the evolving effects of climate change.

Beyond direct human impacts, climate change poses a significant threat to natural and urban ecosystems, particularly urban greenery (Caro et al., 2014; Dervishi et al., 2022). For instance, trees and shrubs, are increasingly facing unfavorable growth conditions (Esperon-Rodriguez et al., 2022; Tubby and Webber, 2010). A global study involving 3,129 tree and shrub species across 146 cities found that 56% and 65% of species are already exposed to temperatures and precipitation levels that exceed their safety margins, respectively. These percentages are expected to increase to 76% for temperature and 68% for precipitation by 2050 (Esperon-Rodriguez et al., 2022). This trend raises concerns about urban biodiversity, which is crucial for maintaining ecosystem services such as air purification, heat mitigation, and stormwater management. In conclusion, climate change poses multifaceted risks to both natural and urban ecosystems, with profound implications for urban living conditions and biodiversity. These challenges underscore the necessity for proactive measures to build resilience in urban infrastructure and ecosystems, ensuring the continued provision of essential services in the face of escalating climate impacts.

3.2 Impacts of Urban Environment on Trees

Urban trees, which play a vital role in city infrastructure, face numerous challenges that diminish their effectiveness in urban settings (Buzási, 2022). Dense building developments, heavy traffic, construction-related excavation, and the widespread use of concrete and glass negatively affect the growth environment of trees. These factors limit available space for roots and branches, reduce access to sunlight, and create multiple stressors that exacerbate the stress on trees (Czaja et al., 2020; Dervishi et al., 2022). In urban settings, basic conditions for plant growth are significantly altered compared to rural areas. Reduced sunlight, due to buildings and other structures, hinders photosynthesis, which in turn lowers tree productivity. This results in slower growth rates, smaller canopies, and reduced tree heights, limiting the development of the large, expansive crowns that are generally preferred by city residents (Caro et al., 2014; Gillner et al., 2017). Additionally, urban trees are exposed to further challenges, including soil compaction, pollution, and the UHI effect, all of which strain their ability to thrive. These combined stressors not only threaten tree survival but also reduce their capacity to provide essential ecosystem services, such as air purification and cooling. To address these issues, urban planners and policymakers must adopt innovative strategies that improve the resilience and performance of urban trees, ensuring that they continue to contribute to healthier, more sustainable urban environments.

3.2.1 Soil Compaction and Alkalization

Soil compaction is a prevalent issue in urban areas, largely caused by frequent human movement, vehicle traffic, and construction activities. Compacted soil reduces the spaces needed for air and water movement, limiting its ability to support healthy root growth. This restriction hinders essential gas exchange and nutrient absorption, which are crucial for optimal root development (Gillner et al., 2017). In urban settings, the space for root expansion is particularly constrained. While in natural environments, up to 90% of tree roots spread within the top 20 cm of soil, this upper layer is often inaccessible in cities due to paved surfaces, restricting water access and gas exchange (Czaja et al., 2020). As a result, tree roots cannot spread as they naturally would, leading to poor anchorage and stability.

Additionally, roadside trees in temperate zones face further challenges when salt is used as a de-icing agent. Salt can lead to soil alkalization and structural changes, which negatively impact tree growth (Dmuchowski et al., 2022; Helama et al., 2020). Increased soil salinity reduces the soil's water potential, making it difficult for roots to absorb water. These adverse effects stress plants at all stages of development, particularly salt-sensitive species (Dmuchowski et al., 2022). Each of these factors exacerbates the challenges faced by urban trees, highlighting the need for thoughtful planning and mitigation strategies.

3.2.2 Drought and Urban Heat Island Effect

Drought is one of the major stresses that urban trees must endure and climate change is expected to lead to more frequent droughts in the future (C. Zhang et al., 2019). Water deficits caused by drought can significantly reduce photosynthesis and hinder tree growth. Under drought conditions, reductions in tree biomass have been observed, with branch biomass decreasing by 30.7%, stem biomass by 16.7%, and coarse root biomass by 45.2% (C. Zhang et al., 2019). Additionally, tree species experienced an 8.3% to 16.6% reduction in diameter at breast height at 100 years of age under similar conditions (Dervishi et al., 2022). Urban trees face additional challenges, including high vapor pressure deficits (VPD) and increased heat loads, which exacerbate the effects of drought (Gillner et al., 2017).

Another stress factor in urban area, UHI effect, which is intensified by several factors, which include the increased absorption of solar energy by built surfaces, a reduction in the reradiation of absorbed energy due to a decrease in the sky view factor, a decrease in evapotranspiration caused by the loss of vegetation and reduced water storage in open soils, and the release of anthropogenic heat from combustion processes (Franceschi et al., 2023). UHI has led to temperature increases of up to 6°C in Munich and 8.2°C in Würzburg, Germany (Franceschi et al., 2023), while Budapest experiences a 5°C rise in urban temperatures compared to surrounding rural areas (Dian et al., 2020). Additionally to general temperature increase, climate change is predicted to lead to a higher frequency of extreme weather events further stressing urban trees (Franceschi et al., 2023). As global warming progresses, urban trees will likely experience more extreme UHI effects, which will hinder their growth and reduce their capacity to deliver crucial ecosystem services (Marselle et al., 2021). Limited water availability and elevated temperatures force trees to close their stomata early, reducing carbon dioxide absorption and primary productivity (Gillner et al., 2017). As a result, a tree's ability to withstand high temperatures and drought has become a critical factor in assessing its suitability for urban environments.

3.2.3 Air Pollution

Despite the forementioned challenges, air pollution is another significant stress factor for urban tress. Among various gaseous air pollutants, SO_2, NO_x, O_3 and PM have the largest impact on plants, because sulphur dioxide causes decline in total chlorophyll content and biomass growth, while NO_2 converts into nitrous and nitric acids and causes damages to cell membranes and chlorophyll degradation (Anand et al., 2022; Czaja et al., 2020; GHassanen et al., 2016). When plants are exposed to high levels of ambient SO_2, their cellular fluid will produce massive H^+ to react with SO_2, which enters through stomata and intercellular space from air, so that H_2SO_4 is generated and leading to a decrease in leaf pH (GHassanen et al., 2016).

Aside from previous mentioned physiological impacts, PM load on leaf surface affect leaf biochemical parameters, bringing some morphological symptoms, the extent of such effects depends on plant tolerance and on the chemical nature of the dust (Ayan et al., 2021; GHassanen et al., 2016). The major effect of PM deposition is that PM can cause stomal occlusion and impost mechanical changes, which will further worsening of the most fundamental and intricate physiological process in green plants, photosynthesis activities (Anand et al., 2022; Czaja et al., 2020). A plant with higher water content can maintain its physiological balance and enhance their tolerance ability under stress. While when trees suffers from air pollution, their stomatal density would increase and lead to a decrease of the water content in plant tissues (GHassanen et al., 2016). And further adverse impacts on plant growth and tolerance ability.

In addition, various TE, such as Pb, Cd, that attach to the surface of PM might translocate into the interior of leaf, lead to reactive oxygen species and induce toxicity (Anand et al., 2022). Oxidative stress occurs when there is an imbalance between the production of reactive oxygen species (ROS) and the plant's ability to detoxify these harmful compounds through its antioxidant defenses. The accumulation of ROS can damage cellular components such as lipids, proteins, and nucleic acids, leading to impaired cellular function and even cell death. This toxicity can manifest in various symptoms, including chlorosis (yellowing of leaves), necrosis (death of tissue), and reduced photosynthetic efficiency, ultimately impacting plant growth and survival (Antisari et al., 2015). The presence of TE and their associated toxicity not only affects the health of individual plants but also has broader ecological implications. Plants suffering from TE-induced stress are less capable of providing essential ecosystem services, such as air purification, carbon sequestration, and temperature regulation. This, in turn, reduces the overall resilience and sustainability of urban green spaces.

In summary, urban trees are exposed to several stresses including compacted soil, lack of nutrients, and limited space for root expansion are the most stress factors in the urban conditions. In addition, development of pests and diseases (Tubby and Webber, 2010). Thus, result in remarkable shorter than the natural lifespan of trees, such as the average lifespan of urban trees in Budapest is only about 29.1 years (Czaja et al., 2020; Szaller et al., 2014).

3.3 The Benefits of Trees in Urban Environment

Urban trees play a crucial role in enhancing the visual appeal of cities, serving as prominent elements of urban design. Their varying sizes, shapes, and seasonal changes in color make them significant features in city landscapes. Beyond aesthetics, trees provide numerous benefits across social, ecological, and economic dimensions. Green spaces offer visual enjoyment, create inviting environments for outdoor activities, and contribute to the overall well-being of urban populations. Trees also serve practical purposes such as producing useful substances, offering educational value, defining open spaces, screening views, and landscaping buildings (Fineschi and Loreto, 2020; Tyrväinen et al., 2005).

As integral components of urban ecosystems, trees provide a wide range of ecological benefits. They contribute to environmental sustainability by enhancing green spaces, creating microclimates, and offering ecosystem services such as carbon storage, air quality improvement, stormwater management, energy conservation, and noise reduction (Roy et al., 2012). In doing so, urban trees help mitigate environmental degradation caused by rapid urbanization (Abhijith et al., 2017; C. Zhang et al., 2019). Woody plants, which are directly exposed to urban conditions, actively absorb toxic elements from the atmosphere and soil, playing a vital role in pollution control. Urban trees help reduce the UHI effect, manage stormwater, and mitigate climate change, all while improving the health and well-being of city dwellers (Abhijith et al., 2017; Alahabadi et al., 2017). Unlike many costly, time-consuming, and environmentally harmful methods of air pollution control, phytoremediation offers an effective, low-cost alternative. This process utilizes living plants to remove or neutralize pollutants in contaminated air, water, and soil (Rajendran et al., 2022).

Urban trees contribute to air quality improvement by absorbing gaseous pollutants through leaf stomata or other plant surfaces (Abhijith et al., 2017). For example, research on 86 North American cities showed that woody plants removed an average of 191 tons of pollutants annually, accounting for a 15% reduction in $PM_{2.5}$ (Nowak et al., 2018). Similarly, in Beijing, urban greenery removed 772 tons of PM_{10} in one year, and concentrations of SO_2 and NO_2 decreased by 5.3% and 2.6%, respectively, in city woodlands (He et al., 2020).

However, the interaction between urban trees and air quality is complex. Different tree species can have both positive and negative effects on air quality, making it essential to understand these interactions when designing green infrastructure (Barwise and Kumar, 2020). Several studies have examined the effects of trees in street canyons (Aničić et al., 2011; Aničić Urošević et al., 2019; Ayan et al., 2021; Catinon et al., 2008; Dadea et al., 2016; Darling et al., 2017; Dzierżanowski et al., 2011; Jeanjean et al., 2016). Designing effective vegetation barriers for pollution abatement requires an understanding of how the shape of these barriers influences air pollutant dispersion (Barwise and Kumar, 2020).

While trees can sometimes have drawbacks, such as reducing wind speeds and concentrating pollution or producing allergenic pollen, their overall contribution to improving urban environments outweighs these disadvantages. (Nowak et al., 2018). For example, rain removes a significant amount of large PM from leaves, while fine PM may be more effectively retained (Corada et al., 2021). Additionally, trees provide valuable shade, with individual trees offering a sun protection factor (SPF) of 6 to 10, reducing exposure to harmful ultraviolet radiation (Tyrväinen et al., 2005). Urban trees also create microclimates that help mitigate the heat island effect, reduce wind speeds, and lower traffic noise (Jeanjean et al., 2016). Urban trees further improve public health by encouraging recreational activities and providing spaces where people can relieve stress. Access to green spaces increases the frequency of visits to natural environments, which positively impacts both mental and physical health (Tyrväinen et al., 2005). Ultimately, the most significant contribution of trees in urban areas is not merely their aesthetic role but their ability to improve environmental quality and living conditions (Antisari et al., 2015). Evidence suggests that urban trees contribute to healthier urban environments by sequestering carbon, improving air and water quality, and enhancing the overall health and well-being of city residents.

3.3.1 Urban Heat Island Mitigation

In parallel with the rapid urbanization, the UHI can profoundly affect the quality of life for urban citizens. The cooling effect of green infrastructure can result in reductions of short-wave radiation reaching the surface by 60-90% with upward of 20°C differences in surface temperatures between shaded areas and sunny asphalt areas (Lüttge and Buckeridge, 2023; Winbourne et al., 2020). Thus, mitigating the UHI has become a core concern for urban sustainability (Xinjun Wang et al., 2021; Winbourne et al., 2020).

Urban green infrastructures, including parks, sport field, community gardens, street trees, and nature conservation areas, have been recognized as potential candidate to mitigate UHI. These green infrastructures reduce the amount of incident solar radiation through directly shading and transpiration (Xinjun Wang et al., 2021). During the hot extremes a clear difference in land surface temperature between areas of continuous urban fabric and areas covered by urban trees is observed. Urban trees have lower temperatures than urban fabric in all analyzed European cities, especially in the Central Europe and Eastern Europe (Schwaab et al., 2021). As seen in **Fig. 1**, there is a clear heat mitigation impact based on land cover type, with lower land surface temperature at forest or park, and higher land surface temperature at artificial surface. Dian et al., (2020) found that the highest UHI intensities in Budapest occur in the city center, reaching up to 7-8°C in the summer. In contrast, the lowest UHI intensities are observed in the Buda hills and public cemeteries, where dense green cover significantly mitigates the effect. Thus, the urban surface settings contribute significantly to the heat exchange between the urban area and the adjacent air. The mitigation effect vary in different seasons, and impacted by the physical structure of greenspaces, size, coverage, as well as the presence of water (Xinjun Wang et al., 2021).

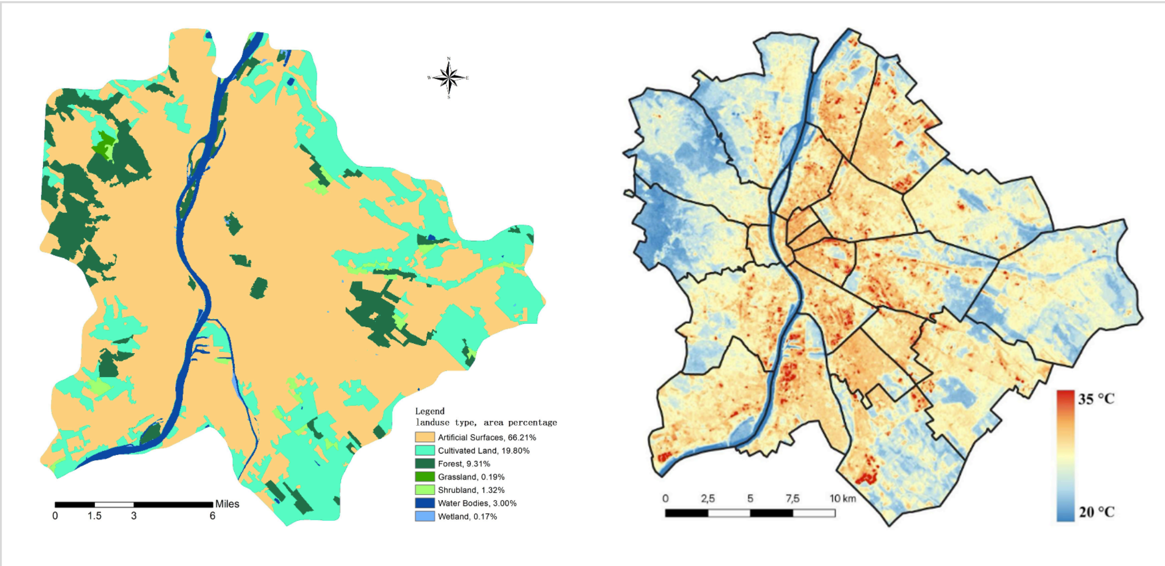

Fig. 1. Land cover of Budapest and calculated land surface temperature in Budapest on 01/07/2020. (Graph created based on sources: GlobeLand30 and Buzási, 2022).

There are substantial differences between tree species in terms of their ability to cool the surrounding air. Trees with dense canopy, high leaf area, and transpiration rates have been shown to be the most effective in terms of UHI mitigation (Xinjun Wang et al., 2021). These can attribute to a higher transpiration, where water is taken up by tree roots and moved through the stem and then evaporates through leaf stomates, and thus higher transpiration result in better UHI mitigation (Winbourne et al., 2020). The impact of transpiration on air temperatures has been shown to vary between 1°C to 8°C (Rahman et al., 2017).

3.3.2. Particulate Matter Reduction

Urban vegetation also plays an essential role in assessing and purifying the surrounding air, it has been recognized that the branches, leaves, trunks, and roots of plant all have the potential to retain atmospheric PM and improve air quality. As lichens and mosses are usually absent in the urban area, trees are considered the most effective bio-indicators and phytoremediation of ambient pollution (Alahabadi et al., 2017; Dadea et al., 2016; Jeanjean et al., 2016). Urban trees provide large leaf area, increases the dust deposition on leaves, as well as the branches, and trunk, are continuously exposed to pollutions, trap or uptake contaminants, thus becoming suitable for long-term interaction (Dadea et al., 2016). They affect not only the local pollution concentrations, but also associated values derived from ecosystem services (Nowak et al., 2018).

Trees can mitigate air pollutants either directly by absorbing gaseous compounds through stomata or indirectly by decreasing air temperature and limiting the activity of chemical reactions. Studies of different plants' ability to capture PM from the airborne have been the perceived center in the past few decades (Dadea et al., 2016; Simon et al., 2011). It has been widely reported that trees significantly contribute to the reduction of PM. For instance, a study demonstrated that with a 10x10 km^2 grid with 25% of tree cover, it removed around 90.4 tons of PM_{10} annually in London (Nowak et al., 2018). Additionally, Nowak et al., (2006) reported an average of 2% air quality improvement for PM, ozone, and sulfur dioxide in a 100% tree covered urban area. In some cities of the USA air quality improved 16% for ozone and sulfur dioxide, 9% for nitrogen dioxide, 8% for PM (Nowak et al., 2006). Furthermore, studies also discovered trees in the city center of Beijing, trees removed 772 tons of PM_{10} per year, whereas in a country's scale, urban trees and shrubs removed approximately 215,000 tons of PM_{10} each year in the United States (Dzierżanowski et al., 2011; Nowak et al., 2006; Yang et al., 2005). Studies also have shown that in the urban area, green walls decrease 40% of NO_2 and 60% of PM_{10} pollution, and in a realistic wind conditions vegetation barriers reduce up to 37% of ultra-fine PM (Jeanjean et al., 2016). Thereby, trees are ideal to be indicator plants and to provide reductions of pollution in the urban area, and thus help to improve human health.

Dust in the air comes from different sources, anthropogenic sources like vehicle exhausts, coal burning, industrial processing and natural sources such as volcanic eruptions, frost fire, soil and rock erosion (Di Lonardo et al., 2011; Jing et al., 2014). Air quality improvement programs throughout Europe use the most planted urban trees for pollution reduction. Such trees are pine, spruce, fir birch, beech, maple, horse-chestnut, linden, oak, poplar, and willow (Kosiorek et al., 2016). Being directly exposed to air contaminants and absorbing gaseous pollution via stomata is the reason that leaves are very sensitive to air pollution. Bui et al., (2023) conducted a study of five species (*Abelia mosanensis* T.H. Chung; *Euonymus japonicus* Thunb.; *Euonymus alatus* Thunb. Siebold; *Zelkova serrata* Thunb. Makino; *Prunus x yedoensis* Mattsum) in Cheongju city, South Korea, these species captured PM on their leaf surface ranged 41.15 to 124.78 $\mu g \cdot cm^{-2}$ in spring, 25.50 to 63.29 $\mu g \cdot cm^{-2}$ in summer, and 24.54 to 66.69 $\mu g \cdot cm^{-2}$ in autumn. Under precipitation, the leaf surface wash-off PM was with average 183 $\mu g \cdot cm^{-2}$ from 16 plants in Beijing, China, which was 1.3 times higher than that in the atmospheric precipitation (Cai et al., 2019). *Ulmus pumila, Catalpa speciosa, Magnolia denudate, Fraxinus pennsylvanica, Pinus tabulaeformis, Liriodendron chinense, Syringa reticulate, Robinia pseudoacacia, Poulus tomentosa, Eucommia ulmoides,* and *Metasequoia glyptostrodoides* have been proof accumulated more than 63.29 $\mu g \cdot cm^{-2} \cdot d^{-1}$ in Bejing. The ability of several species (*Ailanthus altissima, Euonmus japonicus, Ginko biloba, Pinnus tabulaeformis, Platanus* x *acerifolia, Platanus* x *hispanica, Populus tomentosa, Salix matsudana, Sophora japonica)* to trap ambient PM are well studied from different literature from different place (Corada et al., 2021).

In term of TE adsorption, Lovynska et al., (2023) measured that leaf of *A. platanoides* and *Robinia pseudoacacia* accumulated 30.7-185.5 $mg \cdot kg^{-1}$ for Zn, 5.7-22.4 $mg \cdot kg^{-1}$ for Cu, 9.0-31.3 $mg \cdot kg^{-1}$

for Pb, and 0.213-0.598 $mg \cdot kg^{-1}$for Cd in city parks of Dnipro, Ukraine. (Zhu et al., 2018) examined 17 species from downstream of a Pb-Zn mine in Guangxi, China, results showed that Cd ranged from 1.7-219.5 $mg \cdot kg^{-1}$, Cr 2.4 -76.8 $mg \cdot kg^{-1}$, Cu 6.4-94.0 $mg \cdot kg^{-1}$, Ni 0.7-28.9 $mg \cdot kg^{-1}$, Pb 11.0-1406.9 $mg \cdot kg^{-1}$, and Zn 54.4-2787.0 $mg \cdot kg^{-1}$. Thus, the adsorption increases when under higher background concentration.

However, broad-leaved trees capture particles range largely, which impacted by several factors. The different abilities of dust concentration and metal accumulation of plant species vary from one to the other, it is highly depends on the leaf morphological and anatomical parameters (Simon et al., 2011; Tomašević et al., 2004). Species-specific features, such as trichomes, special chemical composition, and epicuticular wax's structure determines the above-mentioned ability. Many studies have proved that the leaf shape, size, orientation, texture, and surface structures influence the amount of dust deposition. Notably, leaves with trichomes and waxes showed a relation to high dust entrapping capacity (Chen et al., 2017; Corada et al., 2021). Additionally, leaves with rough and epicuticle wax on the surface have higher potentials in capturing dust. However, the potential of trapping particles is not only correlated to the leaf morphology, but also species-specific traits and more depends on the chemical composition, exposure and surround environment conditions.

Dust collected from tree canopy composed of fine particles up to 30 µm, whereas road dust are dominated with coarse particles above 30µm (Ram et al., 2014). In considering that fine PM is more dangerous and harder to remove, the important of urban trees is becoming pronounce. In summary, plants develop several mechanisms are defined as plants' pollution tolerance. By changing primary product chlorophyll content, some species lose chlorophyll content in pollution stress, while some species increase chlorophyll to tolerate the pollution stress (Molnár et al., 2018). Change of relative water content is another way of some plants to adapt to the stressed atmosphere. The higher relative water content results in better tolerance because with the increased transpiration rate the plant can maintain better physiological balance under stressed conditions (GHassanen et al., 2016). Plants also respond to environmental stress by modifying the frequency and the size of their stomata (Kwon et al., 2021). Higher antioxidant compounds like ascorbic acid or vitamin C are indicated higher pollution tolerance ability as they are essential for several physiological mechanisms (Molnár et al., 2018). And thus, provide valuable ecological benefits.

3.3.3 Soil Pollution Reduction

The main risk associated with urban soil is the presence of TE deriving from intense human activities (Antisari et al., 2015). Urban trees play a significant role in mitigating these contaminants. They address these TE not only through above ground interaction and also by the extended root system interact with the particles which may wash off from leaves by wind or rain and soaks into the soil (Dzierżanowski et al., 2011; Nowak et al., 2018). A well-developed root system which interact with a relatively large volume of soil can help plants tolerate harsh environments better (Dadea et al., 2016). Root tolerance is the first step in the TE uptake and loading into the xylem vessels, its preservation of the selective property of the cell membrane.

Phytoremediation technology focuses on utilizing plant roots to uptake contaminants from the soil, thereby reducing pollution levels (Ali et al., 2013; Chen et al., 2022; Yasin et al., 2021). The effectiveness of this technology can be significantly improved by selecting plant species that are well-suited to local conditions. In areas heavily burdened by ambient pollution, it is beneficial to choose plant species whose above-ground parts are particularly effective at interacting with aerosol pollutants. Tailoring plant selection to specific environmental conditions ensures that phytoremediation efforts are optimized, enhancing both the health of urban ecosystems and the quality of urban soils.

3.3.4 Other Benefits

In addition, trees play a crucial role in carbon sequestration, capturing carbon dioxide from the atmosphere and storing it in their biomass and the surrounding soil (Havu et al., 2022). This process helps mitigate the effects of climate change by reducing the overall concentration of greenhouse gases. Additionally, Trees not only contribute to climate regulation but also support biodiversity. They provide essential habitats and food sources for a wide range of wildlife, including insects, birds, mammals, and fungi, offering shelter, nesting sites, and nourishment that are crucial for maintaining ecological balance (Xueyan Wang et al., 2021).

Beyond their ecological functions, trees often hold significant symbolic, religious, and historical value for many cultures around the world (Cavender and Donnelly, 2019). Beyond these cultural values, trees contribute significantly to human well-being. They enhance the quality of urban life by improving visual landscapes, reducing noise pollution, and providing shade that helps mitigate the urban heat island effect. The presence of green spaces has been shown to have beneficial effects on mental health, promoting relaxation, reducing stress, and improving overall mood. Spending time in these green environments fosters a sense of connection with nature, further contributing to physical and psychological health.

3.4 Selected tree species and measured trace elements

3.4.1 Selected tree species

Urban trees face challenging and frequently harsh conditions, which restrict their capacity to reach full growth and dimmish the advantages they provide to the environment and humans (Cavender and Donnelly, 2019). Thus, simply tree planting does not result in a long-term increase in tree cover. Urban forests, particularly the street tree component, suffer from a deficiency in both diversity and age structure. Typically, metropolitan areas are mostly occupied by three to five genera, which account for 50 to 70 percent of all street trees (Cavender and Donnelly, 2019). Such as in Minnesota, USA, 9 genera representing over 80% of all trees (Peters et al., 2010). This satuation also applies to the urban areas of Budapest, more than 80% of the urban trees are concentrated in a seven genera: *Acer genus, Aesculus genus, Celtis occidentalis, Fraxinus genus, Robinia pseudoacacia, Sophora japonica,* and *Tilia genus* (Szaller et al., 2014). In addition, leaf morphology is one of the influencing factors that differs in the interaction between trees and the urban environments. It is appeared that leaves that are big, smooth, hairless, and covered with a thick wax coating are less successful at storing PM than leaves that are rough, hairy, sticky, and have a thin wax covering and big, dense stomas (Castanheiro et al., 2020; Corada et al., 2021). The selection of tree species that appropriate and adaptable trees is becoming important. The selected species, *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 (Beck et al., 2016; Kalliopi et al., 2008.; Szaller et al., 2014).

A. platanoides L. 'Globosum' is common know as Norway maple. The leaves are bright green, glabrous, and lustrous beneath, bearded in the axis of the veins. They are palmately lobed, smooth, and measure 8-20 cm across (Aničić Urošević et al., 2019). For a more formal effect, *A. platanoides* makes an impressive round headed tree. This tree is early to leaf and has butter yellow fall foliage, making it ideal for an urban setting. In addition, it has a high tolerance and very high adaption to drought stress (Franceschi et al., 2023). *F. excelsior* L. Westhof's Glorie is also known as common ash, a deciduous tree native to Europe, the Caucasus and Turkey (Aksoy and Demirezen, 2006; Varol et al., 2021). *F. excelsior* has glabrous compound leaves with villous along the midrib beneath. *F. excelsior* bears pinnate compound leaves that are 20-40 cm long and consist of 7 -13 leaflets (Beck et al., 2016; Petrova et al., 2017). It is commonly applied in urban alley tree which can be distinguished by its shoot tip, light-grey bark and large compound leaves (Aksoy and Demirezen, 2006). It can reach heights of over 40m and girth of up to 6m under most favorable conditions (Aksoy and Demirezen, 2006). It prefers calcareous soils with rich in humus and nutrients. *F. excelsior* is known as a pioneer tree because it is tolerant of most environmental factors. However, it may remain a shrub under extreme conditions, such as lack of light. (Varol et al., 2021) discovered that climate changes will affect the *F. excelsior* directly and create secondary threats by affecting the spread of some pests and fungi. *T. tomentosa* Moench belongs to the family Malvaceae that has high ecological and economical values (Yan et al., 2022). *T. tomentosa* leaf, on the contrary, is slightly pubescent above with star-like hairs on the veins, and white tomentose forms a carpet-like layer beneath. *T. tomentosa* has heart-shaped simple leaves alternately arranged on the branches, about 10-20cm in length and 5-10cm in width, recognizable by the snow-white tomentum on the inferior side.

3.4.2 Measured trace elements

The TE, particularly Cu, Cd, Ni, Pb, and Zn have become a serious threat to the urban air environment because of the increasing anthropogenic activities (Yasin et al., 2021). These elements enter the air through vehicle exhaust emission, wear products from road transportation, and various industrial metallurgic processes (Cui et al., 2020; El-Khatib et al., 2020). (Dehghani et al., 2017) suggests that the spread of Cu, Pb, and Zn are associated with brake wear, tire dust, road abrasion, and fossil fuel combustion. Among above mentioned TE, Cd and Pb are not essential elements for plant's growth, and they have a maximum tendency to accumulate in the environmental because of their high environment persistency level. In our previous study, the tested Cd was under the minimum detection level, therefore, it is eliminated in this study. Although Ni might have some roles in the growth of plants, it is also included in the list of Hazardous Air Pollutants (Cui et al., 2020). Although elements like Cu and Zn are essential micronutrient for the growth and development of plants and animals, elevated levels of these element can be hazardous.

4. MATERIALS AND METHODS

4.1 Sampling Sites

Budapest is Hungary's capital city, situated on both sides of the Danube River. It is the 11th largest European capital city, occupying 525 km^2 and having approximately 1.7 million inhabitants (Tóth-Ronkay et al., 2015). The western part of the city, located on the right bank of the Danube, is hilly with forests, while the eastern part is flat (Alföldy et al., 2007). It has a temperate climate with impacts from the oceanic climate, and the Mediterranean climate and its location in the middle of the Carpathian Basin make it very erratic (Alföldy et al., 2007; Tóth-Ronkay et al., 2015). The annual mean temperature is 11.5°C, and the annual average of total sunshine is 2010 hours, and annual rainfall is about 586 mm, which falls mainly in May to June and autumn, with large temporal variability in each year (mean of 1991-2020) (MMSZ, 2024). As the economic center and most populated city in Hungary, Budapest is overburdened with anthropogenic activities. Every year, an average of 111,000- 384,000 new registered vehicles in Hungary, which results increasing traffic and emission (Hungarian Central Statistical Office, 2024). The increase of roadside traffic has become to major air pollution in Budapest (Alföldy et al., 2007; Tóth-Ronkay et al., 2015).

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) to represent urban street and urban park, respectively (**Fig. 2**). Deák Ferenc tér situates in the city center of Budapest, which is surrounded by a densely built-up inner residential belt. This area experiences heavy daily traffic, which can represent as a situation of a typical urban street area. Budai Arborétum, located on the south slope of Gellért Hill, is a suburban park that has 7.5 ha of planting area with around 1900 woody plant species (Schmidt and Sütöri-Diószegi, 2013). Although the other side of Budai Arborétum is next to the Villányi út, which is a double-lane road with public buses and trams (Füri et al., 2020), it is experiencing less car traffic compared to Deák Ferenc tér. Therefore, Budai Arborétum serves as an example of an urban park.

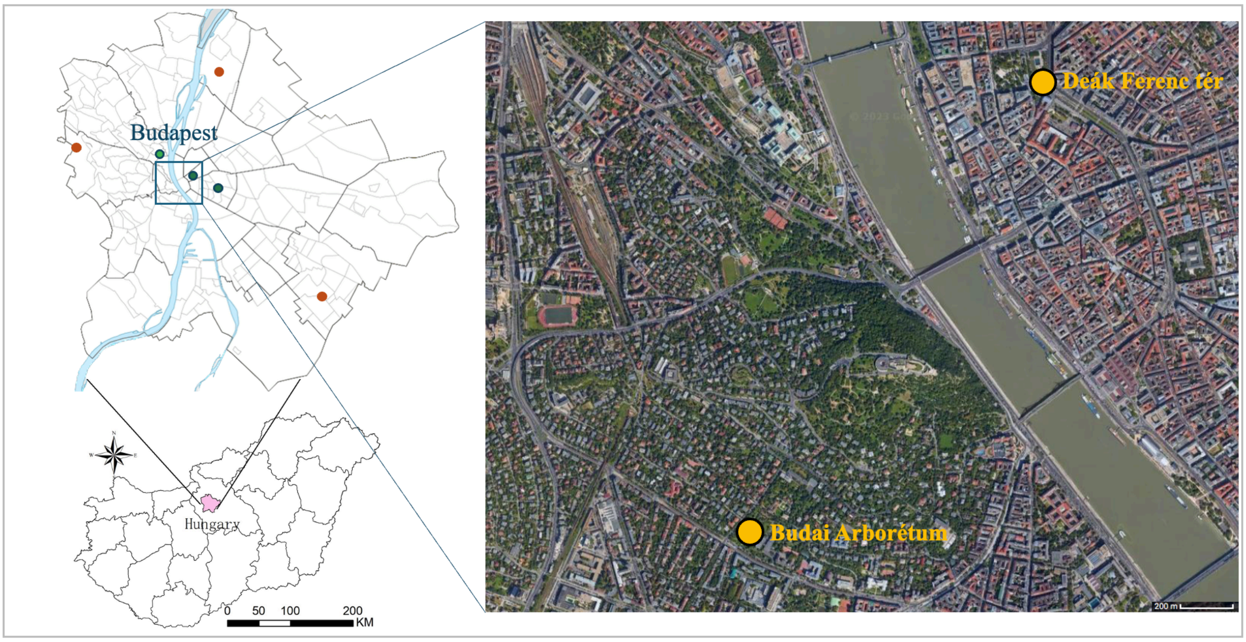

Fig. 2. Maps of sampling sites. Orange dots-metheological measuring sites, János hegy, Ujpest, and Lőrinc; Green dots-$PM_{2.5}$ and PM_{10} measuring sites, Széna tér, Erszerbet tér, and Keleki tér; Yellow dots- sampling sites, Budai Arborétum and Deák Ferenc tér.

4.2 Leaf Morphologies

The habits, tree shapes, and leaf morphologies of selected species are listed in **Table 1** and **Fig. 3** (Microscope lens multiple 40 times).

Table. 1. Botanic information and leaf surface characters of urban trees. Crown shapes are quoted from (Franceschi et al., 2022).

Species	Family	Leaf shape	Leaf surface
A. platanoides	Sapindaceae	palmately lobed leaf	glabrous
F. excelsior	Oleaceae	pinnately compound leaf with oval leaflets	smooth
T. tomentosa	Malvaceae	heart-shaped leaf	with tomentosa

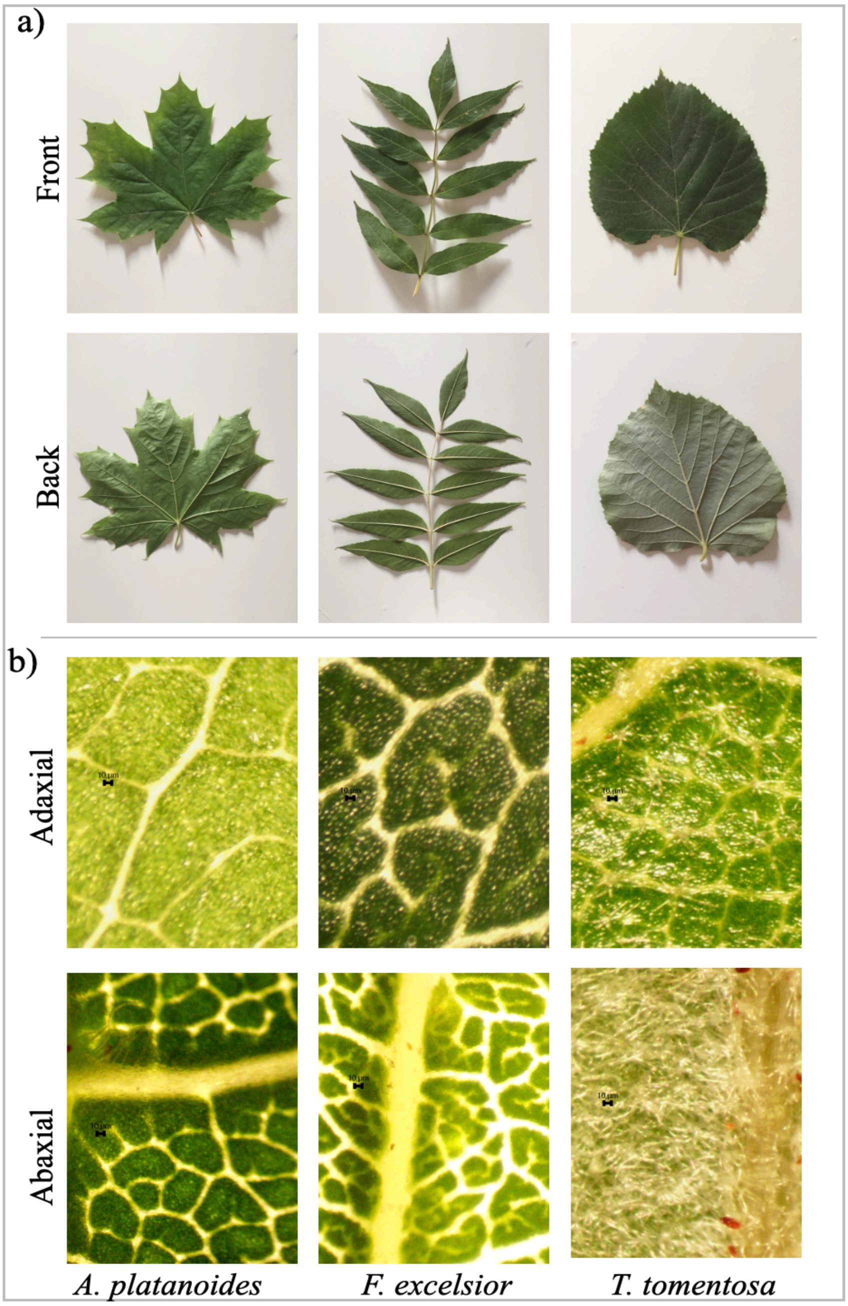

Fig. 3. Leaf morphology (a) and electronic microscopy of leaf surface (b) of urban trees.

4.3 Sampling Methods

4.3.1 Field Sampling

Sampling took place from May 2021 to October 2024 from Deak Ferenc tér (urban street) and Budai Arborétum (urban park). The detailed sampling times are listed in **Table 3-2**. We selected trees that are closely distributed at each site within a 200-meter radius, so it is reasonable to infer that they are exposed to a uniform environment. Five individuals of each species of similar age, with tree heights around 10m (ranged from 9 - 11 m) were marked at each site.

Table 2. Measuring and sampling time (Week of the year, WOY)

	Year	Spring	Summer	Autumn
Photosynthetic activities measuring	2021	21st	32nd	41st
	2022	-	35th	45th
	2023	22nd/26th	30th/35th	39th/43rd
	2024	22nd	35th	43rd
Leaves, branches, soil samples	2021	21st	32nd	41st
	2022	22nd	35th	45th
	2023	21st/26th	30th/35th	39th/43rd

On-site measurements included the structure data, the leaf area index (LAI), and the gas exchange parameters 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 was taking place from 2021 to 2023. We sampled twenty healthy and fully expanded leaves, three 15 cm branches from each individual plant. And each leaf sample was divided into two subsamples. Since the characteries of soil do not change much in time, we collected soil sample in spring of each year from 2021 to 2023. Soil samples were collected from four dimensions of the trunk of each tree, 10-20 cm topsoil were collected and mixed well. At each sampling time, right after samples are collected, the leaves, branches, and soils were gently put into paper bags and delivered to our laboratory for further treatment.

4.3.2 Chemical Properties Evaluation

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 centimeter (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 and salt contents were determined by a portable meter Mettler Toledo SevenGo Duo (Mettler-Toledo International Inc. USA). To determine the humus quantity in soil samples, weigh 0.3 g of the soil sample into an Erlenmeyer flask, add 10 cm^3 of 0.4 $mol \cdot dm^{-3}$ 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 cm^3. Add at least 10 drops of phosphoric acid (H_3PO_4) and 5 drops of diphenylamine indicator. Titrate with 0.2 $mol \cdot dm^{-3}$ 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. The method to determine ion concentrations of NH_4^+ and NO_3^- were similar as to the dust suspension, using the protocol proposed by Tandon H.L.S (2013) and NO_3^- concentrations represented non-volatilized parts of nitrate. 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 $m{\cdot}m\%^{-1}$ 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.

4.3.3 Trace Elements Measurement

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 ($mg{\cdot}kg^{-1}$).

4.4 Calculated parameters

4.4.1 Total Leaf Surface Area

The total leaf area of a tree is assessed using the structure parameters, according to (Franceschi et al. 2022). The crown length (cl) was defined as the upper segment of tree height from the branch start,

$$cl = h - bole\ length \text{ (m)} \tag{1}$$

and the mean crown radius (cr) was defined as the quadratic mean of the four crown radii, where i is the four directions and r is the corresponding crown radius value:

$$cr = \sqrt{\frac{\sum_i^4 r_i^2}{4}} \quad \text{(m)} \tag{2}$$

The crown shapes illustrations based on (Lawrence, 1985) are present in **Fig. 4** and the following crown volume, canopy projected area, and total leaf area are calculated as follow (**Table 3**). Each tree's shape was identified at the sampling site, their canopy projected area and crown volume and total leaf area then calculated according to the formula listed in Table 3.

Table 3. Mathematical formulas for the calculation of canopy parameters. (Franceschi et al., 2022)

Tree shape	Canopy projected area	Crown volume	Total leaf area
Cylindrical	$cr \cdot cl$	$\pi \cdot cr^2 \cdot cl$	$2\pi \cdot cr^2 + 2\pi \cdot cr \cdot cl$
Ovoid	$\frac{\pi \cdot cr \cdot \frac{1}{2}cl}{2} + \frac{\pi \cdot cr^2}{2}$	$\frac{\frac{4}{3}\pi \cdot cr^2 \cdot \frac{1}{2}cl}{2} + \frac{\frac{4}{3}\pi \cdot cr^3}{2}$	$\frac{4\pi \sqrt[1.6075]{(cr^2)^{1.6075} + 2(cr \cdot \frac{1}{2}cl)^{1.6075}}}{2} + \frac{1}{2}4\pi cr^2$
Half-ellipsoid	$\frac{\pi \cdot cr \cdot cl}{2}$	$\frac{\frac{4}{3}\pi \cdot cr^2 \cdot cl}{2}$	$\frac{4\pi \sqrt[1.6075]{(cr^2)^{1.6075} + 2(cr \cdot cl)^{1.6075}}}{2} + \pi cr^2$
Spherical	πcr^2	$\frac{4}{3}\pi \cdot cr^3$	$4\pi cr^2$

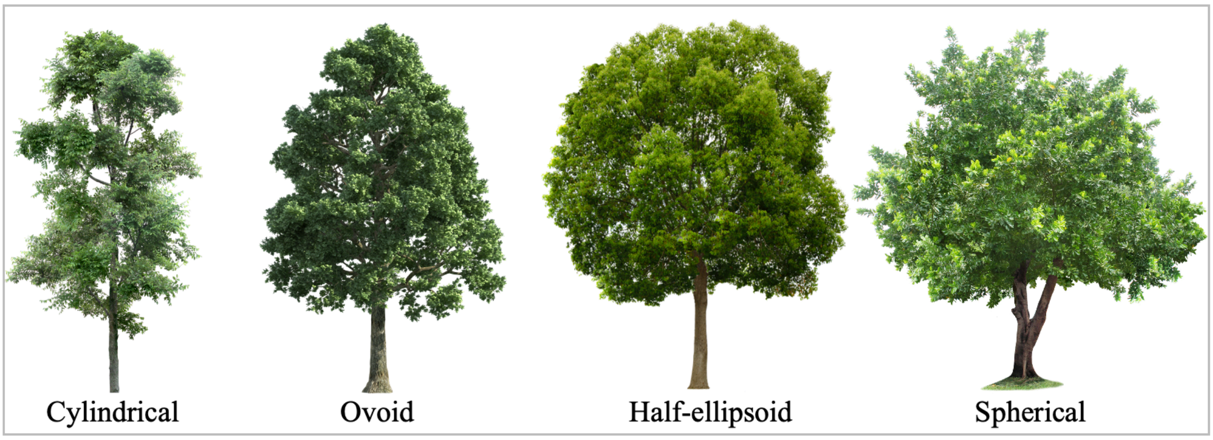

Fig. 4. Illustrations of crown shapes. Graph was created based on sources from (Lawrence, 1985) and https://www.pngwing.com

We also calculated the total leaf area using LAI. The LAI is defined as the amount of vegetation surface area per m^2 of ground area (Abhijith et al., 2017). The calculation of total leaf area according to LAI (Jin et al. 2021) is as follows:

$$LAI = \frac{Total\ leaf\ area}{Canopy\ projected\ area} \quad (\mathrm{m^2 \cdot m^{-2}}) \tag{3}$$

$$Total\ leaf\ area\ = LAI * Canopy\ projected\ area\ \ (\mathrm{m^2}) \tag{4}$$

4.4.2 Photosynthetic Parameters

Water-use efficiency (WUE) is the amount of CO_2 taken up by photosynthesis for a given amount of water vapor lost to the atmosphere (Cernusak 2020). It was discovered that measuring WUE can be a useful indicator of species trade-offs in urban areas (Gillner et al., 2017). It was calculated as follows:

$$WUE = \frac{A}{E} \qquad (\mathrm{\mu mol \cdot mol^{-1}}) \tag{5}$$

We then used a calculation based on the unified stomatal optimization (USO) model, as described by Medlyn et al., (2011):

$$g_s \cong g_0 + 1.6 * (1 + \frac{g_1}{\sqrt{D_{leaf}}}) * \frac{A_{net}}{C_a} \qquad (\mathrm{mol \cdot m^{-2} \cdot s^{-1}}) \tag{6}$$

In which D_{leaf} is leaf-to-air vapor pressure deficit, A_{net} represents net photosynthesis, and C_a represents atmospheric CO_2 concentration. Additionally, g_0 is the g_s value when photosynthesis is zero, and g_1 is the slope parameter, inversely related to plant WUE.

4.4.3 Fine Particulate Matter Deposition

The fine PM deposit on leaf surface was calculated as the difference of the dry clean beaker weight (W_1) and the dry suspension contained beaker weight (W_2).

$$\mathrm{PM\ DW} = W_2 - W_1\ (\mathrm{\mu g}) \tag{7}$$

The PM load in every unit of cm^2 was calculated by the ratio of the measured weight of PM and the measured leaf area:

$$PM\ per\ unit\ area = \frac{PM\ DW}{Measured\ leaf\ area} \ \ (\mathrm{\mu g \cdot cm^{-2}}) \tag{8}$$

$$PM\ adsorption\ = \ Total\ leaf\ area\ \cdot\ PM\ per\ unit\ area\ \ (\mathrm{kg}) \tag{9}$$

4.4.4 Pollution Indices

The index of geo-accumulation (I_{geo}) has been proposed to determine the contamination level of the soil. It applies a logarithm operation of the data set, in which C_n is the measured metal content,

B_n is the background value and the 1.5 is the correction factor allows for the elimination of possible differences in the content of the studies element in the soil due to the possible variation in the B_n and a small influence of anthropogenic activity (Dadea et al., 2016; Hołtra and Zamorska-Wojdyła, 2020). Equation list as follows:

$$I_{geo} = \log_2\left(\frac{C_n}{1.5B_n}\right) \tag{10}$$

The application of the geochemical background values and selection of the standards were inconsistent in worldwide studies. To properly indicate the contamination levels, we applied data listed by Rékási and Filep, (2012) (Cu:19 mg·kg^{-1},Ni: 27 mg·kg^{-1}, Pb: 21 mg·kg^{-1}, Zn: 53 mg·kg^{-1}) which was sampled from over all Hungary and Fe: 12000 mg·kg^{-1}as the soil background values in the calculation and the ranges of I_{geo} indicate the soil qualities listed in **Table 4**.

Table 4. Ranges of I_{geo} and soil quality. Source: (Hołtra and Zamorska-Wojdyła, 2020)

I_{geo} class	I_{geo} value	Soil quality
0	$I_{geo} \leq 0$	Practically uncontaminated
1	$0 < I_{geo} < 1$	Uncontaminated to moderately contaminated
2	$1 < I_{geo} < 2$	Moderately contaminated
3	$2 < I_{geo} < 3$	Moderately to heavily contaminated
4	$3 < I_{geo} < 4$	Heavily contaminated
5	$4 < I_{geo} < 5$	Heavily to extremely contaminated
6	$5 < I_{geo}$	Extremely contaminated

Enrichment factor (EF) is often used to indicate the source identification of TE abundance in the atmosphere. Because Fe is ubiquitous in the environment and has no substantial manmade origins, it is utilized as a reference element (Cui et al., 2020). The crust refence of Cu: 60 mg·kg^{-1}, Fe: 50000 mg·kg^{-1}, Ni: 84 mg·kg^{-1}, Pb: 14 mg·kg^{-1}, Zn: 70 mg·kg^{-1}. The ranges of EF and soil quality as shown in **Table 5**.

The EF of TE can be calculated by using the following equation:

$$EF = \frac{(C/Fe)_{aerosol}}{(C/Fe)_{crust}} \tag{11}$$

Table 5. Ranges of EF and soil qualities

Value	Pollution sources
EF<10	from natural crustal elements
10<EF<100	both natural and anthropogenic sources
EF>100	anthropogenic or exceptional geological events

The bio-concentration factor (BCF) is widely used parameter to assess a plant's ability to accumulate heavy metals from its surrounding environment. It is defined as the ratio of the total metal concentrations in the sampled plant tissues (leaves or branches) to those in the soil samples taken from the same location where the plant is grown. BCF provides valuable insights into the plant's capacity to uptake specific heavy metals from the soil (Zhang et al., 2024). In this study, the BCF is calculated by substituting the metal concentrations in the soil with the corresponding metal content found in the dust samples collected from the same location as the plant. This approach allows for a comprehensive evaluation of the TE accumulation potential of the selected plant species based on the metal concentrations in the soil.

$$BCF = \frac{C_{plant\ tissue}}{C_{environment}} \quad (12)$$

Where $C_{plant\ tissue}$ is the metal concentration in leaves and branches and $C_{environment}$ is the metal concentration in dust and soil.

Comprehensive bio-concentration index ($CBCI$) was proposed by Zhao et al., (2014), it has been practiced to estimate the capacity of urban trees for the comprehensive accumulation of TE. The fuzzy method is applied in the procedures to obtain $CBCI$ (Alahabadi et al., 2017; Zhao et al., 2014).

First of all, the fuzzy set U which is the level of comprehensive accumulation ability for a tree is calculated, U = (μ_1, μ_2, μ_3......μ_i). μ_i is the various metal pollution factor. Further on, calculate the value of fuzzy membership function by synthetic evaluation

$$\mu(x) = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (13)$$

In the equation, x is the BCF of a certain metal, x_{max} and x_{min} are the maximum and minimum values of the BCF of the given metal, which reflect the highest and the lowest comprehensive accumulation factors of different TE. Finally,

$$CBCI = \frac{1}{N}\sum_{i=1}^{N} \mu_i \quad (14)$$

Where, N is the total number of elements, and μ_i is $\mu(x)$ of metal i.

4.5 Air Quality Data

The meteorological data of Budapest were obtained from the database of Hungarian Meteorological Service (MMSZ, 2024). 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 (as in **Fig. 2**). We visualized the meteorological data including $PM_{2.5}$, PM_{10}, max wind speed, and precipitation from the 21st to 44th week of 2021 to 2024 which covered all sampling time, as showed in **Fig. 5**.

The average temperature in 2021 was 12.34°C, 446.8 mm of precipitation, the average PM_{10} was 27.13 $\mu g \cdot m^{-3}$ (range: 8.33 - 98.67 $\mu g \cdot m^{-3}$), and $PM_{2.5}$ 13.84 $\mu g \cdot m^{-3}$ (range: 3.00 - 48.00 $\mu g \cdot m^{-3}$). In 2022, the average temperature was 13.35°C, 448 mm of precipitation, the average PM_{10} was 23.13 $\mu g \cdot m^{-3}$ (range: 5.00 - 70.00 $\mu g \cdot m^{-3}$), and $PM_{2.5}$ 11.82 $\mu g \cdot m^{-3}$ (range: 2.00 - 30.00 $\mu g \cdot m^{-3}$). In 2023, the average temperature was 13.75°C, 679 mm of precipitation, and the average PM_{10} was 22.37 $\mu g \cdot m^{-3}$ (range: 4.67 - 61.67 $\mu g \cdot m^{-3}$), and $PM_{2.5}$ 12.06 $\mu g \cdot m^{-3}$ (range: 2.50 - 42.50 $\mu g \cdot m^{-3}$). The steadily increasing average annual temperature confirms the worsening impact of global climate change and the intensification of the UHI effect. The average wind speed with the dominant northern wind direction.

It can be seen from the graph the concentration of $PM_{2.5}$ is positively correlated with the concentration PM_{10}, and negatively correlated with max win speed. When the volume of precipitation is more than 40 mm, correspondingly the PM concentrations decreased. In 2021, during the 29th week, there was significant precipitation totaling 103.4 mm. Because in urban areas, pavements and other impermeable surfaces often prevent much of this precipitation from reaching the tree roots, leading to inadequate water supply for their growth and health. Thus, this level of rainfall is crucial for urban trees, as it can penetrate the soil and provide sufficient water for their root systems. In contrast, the drought level in 2022 is higher, because between 23rd and 39th week, there was not enough precipitation.

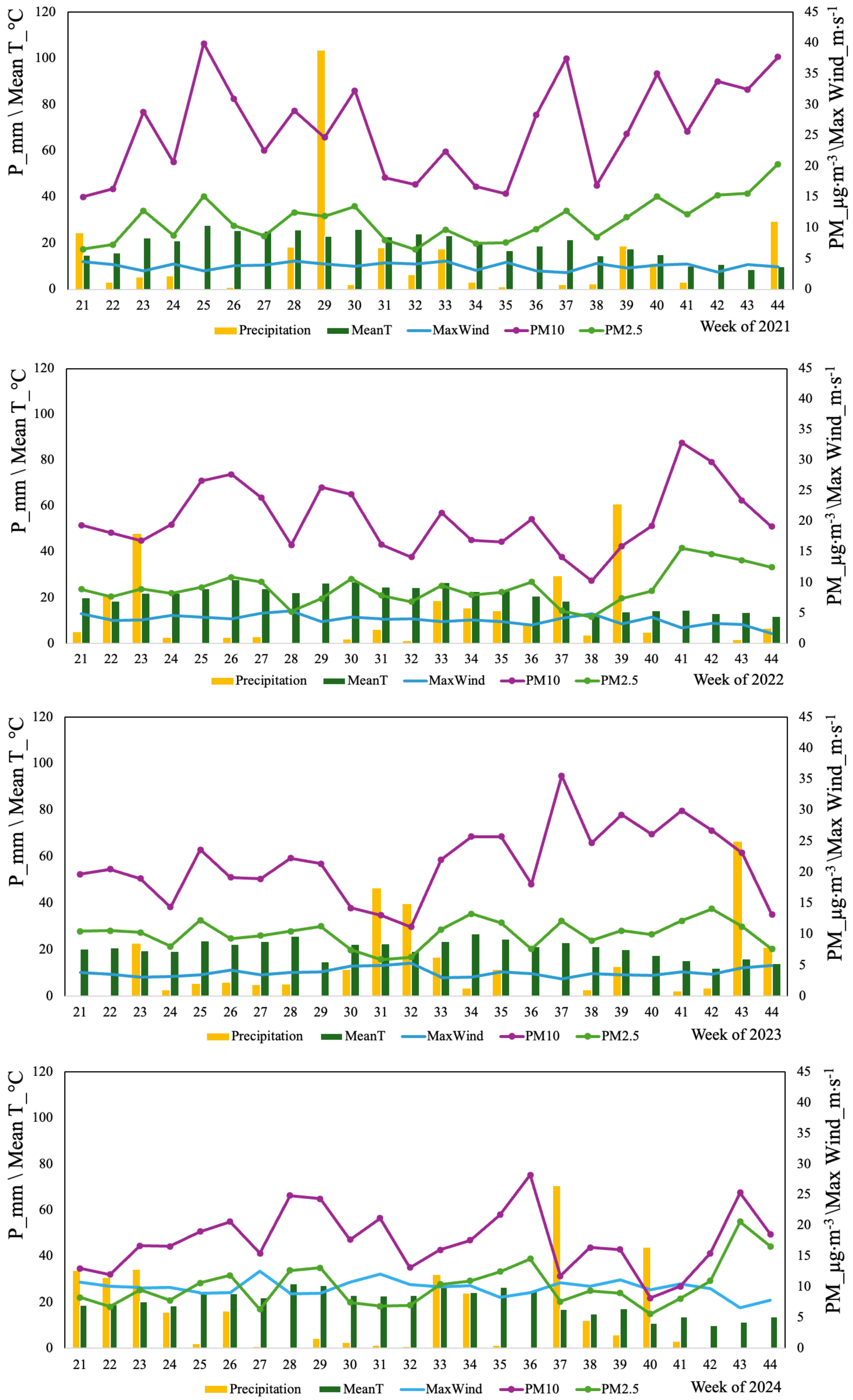

Fig. 5. Meteorological data during the sampling time from 2021-2024. The graph was created based on data accessed from Hungarian Meteorological Services (MMSZ, 2024). Axis 1 represents column values and axis 2 represents line values.

4.6 Data Analysis

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. Descriptive statistics were computed to summarize the central tendencies and variability of each variable under study. The mean and standard deviation for all variables are presented in the accompanying tables. To ensure the appropriateness of subsequent analyses, each dataset was subjected to a normality test. Normality was considered acceptable when the absolute values of kurtosis and skewness were less than 2, and the p-value for the Kolmogorov-Smirnov test exceeded 0.05. For datasets that failed the normality test, a logarithmic transformation was applied to achieve a more normal distribution.

An independent t-test was conducted to compare differences between the two locations, while one-way ANOVA was performed to analyze the effects of species and seasons as fixed factors. The assumption of homogeneity of variances was assessed using Levene's test, with a threshold of $p>0.05$ indicating homogeneity. If Levene's test was significant, a Tukey HSD post hoc test was applied to identify specific pairwise differences. Statistical significance was determined at the $p<0.05$ confidence level. The MANOVA revealed significant effects across multiple factors, with Wilks' lambda and partial eta-squared ($\eta2$) values highlighting the varying influence of these factors on the dependent variables at the group level.

For the photosynthesis parameter which obtained in 2021 (n=578), an auto linear modeling was run to detect the important contribution of E, WUE, C_i, T_{leaf}, g_s, and PAR to A. And Pearson correlation coefficients were calculated between photosynthesis activities parameters. The multiple relationships between physiological parameters and environmental factors were carried out in Canoco 5 (Biomeris, Wageningen, The Netherlands). De-trended correspondence analyses (DCA) were performed to analyze the data. When the lengths of the first DCA ordination axis lower than 1, indicating that redundancy analysis (RDA) should be used to ordinate environmental factors. The Monte Carlo permutation tests on eigenvalues for both axes were statistically significant, $p=0.002 < 0.05$.

5. RESULTS AND DISCUSSION

5.1 Structure of urban trees

For most eco-physiological research, including light interception, photosynthetic efficiency, respiration, and evapotranspiration, an accurate estimation of a tree's leaf area is a crucial variable (Pandey and Singh, 2011). Phenological data can be used to support the scheduling of plant's ecological benefits (Ianovici et al., 2015). Tree leaf area is important in pollution removal, thus through the assessment of leaf area in cities will contribute to the estimating of their capacities in pollution retention. As the mitigation potential of the trees is governed by several factors including anatomy, morphology, physiology and biochemistry of plant tissues (Singh et al., 2020; Yang, 2009). Three main variables are used to estimate leaf area: tree cover, LAI within tree canopies, and percent evergreen (Nowak et al., 2018). In this study, we evaluated the individual leaf area, LAI, and the total leaf surface, with which to estimate the potential of different trees in PM deposition and adaptation to the urban circumstance.

5.1.1 Individual Leaf Area

The leaf development of deciduous trees has different states: the leaf-off state, leaf expansion state, full-leaf state, and defoliation season (Miao et al., 2021). However, when we compared the leaf area of all the species in our study by sampling season, there were no big changes. This is because we sampled when the leaves were fully extended.

Nevertheless, the growth condition can impact the development of leaves. The leaf surface of urban trees is shown in **Table 6**. 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.

Table 6. Mean and standard deviation (SD) of individual leaf area (cm^2) urban trees in Budapest with the results of the independent-sample T-test. The letter after the data shows significant variance ($p<0.05$) between the two different locations.

Species	*A. platanoides*	*F. excelsior*	*T. tomentosa*
Urban Park	102.82±27.59 b	123.74±20.31 a	42.51±8.04 a
Urban Street	86.40±20.51 a	121.45±18.70 a	57.64±11.04 b

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. The leaf scorch also happening to other *Acer* species (Krutul et al., 2018; Uhrin et al., 2018). Furthermore, under shade leaves are larger, the position of *A. platanoides* at Deák Ferenc tér 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. It also confirms that species selection is important strategy for a sustainable city management.

5.1.2 Leaf Area Index

LAI is the total one-sided area all the leaves above a given ground area divided by the ground area. It is a dimensionless metric describes the total leaf surface area per unit ground area ($m^2 \cdot m^{-2}$) (Abhijith et al., 2017). LAI of trees can vary spatially and temporally in accordance with species composition, tree phenology, tree health, and management practices (Dowtin et al., 2023). Furthermore, it is a factor in determining the amount of light intercepted by the canopy, which in turn controls photosynthetic rates and sets limits on transpiration. Thus, it is a sustainable approach for air pollution mitigation (Jin et al., 2014; Pace et al., 2021).

In our study, the LAI of urban trees (n=150) are listed in **Table 7**. *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 $m^2 \cdot m^{-2}$). In the comparison of two locations, both *A. platanoides* and *F. excelsior* exhibited a greater LAI in the urban park, however *T. tomentosa* did not demonstrate significant variations between the two locations.

Table 7. Means and SDs of LAI ($m^2 \cdot m^{-2}$) urban trees in Budapest with the results of the Tukey HSD test for the overall among all species and an independent-samples T-test between two locations of same species. The lower-case letters show significant differences among species, whereas capital letters indicate significant differences between species, both at a confident level of p=0.05.

Species	*A. platanoides*	*F. excelsior*	*T. tomentosa*
Overall	4.11±1.29 ab	3.37±1.28 b	4.67±2.01 a
Urban park	5.38±0.43 A	4.15±0.70 A	5.71±0.66 A
Urban street	3.30±0.55 B	2.98±0.59 B	5.44±0.76 A

Since LAI vary among different places and seasons, we measured their changes in one vegetation phrase. **Fig. 6** illustrates that 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. This pattern contrasts with the typical trend in forest plantations, where LAI increases from spring to summer before decreasing in autumn (Liu et al., 2018). 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 (Moser et al., 2017). 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. It is one of the most common phenology changes of urban trees under climate changes (Yang, 2009). Which in turn also limited their ecological benefits.

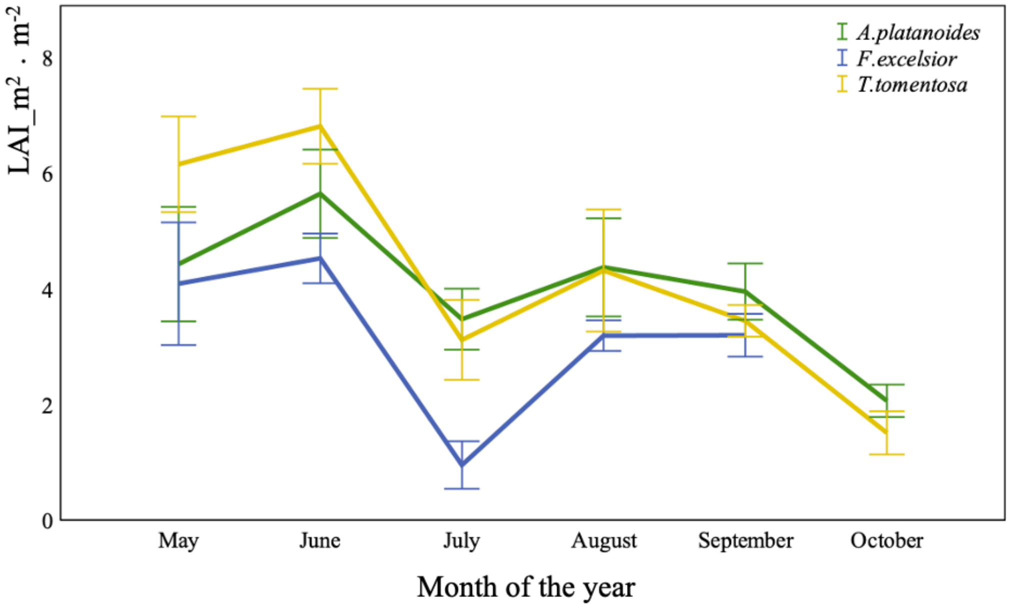

Fig. 6. Leaf area index of urban trees in Budapest within a vegetation phase. The bars represent the standard error at the confidence level of $p<0.05$.

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. Furthermore, a higher LAI of trees also suggests a denser canopy, which can have significant ecological implications, such as higher interaction of the plants with environmental pollutants (Barwise and Kumar, 2020; Cavender and Donnelly, 2019; Dowtin et al., 2023). Jin et al., (2014) and Schaubroeck et al., (2014) discovered that LAI is one of the most important predictors of $PM_{2.5}$ dispersion in urban area, the dry deposition and $PM_{2.5}$ removal follow the same patterns as LAI, it is because the increase of LAI reduces wind speed within the canopy, which is negative feedback on deposition and removal. Thus *T. tomentosa* has adapted better than other two species and has a higher potential interaction with the ambient pollution in Budapest.

5.1.3 Total Leaf Area

The plant's architecture - its shape and structure - reflects the interplay between developmental processes and environmental constraints (Ianovici et al., 2015). The larger and more mature trees, with their fuller crowns and leaf surfaces, provide more carbon storage, economic benefits, and other ecosystem services than smaller trees do in urban environments (Cavender and Donnelly, 2019). Crown shapes is important for the calculation of crown volume; however, it depends on tree species and local environment (Franceschi et al., 2022). In our study, the crown shapes of *A. platanoides* included cylindrical, ovoid, and spherical; *F. excelsior* was ovoid and spherical; and *T. tomentosa* was ovoid, half-ellipsoid, and spherical (**Table 8**). The result corresponds to the study of (Franceschi et al., 2022), most species showed one or two prevalent crown shapes with changes due to their growing situations.

Table 8. Means and SDs of crown parameters of urban trees. Total leaf area 1 was calculated by structural parameters and Total leaf area 2 was calculated by measuring LAI. Letters indicate the Tukey HSD test result of the differences between two total surface areas at a confident level of $p<0.05$.

Tree shape	*A. platanoides*	*F. excelsior*	*T. tomentosa*
Crown shape	cylindrical, ovoid, spherical	ovoid, spherical	ovoid, half-ellipsoid, spherical
Crown volume (m^3)	253.24±147.6	186.24±65.8	268.03±82.2
Canopy projected area (m^2)	43.3±19.3	38.93±9.2	49.48±9.3
Total leaf area 1(m^2)	213.29±117.4 a	155.75±36.9 a	241.19±157.4 a
Total leaf area 2 (m^2)	262.25±202.9 a	144.78±53.2 a	282.50±89.7 a

Urban trees have the highest amount of leaf surface area in parks and street plantations (Hrotkó et al., 2021). Phenology is a simple and cost-efficient tool for the early detection of changes in the ecosystems and can be viewed as comprehensive measurement device for the environment (Ianovici et al., 2015). The average crown volume and canopy projected area 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 (Pandey and Singh, 2011), 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 (Wang et al., 2020).

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.

5.2 Physiological Parameters of Urban Trees in 2021

5.2.1Photosynthetic Parameters

In urban areas, plants are growing under conditions of constant readapt to the dynamic presence of various stresses in the environment. These stresses namely drought, salinity in the soil, and air pollution. The presence of air pollution has been observed to have a detrimental effect on photosynthetic pigments, leading to a decrease in their leaves. This disruption can extend to disrupt metabolic functions and enzyme activities, thereby affecting several physiological processes (Singh et al., 2021). Since photosynthesis is the basis for carbon assimilation and, in turn, ecosystem productivity, leaf-level observations can be useful for estimating what is going on at the ecosystem level (Gulías et al., 2009; Singh et al., 2020). Analyses of physiological characteristics, such as leaf water potential and leaf gas exchange, have the potential to offer valuable understanding regarding the adaptability of various woody plant species in urban settings (Kesić et al., 2020). Therefore, to comprehensive understand how stressful urban environments impact the ability of urban trees to provide various ecosystem services (Roy et al., 2012).

The overall photosynthetic activities of urban trees are listed in **Table 9**. 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 $\mu mol\cdot m^{-2}\cdot s^{-1}$.

Table 9. Descriptive of photosynthetic activities of urban trees in Budapest in 2021. (A_$\mu mol\cdot m^{-2}\cdot s^{-1}$, E_ $mmol\cdot m^{-2}\cdot s^{-1}$, WUE_ $\mu mol\cdot mol^{-1}$, C*i* ppm; g_s; T_{leaf}_°C, PAR_$mol\cdot m^{-2}\cdot s^{-1}$)

Species	*A. platanoides*	*F. excelsior*	*T. tomentosa*
A	4.85±2.76 b	4.64±3.01 b	6.70±5.08 a
E	1.88±1.43 a	1.34±1.11 b	2.26±1.89 a
WUE	3.61±2.23 a	4.19±2.64 a	4.10±2.60 a
C*i*	228.73±53.81a	213.39±65.92 b	227.52±58.57 ab
g_s	0.06±0.03 b	0.04±0.02 c	0.08±0.06 a
T_{leaf}	29.20±4.76 a	29.46±4.68 a	27.85±4.44 b
PAR	793.86±704.53 a	743.40±648.54 a	775.67±701.27 a

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 concentration positively impact the net photosynthesis rate of urban trees, whereas leaf temperature exhibits negative effects. Our results confirm Forrai, (2012) who found that *Tilia* genus had higher photosynthetic activity and transpiration rates than *Acer* and *Fraxinus* at similar PAR values.

Detailed descriptive results of photosynthesis parameters from different locations in 2021 (n=578) are listed in **Table 10**. The overall result corresponds to the observed trends in urban parks, while at urban street no significant differences were found in all photosynthesis parameters among all species. This 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. When comparing the two locations, all species exhibited higher net photosynthesis and PAR in urban park compared to street site, while it was opposite for WUE. Similarly, Singh et al., (2020) also discovered declined net photosynthesis rate and increased WUE of roadside trees. The concentration of internal CO_2 showed no difference across species. However, the transpiration rates for *A. platanoides* and *T. tomentosa* were higher at urban park, with no difference for *F. excelsior*. In terms of stomatal conductance and surface temperature, differences were only found in *T. tomentosa*, which showed higher stomatal conductance at urban park and higher surface temperature at street site.

Table 10. Means and SDs of photosynthetic parameters from different locations in Budapest. The capital letters indicate a significant difference result of independent-samples T-test between two locations and lower-case letters indicate a significant difference result between species with Tukey HSD tests, both at the confidence level of p<0.05. (A_µmol·m^{-2}·s^{-1}; E_ mmol·m^{-2}·s^{-1}; WUE_ µmol·mol^{-1}; Ci ppm; g_s; T_{leaf} _°C; PAR_mol·m^{-2}·s^{-1}).

	Species	*A. platanoides*	*F.excelsior*	*T. tomentosa*
	A	4.53±3.35 bA	3.37±2.05 bB	7.91±6.12 aA
	E	2.36±1.71 bA	1.43±1.30 cA	3.10±2.17 aA
	WUE	2.65±1.55 bB	3.17±2.05 abB	3.55±2.04 aB
Urban park	Ci	228.53±46.65 aA	211.02±62.23 aA	220.94±45.12 abA
	g_s	0.06±0.03 bA	0.04±0.02 cA	0.10±0.07 aA
	T_{leaf}	30.26±3.63 aA	31.04±2.012 aA	28.12±3.02 bA
	PAR	992.16±704.37 aA	752.99±673.81 bA	962.03±737.08 abA
	A	5.21±1.87 aA	6.01±3.29 aA	5.28±2.97 aB
	E	1.35±0.71 aB	1.24±0.69 aA	1.25±0.68 aB
	WUE	4.67±2.39 aA	5.31±2.76 aA	4.94±3.17 aA
Urban street	Ci	228.96±61.04 aA	215.98±69.97 aA	235.20±70.64 aA
	g_s	0.06±0.02 aA	0.05±0.02 aA	0.05±0.02 aB
	T_{leaf}	28.025.56 aB	27.74±5.98 aB	27.48±5.58 aA
	PAR	573.77±639.57 aB	732.96±623.48 aA	596.65±618.06 aB

5.2.2 Net Photosynthesis Rate

Photosynthesis, the most fundamental and intricate physiological process of plants, is highly influenced by environmental conditions, including temperature, light intensity, air CO_2 concentration, air humidity, and soil moisture (Ashraf and Harris, 2013). Furthermore, pavements in metropolitan locations can induce high temperatures and soil drought, detrimentally impacting photosynthesis activities (Czaja et al., 2020; Y. Wang et al., 2019). The comparison of different photosynthetic activities among different seasons and locations is shown in **Fig. 7**. All species 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, this is agreed with Lahr et al., (2018), that urban trees have a greater adaptation to maximize the photosynthesis than suburban or rural area.

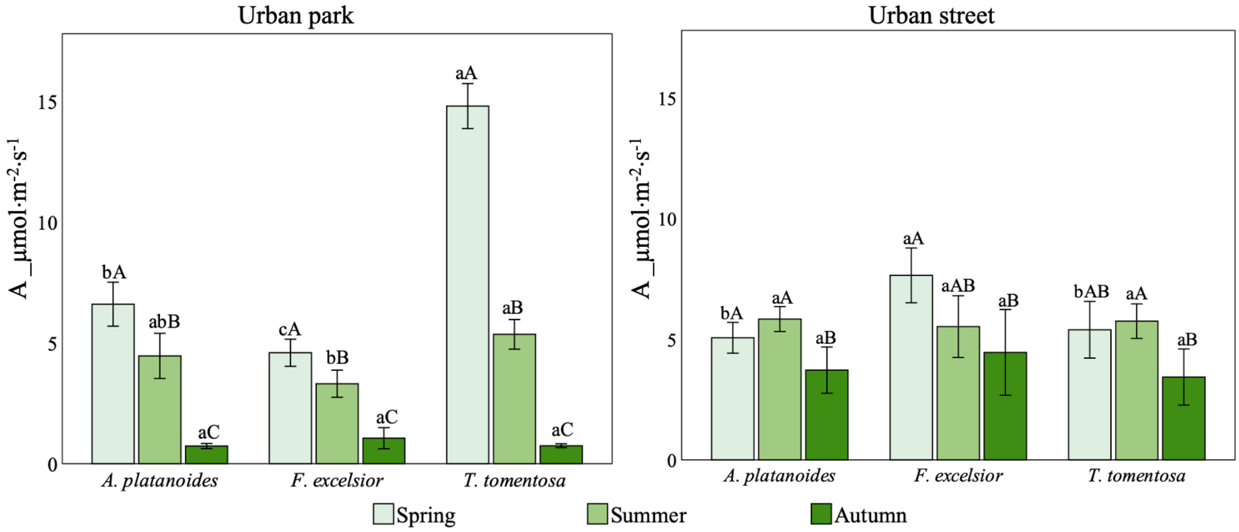

Fig. 7. Comparison of net photosynthesis between seasons at Budai Arborétum (urban park) and Deák Ferenc tér (urban street). Lowercase letters indicate significant differences between species, capital letters indicate significant differences between seasons at confidence level $p<0.05$.

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. A plant's ability to cope with stressors, either through photosynthetic acclimation or thermal regulation, can vary between species and across canopy vertical gradients; therefore, species with low leaf area, complex leaves, and high stomatal conductance can result in high thermoregulation capacity and maximize carbon gain by preventing excessively high leaf temperature (Carter and Cavaleri, 2018). Thus, in order to find out which factors contribute to the changes in the net photosynthesis rate, we followed up with a correlation analysis of all parameters. Their Pearson correlation coefficients were calculated, and an auto-linear regression model was fitted to compare each parameter's contribution. The results are listed in **Fig. 8**.

The strongest correlation (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. The connection of these parameters can be explained by plants with a higher rate of stomatal conductance have an increased ability to regulate their rates of transpiration, which enables them to maintain a better rate of photosynthesis even at higher air temperatures or prevent long-term damage that can occur when temperatures exceed certain thresholds (Carter and Cavaleri, 2018). Stomatal conductance regulates the exchange of carbon and water between plants and the atmosphere (Santos et al., 2023). In urban environments where drought is one of the primary characteristics, insufficient water supply causes stomata closure and decreases water uptake and thus transpiration (Rötzer et al., 2019). Other factors that are positively correlated with stomatal conductance, such as PAR (0.32) and internal CO_2 (0.15), are because stomata tend to open when there is higher radiation (Pace et al., 2021), which in turn lets in higher concentrations of CO_2.

WUE is strongly influenced by environmental parameters and is species-specific (Gillner et al., 2017). 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.

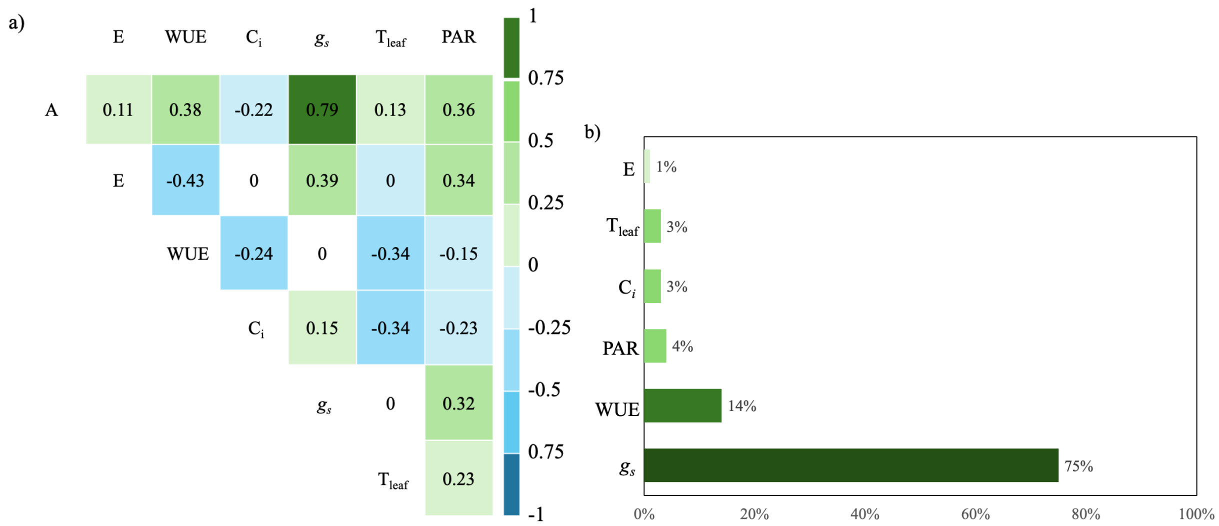

Fig. 8. Person correlation coefficients between different parameters (2-tailed, p<0.01) (a) and auto linear modeling importance contribution (b).

The auto linear modeling (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, whereas WUE contributes 14%, and PAR contributes 4%, internal CO_2 concentration and leaf surface temperature both contribute 3%, and transpiration takes up only 1%. This result validates the correlation coefficient, indicating that drought is the primary factor influencing the growth and survival of urban trees in Budapest. The decline in photosynthetic rate due to environmental stress is primarily caused by three mechanisms: stomatal regulation, nonstomatal regulation, and a combination of both (X.-M. Wang et al., 2019). Under moderate drought, plants close their stomata to prevent xylem embolism and thus a corresponding reduction in net photosynthesis (Farooq et al., 2009; Lahr et al., 2018). However, 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 deposition of PM affects plants' photosynthetic rates, altering the light absorption and PAR reflections in leaves (Anand et al., 2022; Przybysz et al., 2014). Thus, the decrease in net photosynthesis is associated with a corresponding decrease in transpiration rates. This might be because in the summer and autumn, dust has covered the leaf surface and influenced the efficiency of photosynthesis and transpiration rate. All species showed their highest net photosynthesis in the spring, which then decreased in the summer due to the strong limitation of photosynthesis by the summer drought (Gulías et al., 2009). In the comparison of WUE, there was no significant difference in spring among all species. In summer, *T. tomentosa* and *F. excelsior* showed higher WUE than *A. platanoides*. *T. tomentosa* outperformed both *A. platanoides* and *F. excelsior* in terms of WUE. In this aspect, T. *tomentosa* shows better adaptation to urban drought conditions. There is no universal observation between species origin and WUE. However, plants and ecotypes that occur in habitats where water sufficiency is a long-term condition tend to have a high capacity for rapid water use and a lower WUE (Cernusak, 2020). This phenomenon occurs due to the exposure of plants to a stressful environment; their stomatal density increases, leading to a decrease in water content in plant tissues. Therefore, a higher water content within a plant can help to maintain its physiological balance and enhance plants' tolerance ability under stressful conditions (GHassanen et al., 2016). The internal CO_2 concentration has a negatively correlation with net photosynthesis, as during photosynthesis, terrestrial plants must open their stomata to allow CO_2 molecules to diffuse into the chloroplast stroma (Cernusak, 2020). Terrestrial plants often have high intercellular CO_2 levels and low WUE, as shown by the negative correlations between WUE and internal CO_2 levels (Cernusak, 2020; Lahr et al., 2018). Moreover, microclimate differences can have a strong influence on the performance of landscape plants, an increase in WUE might result in a decrease in photosynthetic activity (Mueller and Day, 2005; Osone et al., 2014). Air pollution influences stomatal functioning and leaf thickness in urban plantations (Singh et al., 2020). The urban environment exerts stress on the physiological processes of urban trees, thereby constraining their ecological contributions.

5.2.3 Comparison of Stomatal Conductance

Stomatal conductance is one of the primary determinants of photosynthesis, as it describes the first step in the diffusion path of CO_2 from the atmosphere to substomatal cavities (Warren, 2007). It depends on various environmental factors, position, and age of the tree leaves (Singh et al., 2020).

The behavior of the leaves greatly influences their acclimation and adaptation to water and carbon fluxes (Héroult et al., 2013; Medlyn et al., 2013).

The comparison of stomatal conductance of tree at urban park and street sites is listed in **Table 11**. 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. This finding agreed with other studies that *A. platanoides* (Franceschi et al., 2023), *F. excelsior* (Varol et al., 2021), and *T. tomentosa* (C. Zhang et al., 2019) grow impacted by stimulated drought events. Furthermore, the significantly higher *T. tomentosa* at urban park indicates that *T. tomentosa* at the urban park will grow better than *A. platanoides* and *F. excelsior*. (Heinrichs et al., 2021; C. Zhang et al., 2019) also demonstrated that *T. tomentosa* is an excellent species for future urban tree species that tolerate drought. 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.

Table 11. Means and SDs of urban trees stomatal conductance ($mol \cdot m^{-2} \cdot s^{-1}$) from different locations. The number after the average value is the standard deviation. Lowercase letters indicate significant differences between species and capital letters indicate significant differences between locations, both at a confident level of $p<0.05$.

Species	*A. platanoides*	*F. excelsior*	*T. tomentosa*
Urban Park	0.06±0.03 bA	0.04±0.02 cB	0.10±0.07 aA
Street Site	0.06±0.02 aA	0.05±0.02 aA	0.05±0.02 aB

5.2.4 Optimal Stomatal Conductance Modeling

Several models have been developed to reveal the differences in responses among conductance models, such as the Ball-Berry model (Ball et al., 1987), the Ball-Berry-Leuning model (Leuning, 1995), and the Optimal stomatal conductance model (USO model) (Medlyn et al., 2011). The

Ball-Berry model represents g_s responses to relative humidity, whereas the Ball-Berry-Leuning model and the USO model represent g_s responses to the vapor pressure deficit (Santos et al., 2023). Among these models, the USO model has demonstrated a better fit for predicting photosynthesis activities (Santos et al., 2023). It postulates that stomata should act to maximize carbon gain while minimizing water loss. This model is widely used because it is straightforward to parameterize from the leaf scale to implement at large scales (Medlyn et al., 2011). 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 (Davidson et al., 2022). Furthermore, the stomatal conductance also influenced by vapor pressure deficit. This is because the vapor pressure deficit can explain the variation of transpiration through sap flux densities (Rahman et al., 2017).

Fig. 9 and **Fig. 10** show the average values of g_1 from all species and the relationship between the USO model index. As can be seen from **Fig. 9a**, 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. It is well known that stomatal conductance is correlated with net photosynthesis, but the ratio is species-specific and depends on other factors, such as humidity (Medlyn et al., 2011). After fitting in the USO model (**Fig. 9b**), 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.

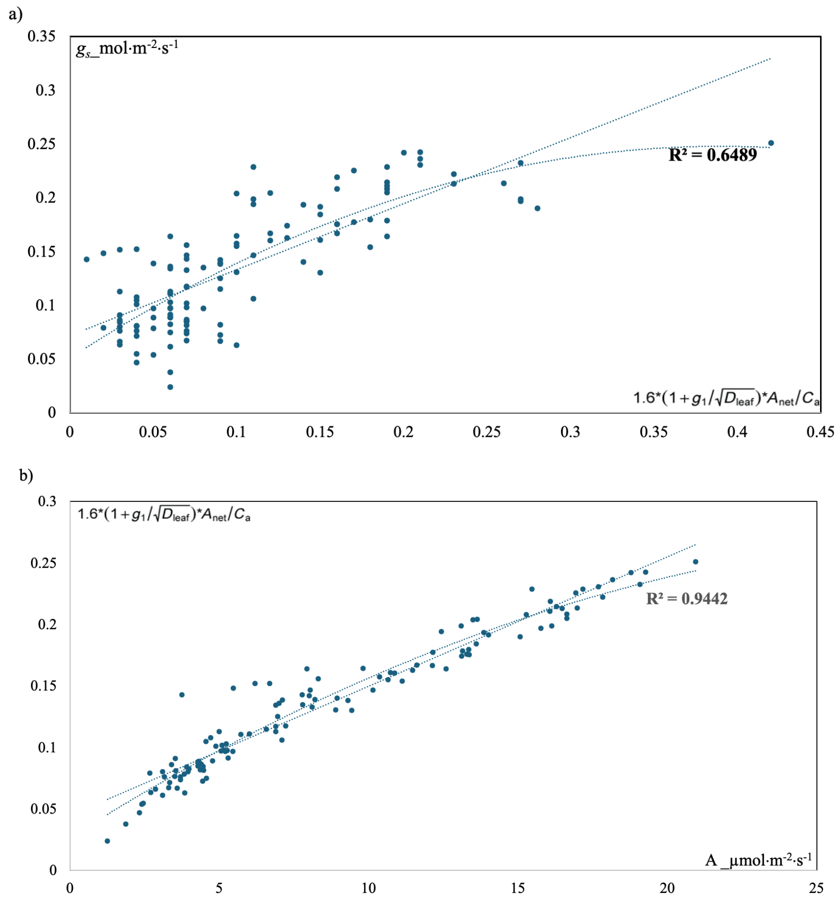

Fig. 9. Relationship between g_s and the USO of urban trees in Budapest (a) and relationship between USO model indexed g_s and net photosynthesis (b). Line splines for the overall linear regression fit of the USO to the measured g_s and indexed g_s to the net photosynthesis.

The detailed relations between g_s and the USO of each species, as well as the USO parameter g_s with net photosynthesis, are shown in **Fig.10**. The slope response (g_1) is proportional to the marginal water cost of carbon gain, which varies with species and environmental conditions (Héroult et al., 2013). In our study, the model intercepts (g_1) of *T. tomentosa* (g_1= 7.54±0.45) and *A. platanoides* (g_1=6.24±0.32) showed a significantly higher value than in *F. excelsior* (g_1= 4.89±0.51). 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). The USO model index and g_1 varied significantly between the species.

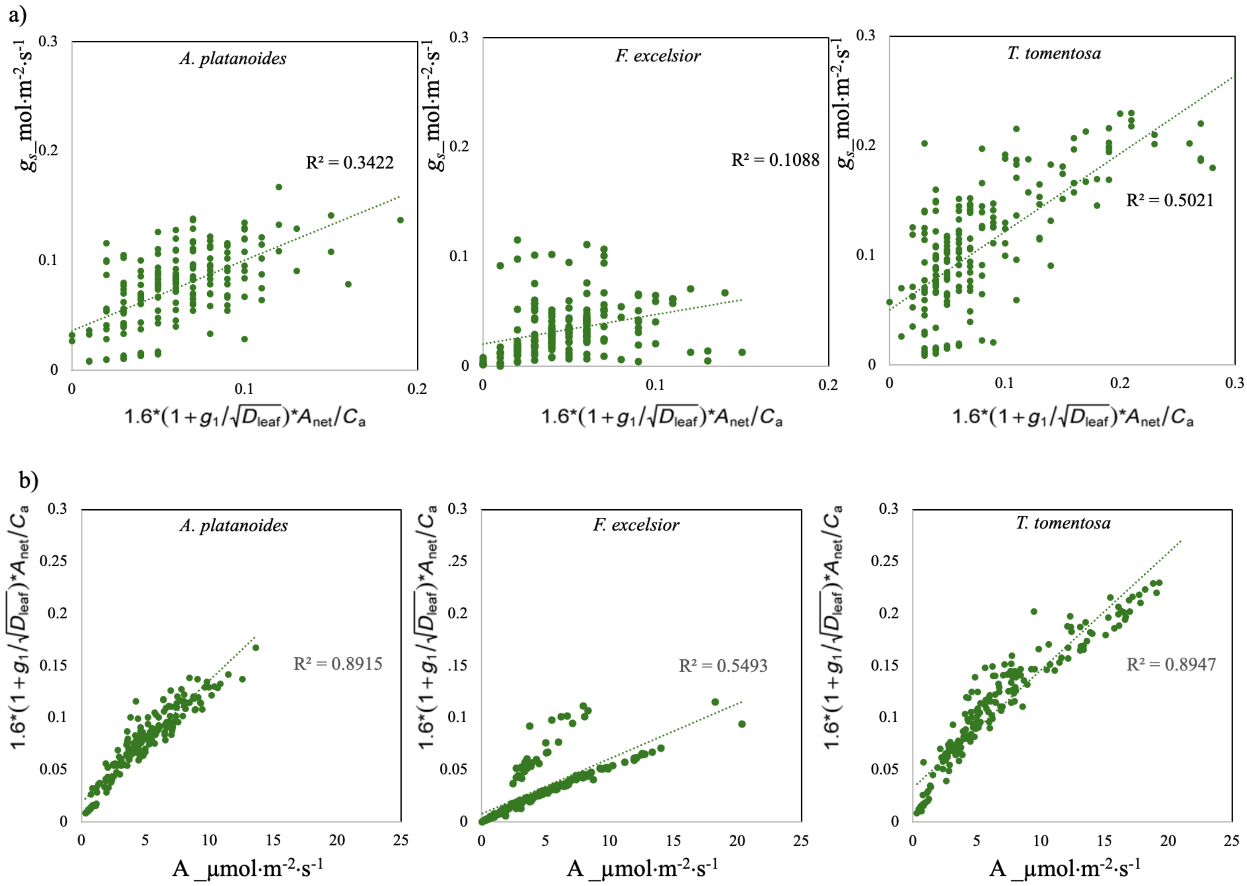

Fig. 10. Relationship between g_s and the USO of different tree species in Budapest (a) and relationship between USO model indexed g_s and net photosynthesis of different tree species (b). Line splines for the overall linear regression fit of the USO to the measured g_s and indexed g_s to the net photosynthesis.

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 reason for this is that when stomata are open, gaseous pollutants such as ozone diffuse into the intercellular space, where they are destroyed by antioxidant reactions (Pace et al., 2021). 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*. This indicates that the variations in slope at the species level, which are observed under optimal watering conditions, are significantly reduced when there is moderate water stress between these two species (Héroult et al., 2013). 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.

The output from this model is useful in understanding how plants adapt to different environmental conditions, which is crucial for predicting plant responses to climate change, improving water-use efficiency in agriculture, and enhancing our understanding of ecosystem carbon and water cycles. Nevertheless, there are significant limitations to the use of these models of stomatal conductance. The overall comparison of physiological parameters, including leaf area, LAI, total leaf areas, as well as their photosynthetic parameters in 2021, suggests that *T. tomentosa* copes better with the current urban stressors in Budapest, followed by *A. platanoides*, and the *F. excelsior* the least.

5.3 Physiological Parameters of Urban Trees in 2022 -2024

Stomatal control is a short-term response to factors such as temperature, moisture, and light. Foliage display is, for the most part, a cumulative response to these same stress factors acting over a longer period. Diurnal and seasonal climatic factors, such as irradiance, temperature, and air humidity, as well as edaphic factors, strongly influence plant water status, water loss, and water usage (Gillner et al., 2017). In addition, the harmful action of dust is determined by the amount of fall, degree of fragmentation, chemical composition, and solubility in water (Krutul et al., 2018). It is also critical to understand how stressful urban environments that urban trees interact with affect tree health and longevity in urban areas, as well as their ability to provide various ecosystem services (Lüttge and Buckeridge, 2023; Roy et al., 2012).

5.3.1 Net Photosynthesis, Transpiration, and Water Use Efficiency in 2022 to 2024

The averages of net photosynthesis, transpiration, and WUE of *A. platanoides*, *F. excelsior*, and *T. tomentosa* from 2022 to 2024 are listed in **Table 12**. The net photosynthesis ranged from 0.15 to 38.75 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 0.24 to 38.27 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and 0.45 to 41.70 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for *A. platanoides, F. excelsior*, and *T. tomentosa*, respectively. Transpiration rate ranged from 0.08 to 4.10 $mmol \cdot m^{-2} \cdot s^{-1}$, 0.26 to 5.05 $mmol \cdot m^{-2} \cdot s^{-1}$, and 0.10 to 6.96 $mmol \cdot m^{-2} \cdot s^{-1}$ for *A. platanoides, F. excelsior*, and *T. tomentosa*, respectively. Whereas WUE ranged from 0.18 to 62.07 $\mu mol \cdot mmol^{-1}$, 0.19 to 63.69 $\mu mol \cdot mmol^{-1}$, and 0.69 to 80.14 $\mu mol \cdot mmol^{-1}$ for *A. platanoides, F. excelsior*, and *T. tomentosa*, respectively. It can be seen that 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.

To compare the differences in years and seasons from 2022 to 2024, the results are shown in **Fig. 11**. 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. Yearly changes do not significantly affect the net photosynthesis of *A. platanoides* and *F. excelsior*. This can be because of their physiological condition already under stress in the conditions in Budapest despite the seasons. All species showed lower net photosynthesis and transpiration is corresponding to the statement of (Yuzbekov and Zuxun, 2019), plants adapt to low air temperatures in autumn by their transition to a dormant state.

Table 12. Means and SDs of physiological parameters of trees in urban areas. (A_ $\mu mol \cdot m^{-2} \cdot s^{-1}$, E _$mmol \cdot m^{-2} \cdot s^{-1}$, WUE_$\mu mol \cdot mmol^{-1}$), Lower case letters indicate the difference between different species at $p < 0.05$.

Species	*A. platanoides*	*F. excelsior*	*T. tomentosa*
A	8.61±7.84	10.06±7.99	14.40±10.37
E	1.23±0.80	1.89±1.09	2.42±1.80
WUE	9.68±11.30	6.99±8.55	9.48±10.96

In plants, CO_2 diffuses into the leaves through stomatal pores on the leaf surface, enabling photosynthesis and serving as the primary interface with the atmosphere. These stomatal pores also allow water vapor to escape from the leaves through transpiration (Tominaga et al., 2018). In urban areas, tree transpiration offers significant ecosystem services, constituting the primary factor in terrestrial heat reduction with estimates indicating that it represents approximately 50% to 90% of the annual global land surface water flux (Berkelhammer et al., 2016; Peters et al., 2010). In terms of net photosynthesis and transpiration, *T. tomentosa* is a superior choice in Budapest. 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 finding aligns with the findings of McCarthy et al., (2011), who found that there were no significant differences in leaf-level WUE among species in a common environment. This also demonstrates their ability to adapt to the drought conditions of the urban areas. The WUE trended upward from spring to autumn, indicating an increase in response to a decrease in water availability (McCarthy et al., 2011). Conversely, during the spring, when precipitation levels were higher, the WUE decreased.

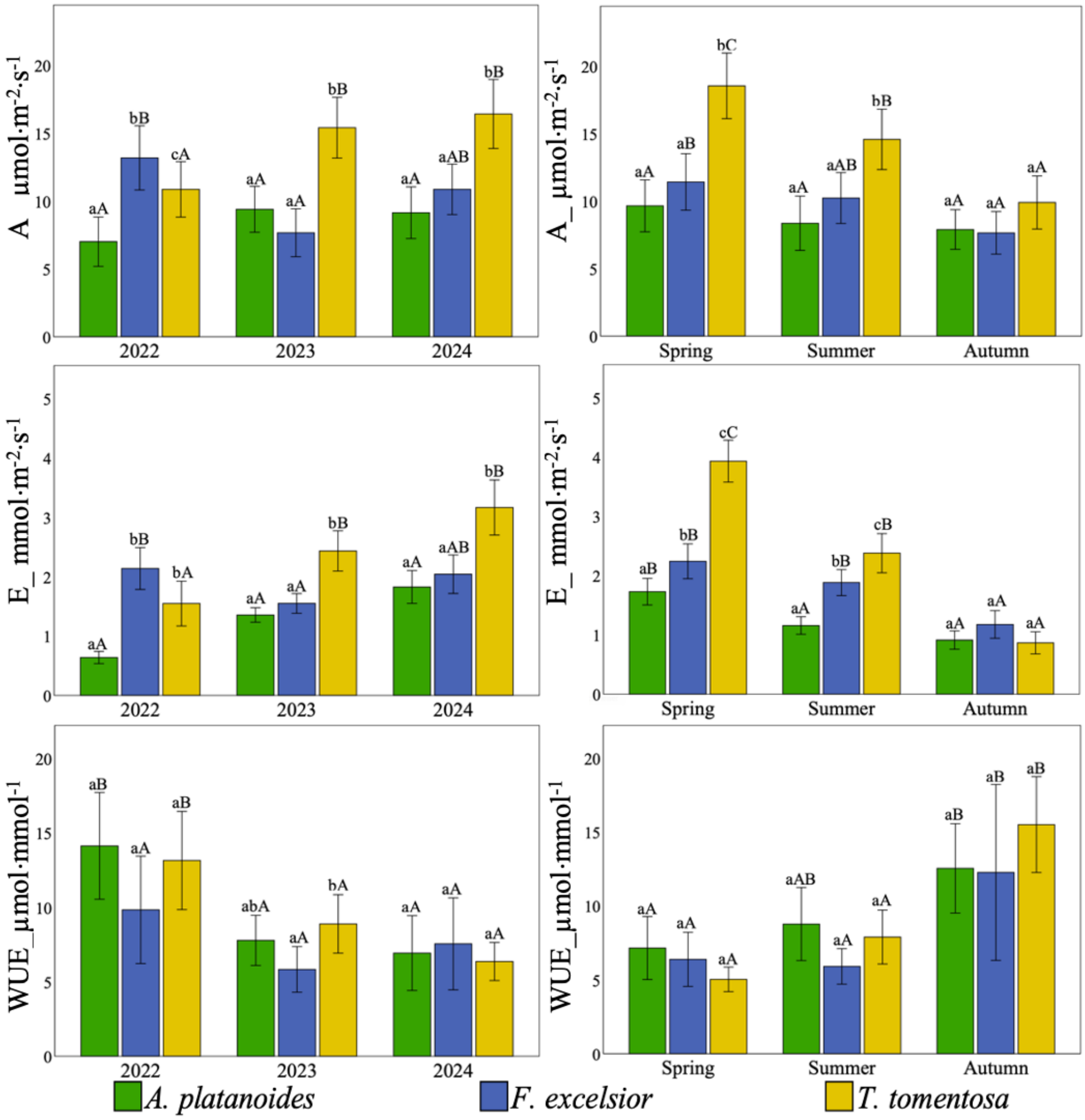

Fig. 11. Comparison of urban trees' photosynthesis parameters between years (leaf) and seasons (right). Lowercase letters indicate Tukey HSD post-hoc test results across different species in the same year or in the same season, and capital letters indicate Tukey HSD post-hoc test results across different years of the same species, both at a confidence interval of $p<0.05$.

5.3.2 Correlation between Leaf Area Index and Photosynthetic Activities

LAI is a vital structural characteristic of vegetation and plays a crucial role in the interaction between it and the climatic system (Fang et al., 2019). **Table 13** lists the results of Spearman's correlation coefficient between LAI and photosynthesis activity parameters. The net photosynthesis is positively correlated (0.37) with transpiration, agreeing with the study of (Yuzbekov and Zuxun, 2019), that the level of transpiration increased or decreased simultaneously with the changes in the intensity of photosynthesis. The significant correlation between LAI and transpiration confirms that canopy structure has a significant impact on tree transpiration rate (Peters et al., 2010). Although few studies have evaluated tree transpiration on a canopy basis, some studies have proof that low transpiration rates are associated with low LAI (Peters et al., 2010). However, no correlation was found between LAI and WUE.

Table 13. Spearman's correlation coefficient (** indicates significant correlation at the level of p<0.01)

	E	WUE	LAI
A	0.370**	0.663**	0.210*
	E	-0.379**	0.483**
		WUE	-0.108

The changes of photosynthesis and transpiration of urban trees are shown in **Fig. 12**. The significant decrease in July coincided with the decrease of LAI (**Fig. 6**). Studies have shown that plant transpiration is related to air temperature, relative humidity, illumination, and the LAI (Li et al., 2020). Climatic variables also influence the estimation of LAI (Fang et al., 2019). 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.

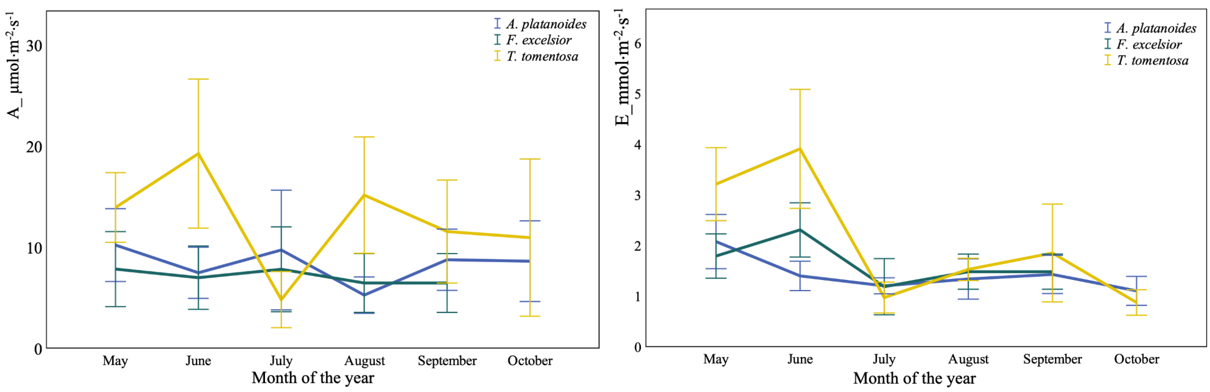

Fig. 12. Urban trees' net photosynthesis and transpiration changes in a vegetation phase. T-bars represent a confidence interval of 95%.

5.4 Fine Particulate Matter Reduction Potential

With rapid urbanization and global climate change, trees have become essential to the climate of urban areas. Cities increasingly recognize them as vital solutions to two major global challenges cities face: mitigating the UHI and improving urban air quality (Fineschi and Loreto, 2020; Grylls and Van Reeuwijk, 2022; Roy et al., 2012). Beyond their role in mitigation and influencing the dispersal and dilution of local pollutants, urban trees provide a unique opportunity to closely study

the chemical and physical characteristics of PM under varying spatial and temporal conditions, as well as local and regional emissions (Castanheiro et al., 2020). Furthermore, not only do vegetation properties and climatic conditions affect the efficiency of particle removal, but they also wash off and resuspend PM into the atmosphere during precipitation events (Pace et al., 2021).
Current literature indicates that studies on urban trees are relatively less common in Europe compared to America or Asia (Roy et al., 2012). Moreover, the interaction between urban trees and their ambient environment is highly dependent on local climate, environmental circumstances, plant growth conditions, and species-specific traits. To address this gap in the literature, our study focuses on the potential of three common woody plant species to accumulate fine PM and TE on urban trees' leaf surfaces in Budapest, which will be beneficial to the Central Europe region in future planning.

5.4.1 Fine Particulate Matter Load on Leaf Surface

Trees, with their extensive leaf surface, retain large amounts of PM on the surface from the surrounding environment to purify contaminated air. We analyzed the effects of different locations on the deposition of fine PM on urban trees, and **Table 14** lists the results. 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. The differences among species were more pronounced at the urban street than at the park. This disparity is likely due to the influence of leaf traits on the wash-off rate, with plants possessing smooth leaves exhibiting higher wash-off compared to those with rough leaves (Weerakkody et al., 2018). 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.

Table 14. Means and SDs of fine PM retention ($\mu g \cdot cm^{-2}$) on leaf surface of urban trees. Capital letters indicate results of independent samples T-test, the difference between two locations in the same species. Lower case letters indicate the results of Tukey HSD test, difference between species at a confident level of $p< 0.05$.

Species	*A. platanoides*	*F. excelsior*	*T. tomentosa*
Urban park	10.25±5.85 abB	13.58±7.64 aB	8.28±4.33 bA
Urban street	23.74±10.18 aA	20.94±17.27 aA	8.87±5.32 bA

Table 15 lists 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.

Table 15. Means and SDs of fine PM retention ($\mu g \cdot cm^{-2}$) on leaf surface of urban trees from 2021 to 2023 with Tukey HSD post-hoc test results (*n*=432). Capital letters indicate the difference between different years in the same species; lower case letters indicate the difference between different species, both at a confident level of $p < 0.05$.

Species	*A. platanoides*	*F. excelsior*	*T. tomentosa*
2021	2.74±1.53 aA	2.96±2.02 aA	3.68±3.38 aA
2022	17.11±10.70 aC	17.19±13.67 aB	8.57±4.82 bB
2023	10.02±6.03 bB	34.43±21.40 aC	9.00±6.74 bB

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. The difference maybe impacts by the different environmental factors, such as location and precipitation amount. Since the wash-off of PM depends on the precipitation amount, size of PM, and closely related plant species (Xu et al., 2020).

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. It can correspond to a higher amount of precipitation, the fine PM wash-off mass is positively correlated with the amount of precipitation (X. Xu et al., 2019). 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*, there was no difference discovered between 2022 and 2023.

We further compared the wash-off fine PM deposition of urban trees in each season from 2021 to 2023; the results are shown in **Fig. 13**. 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. Thus, deciduous trees in urban area leaf fall does not have difference among species. This aligns with the observation that during autumn leaf senescence, the PM stored on leaf surfaces eventually returns to the ground (X. Xu et al., 2019). Therefore, most healthy urban trees contribute to fine PM retention, regardless of the species. However, there is no literature that has evaluated this potential of urban trees in urban areas for the reduction of ambient fine PM yet. Therefore, conducting further evaluation studies would provide valuable insights into this matter.

In 2022, the wash off fine PM concentration was ranged from 1.01 to 67.46 μg·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*. As can be seem from **Fig. 3**, 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 (Schaubroeck et al., 2014; H. Xu et al., 2019; Xu et al., 2020).

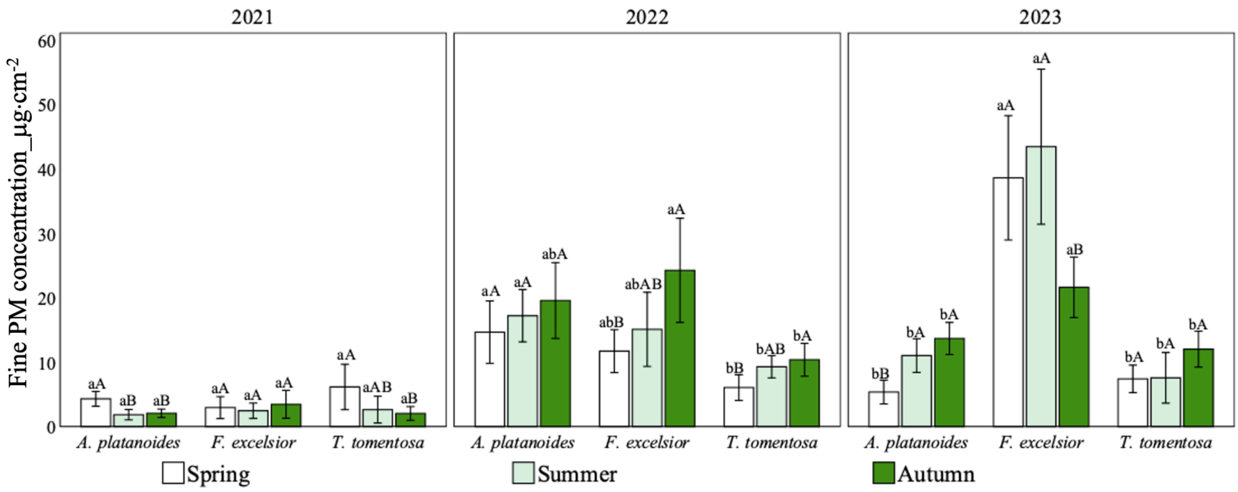

Fig. 13. Comparison of fine PM deposition from urban trees in Budapest in different seasons from 2021 to 2023. Lower case letters indicate the results of Tukey HSD post-hoc test between species at the same sampling season in each year; capital letters indicate results of Tukey HSD post-hoc test of different season in each year from same species; both represent at confidence interval of $p<0.05$.

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. The constant performance of *T. tomentosa* further confirm that environmental factors do not strong impact on the fine PM wash off rate from *T. tomentose*. 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. Differences in location between Budai Arborétum and Deák Ferenc tér, as well as environmental factors like precipitation and wind, did not significantly affect the wash-off of fine PM from *T. tomentosa* leaves. This consistency in PM retention can be attributed to the species-specific characteristics of plant leaves. Research has shown that different plant species exhibit varying capacities to retain PM, particularly smaller particles like $PM_{2.5}$, which tend to adhere more strongly to leaf surfaces than larger particles like PM_{10} (Shao et al., 2019). The accumulation of particles on leaf surfaces is influenced by species-specific traits, including the presence of trichomes, epicuticular waxes, and surface roughness (Pace et al., 2021). Leaves with trichomes and wax accumulations are particularly effective at retaining PM, often holding onto smaller particles regardless of precipitation intensity (Pace et al., 2021).

While leaf traits play a crucial role in capturing PM, currently literature are focus on species which having hairy surface to address their potential in capturing PM on the leaf surface (Abhijith and Kumar, 2020; He et al., 2020; Jia et al., 2021; Kończak et al., 2021). However, plants interact with the ambient is a complex dynamic process. Since most particles are not taken up inside leaves through their stomata, plants serve manly as an intermediary sink to store PM with could be washed off by rain, resuspended by wind or fall back to groud via leaf senescence in autumn (Cai et al., 2019; X. Xu et al., 2019). 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.

5.4.2 Relationship Between Fine Particulate Matter Deposition and Microclimatic Conditions

Ordination is a frequently used technique in ecology that seeks to describe intricate biological data in a space with fewer dimensions (Capblancq et al., 2018). RDA is a statistical technique that is particularly effective in identifying adaptive variation. Studies showed that the observed variations of PM deposit were partly caused by tree-regulated microclimate condition in the urban canyon (Miao et al., 2021). In addition, (Cai et al., 2017) demonstrated that PM deposition to leaves was in a dynamic equilibrium with the environment after 10 days of no precipitation, while 6 days were identified by (Mitchell et al., 2010). We obtained 10 days of environmental data ahead of each sampling date to discover their impacts on the fine PM deposition.

The RDA allowed us to confirm the relationship between fine PM concentration and microclimatic conditions at urban park and street site in 2022 (**Fig. 14**). Eigenvalues associated with RDA axis 1 and 2 were 43.8% and 45.1%, for urban park and street ($p=0.002$), respectively. 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, this is agreed with the climate characters in Budapest the precipitation majority fall in the end of spring and summer time. 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 that the Monte Carlo permutation tests were significant ($p=0.002$) while 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. It has been reported that 27-36% of the accumulated PM on leaves can be resuspended by strong winds, in some study even up to 76% (Wang et al., 2015; Xu et al., 2020). Whereas precipitation can remove PM deposition by 28% to 70%, depending on the amount of precipitation (Wang et al., 2015).

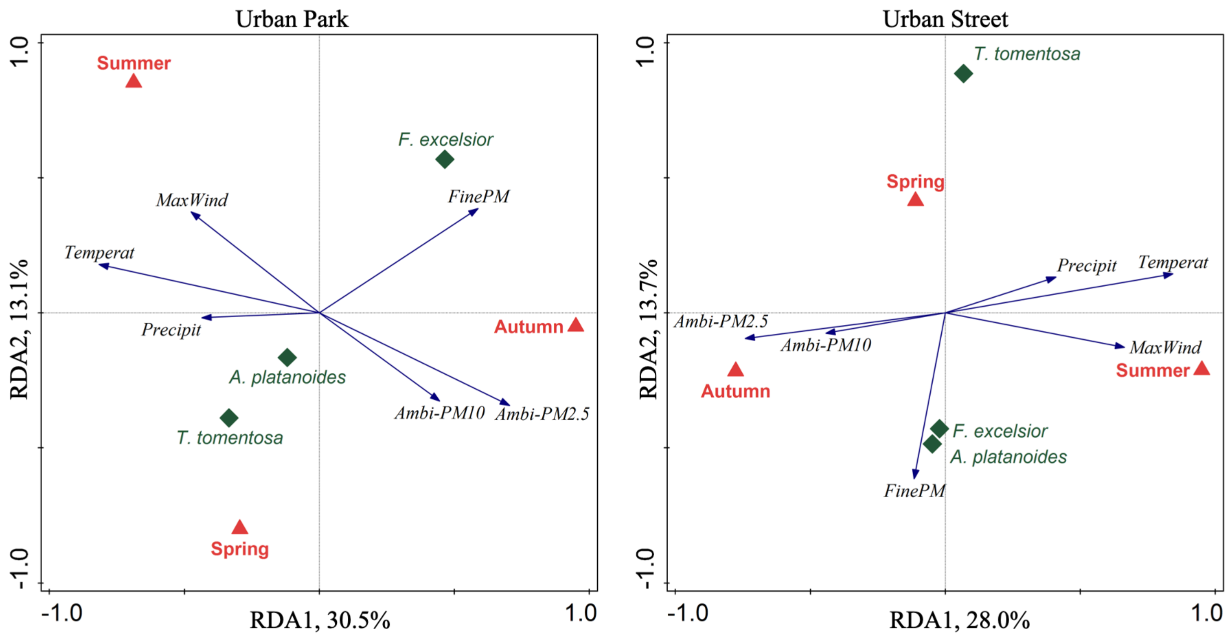

Fig. 14. Biplot of RDA ordination plot of urban trees PM adsorption potential (n=180) at urban park (Budai Arborétum) and street site (Deák Ferenc tér) in 2022. Arrows indicate the fine PM deposit on unit leaf surface (Fine PM), the ambient $PM_{2.5}$ concentration (Ambi-PM2.5), ambient PM_{10} concentration (Ambi-PM10), max wind speed (Max Wind), precipitation (Precipit), and temperature (Temperat). RDA1 and RDA2 axis accounted for 30.5%, 13.1% and 28.0%,13.7% of the total explained variation in PM deposition, respectively (F=9.6, p=0.002).

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*. Both plant species and interactions with rainfall or wind can contribute to fine PM accumulation on leaf surface (X. Xu et al., 2019). Although the results suggest that the load of fine PM on leaf surface were significant influenced by average temperature, wind speed, and precipitation. However, the influences of wind and precipitation, the maximum retention values could exceed minimum values by 10 folds, some study found that PM retention reached a saturated maximum after 24 days, thus, the PM retained by plant leaves over time are complex dynamic processes (Xu et al., 2020). Thus, our results agree with that the correlations between PM concentration with average temperature, relative humidity and average wind speed are very low (Aksu, 2015). And it is hard to evaluate a plant potential in trapping fine PM on the leaf surface.

Rainfall not only remove PM from leaf surface, but also facilitated PM accumulation on leaf surfaces when PM concentrations was high (X. Xu et al., 2019). Compared to 2022, the precipitation in 2023 was higher and distributed in different times, the accumulation of PM leaf surface thus become shorter. Moreover, air humidity and wind direction also significantly influence the fine PM accumulation on leaf surface, higher air humidity is more likely to promote collision-coalescence for fine PM and wind direction that parallel to street direction removes PM more efficiently (Miao et al., 2021). Decision-making to add green infrastructures in urban areas should consider a multidisciplinary work between botanists, architects, urban designers, and air pollution experts. The decision to add green infrastructure to streets should consider botanical (e.g. species, type of GI, leaf traits), weather conditions (e.g. rainfall duration and intensity, wind) and external parameters (e.g. location, seasonality) in order to successfully maximize PM removal (Corada et al., 2021). The influences of fine PM load on leaf surface impact on the plants physiological was further discussed.

5.4.3 Impact of Fine Particulate Matter Deposition on Physiological Activities

The RDA analysis results of fine PM deposition on leaf surface in 2023 (**Fig. 15**) Budai Arborétum (*n*=180). The initial DCA supported (gradient length were 0.89 and 0.59) the use of RDA, and the RDA model itself is robust and statistically significant (F=8.6, p=0.002). This 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. *F. excelsior* is positioned far from the environmental variables, which might indicate that these species are less influenced by the measured environmental factors or are influenced by different factors not included in the analysis.
A. platanoides and *T. tomentosa* are closer to certain environmental vectors, suggesting they are more influenced by these factors. Furthermore, the RDA results further confirm the correlation between LAI and transpiration, LAI and net photosynthesis.

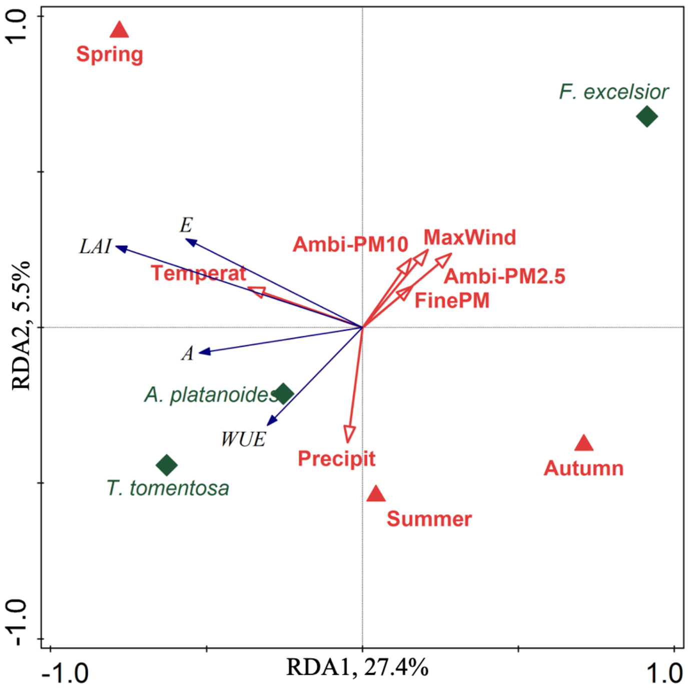

Fig. 15. Biplot of RDA analysis ordination plot of urban trees PM adsorption potential (*n*=360). Arrows indicate the fine PM deposit on unit leaf surface (Fine PM), the ambient $PM_{2.5}$ concentration (Ambi-PM2.5), ambient PM_{10} concentration (Ambi-PM10), max wind speed (Max Wind), precipitation (Precipit), and temperature (Temperat). RDA1 and RDA2 axis accounted for 27.4% and 5.5% of the total explained variation in PM deposition, respectively (F=9.6, p=0.002).

5.4.4 Total Potential of Fine Particulate Matter Retention in Budapest

The emission, transport, and interaction of air pollutants within cities are major contributors to the rising air pollution problems in today's urbanized societies (Abhijith et al., 2017; Cao et al., 2011). Because of the slow sedimentation rate and long-range transport of fine PM, it is hard to eliminate and poses a serious threat to human health (Ferenczi and Bozó, 2017; Yin et al., 2019). The implementation of urban tree planting is widely recognized as a significant strategy for the phytoremediation of ambient PM pollution on a global scale, including in the city of Budapest. According to the database of the European Environment Agency (EEA), of the total area (526 km2) in Budapest, representing 136.5 km^2 (European Environment Agency, 2024; Tóth-Ronkay et al., 2015). However, given the temporal and spatial variability of both tree structure and PM deposition, these figures are only approximate.

We used the average data obtained in our study. LAI and fine PM deposition of all trees were 5.03 and 5.56 $\mu g \cdot cm^{-2}$ respectively. This suggests that, at a given time, the tree cover in Budapest could capture up to 38.17 tons of fine PM. If considering the spatial factor, the potential of the tree cover could contribute significantly to fine PM removal. However, since the artificial surface is the main land cover type in Budapest, it accounts for 66.21% of the total land. The dynamic $PM_{2.5}$ significant response to land cover type, with highest in artificial surfaces areas and lowest in forested regions (Yang and Jiang, 2021). Thus, while tree cover can significantly contribute to PM reduction, achieving large-scale fine PM reductions in Budapest requires additional strategies. According to the GlobeLand 30 database, as shown in **Fig. 1**. The artificial surface is the main land cover type in Budapest, accounting for 66.21% of the total land. This percentage is more than double the combined area (30.62%) of cultivated land, forest, shrubland, and grassland. And the ratio is believed continue to increase (Buzási, 2022). 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.

There is still lack of an effective system to evaluate the relative efficiency of different plants in reducing airborne PM pollution in urban area (Xu et al., 2020). In addition to the leaf traits, this has emphasized that ancillary factors and the context of plantings are of substantial influence on PM capture (Corada et al., 2021). Any technique using leaves as passive samplers of airborne PM will need to be accurate, precise, repeatable, reproducible, and chemically informative (Baldacchini et al., 2019). Although it is understood that urban tree retention of PM is a sustainable strategy, it can reduce atmospheric PM concentrations and improve human health (Chen et al., 2017). However, 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.

5.5 Chemical Properties of Wash-off Fine Particulate Matter and Soil

5.5.1 Chemical Properties of Fine Particulate Matter

Fine PM has different chemicals depending on where it comes from, how the atmosphere changes (evaporation and condensation), chemical reactions, and plants moving around (Alwadei et al., 2022). However, it is agreed that changes in the chemical components of PM can basically reflect its sources and characteristics (Y. Wang et al., 2019). Understanding the chemical characteristics of fine PM deposits in detail can help to evaluate their toxicity and facilitate the implementation of policies aim at air pollution retention from specific emission sources (Alwadei et al., 2022; Y. Wang et al., 2019).

Fig. 16 presents the analyzed chemical characteristics of fine PM in Budapest. The pH values of fine PM suspension ranged from 4.62 to 7.71, with some falling outside the typical range for natural rainwater (5.0-5.6), though the deviations were not substantial. In contrast, the electrical conductivity (EC) values ranged from 15.99 to 732.1 $\mu s \cdot cm^{-1}$, significantly exceeding the guideline for natural rainwater (0-50 $\mu S \cdot cm^{-1}$). These EC values fell within the range reported by previous studies conducted in different cities worldwide, 100 to 2800 $\mu S \cdot cm^{-1}$(Rehman et al., 2023).

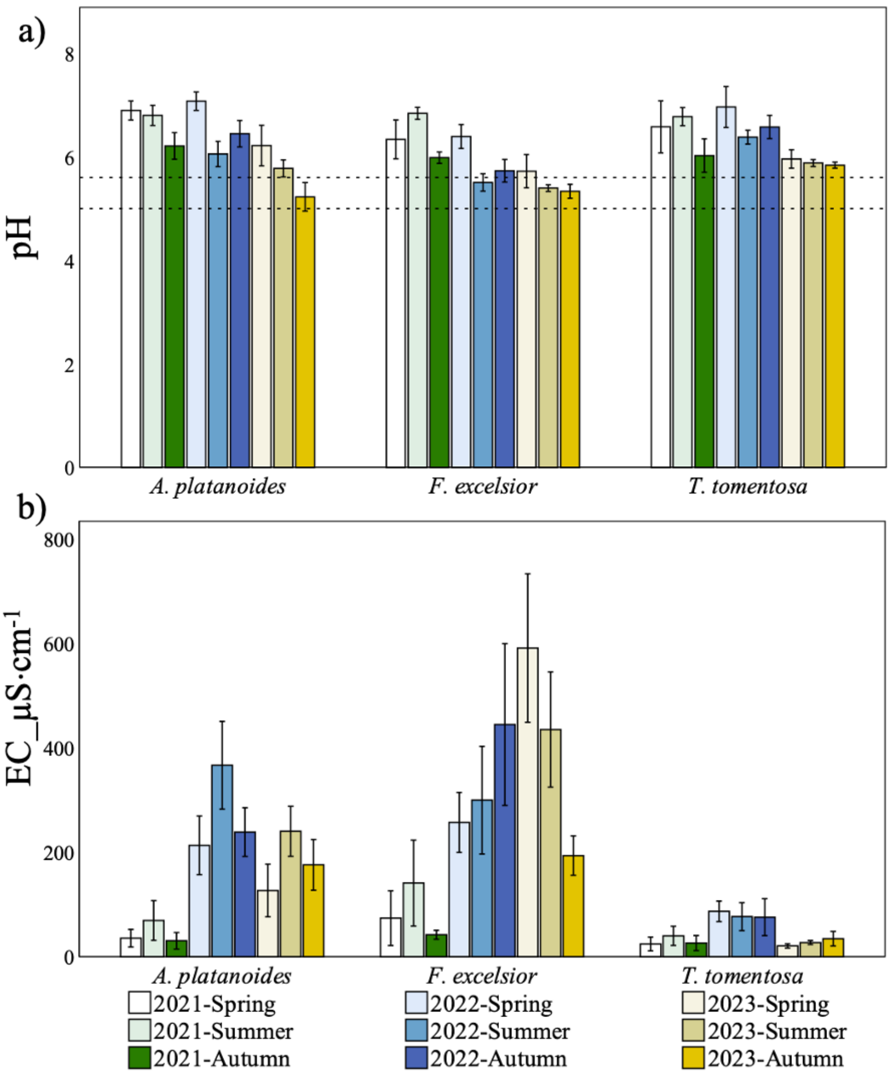

Fig. 16. The pH (a) and EC (b) of wash-off fine PM suspension from urban trees in Budapest from 2021 to 2023. T-bars represent SDs at the confidence interval of 95%, in reference lines in (a) represent of pH 5.0 and 5.6.

Since the increased EC is likely to be mainly of secondary origin (Alwadei et al., 2022), we can conclude that the changes in EC in the wash-off suspension are results of PM retentions on urban trees. 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. In 2021, although the contents differed in different species, however they showed a similar trend of seasonal changes among all species. This can be attributed by the dry samples of different species does not differ one each other of wash off ability. Whereas, in 2022 and 2023, the contents varied among different species as well as seasonal changes. In constant to the above-mentioned fine PM wash off concentration, *A. platanoides* and *F. excelsior* showed higher fine PM wash-off.

The dominant water-soluble ions of fine PM suspension are NH_4^+, NO_3^- , SO_4^{2-}, and Cl^-, account for up to 80% of the total concentration (Correa et al., 2023). **Fig. 17** shows the concentration of different ions (NH_4^+, NO_3^- , SO_4^{2-}, and Cl^-) in the leaf surface washed off fine PM suspensions. 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 and demonstrated a concentration of NH_4^+1.2 mg·L^{-1} and NO_3^- 1.9 mg·L^{-1}. Since the ambient PM$_{2.5}$ generates from different sources, the concentration of NH_4^+ was 3.3 mg·L^{-1} to 5 mg·L^{-1}, which was higher than that in Budapest (Alwadei et al., 2022). The total ion content was corresponded to the EC value, *A. platanoides* and *F. excelsior* always higher than *T. tomentosa,* except in Autumn of 2022.

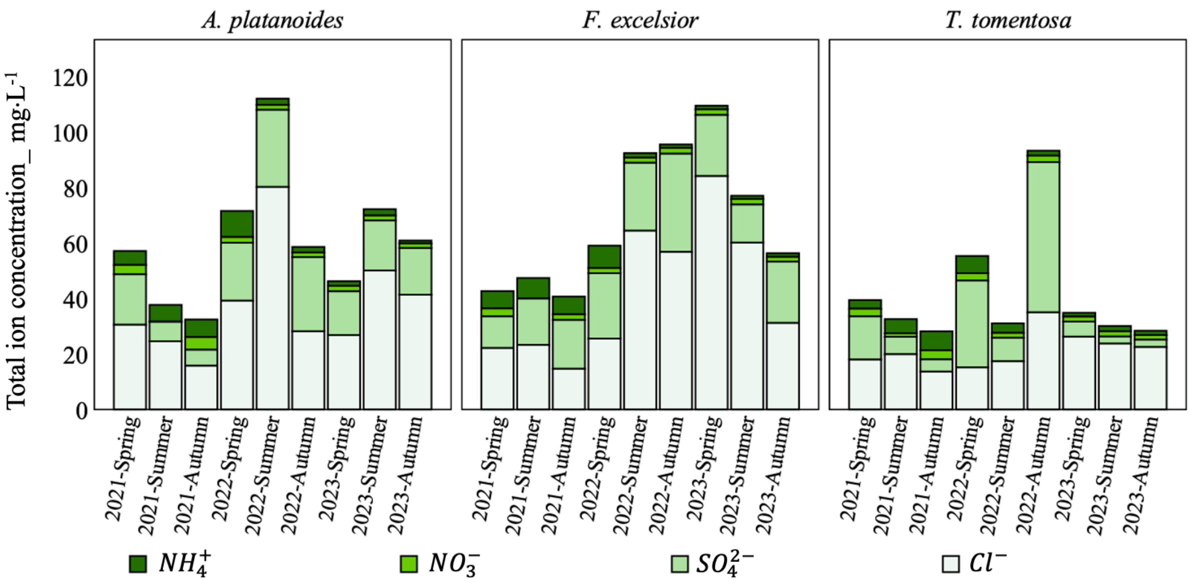

Fig. 17. The ion concentration of fine PM suspension from urban trees from 2021 to 2023.

Fig. 18 presents 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.

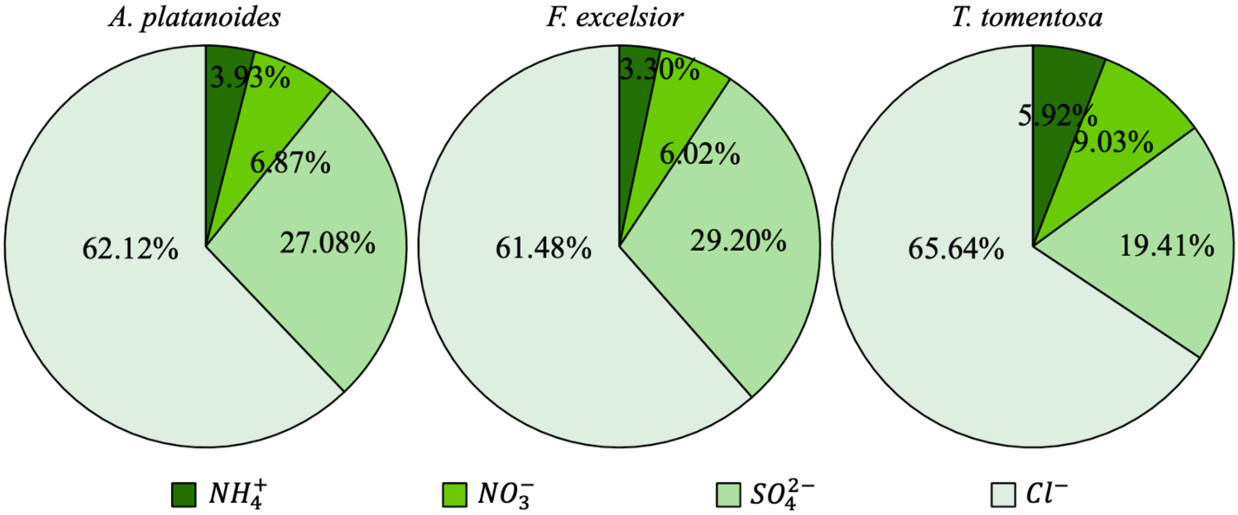

Fig. 18. Proportions of major ions in fine PM accumulation on leaf surface of urban trees from 2021 to 2023.

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 (Kolesar et al., 2018). 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 (Kolesar et al., 2018). Road salt aerosols are like a large, uncharacterized, source of chloride in the inland urban atmosphere, especially in winter (Kolesar et al., 2018). Similar to (Baricza et al., 2016), we also detected high concentration of sulfate. 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. When SO_2 interacts with Ca- and Na-bearing particles (e.g., calcite, feldspar), it readily leads to the formation of gypsum or other sulphate minerals. which might be because the stronger solar radiation increased the formation of OH radicals and promoted the formation of secondary sulfate (Samek et al., 2020). Compared to the concentration of SO_4^{2-}in the air, which ranged from 2.44 to 6.35 $\mu g \cdot m^{-3}$ (Samek et al., 2020), this demonstrates the accumulation of SO_4^{2-} on the leaf surface. In the study of (Alwadei et al., 2022), SO_4^{2-} showed significant difference between different location, 7 $mg \cdot L^{-1}$ at the city center and 87 $mg \cdot L^{-1}$ at a university at the same sampling time. This indicates the primary sources of SO_4^{2-} and Cl^- are anthropogenic (Samek et al., 2020). Therefore, 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.

To discover whether the two locations contribute to the difference of chemical components of fine PM suspension, the results of comparison are present in **Fig. 19**. As shown in the graph, 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 a urban park and a urban street.

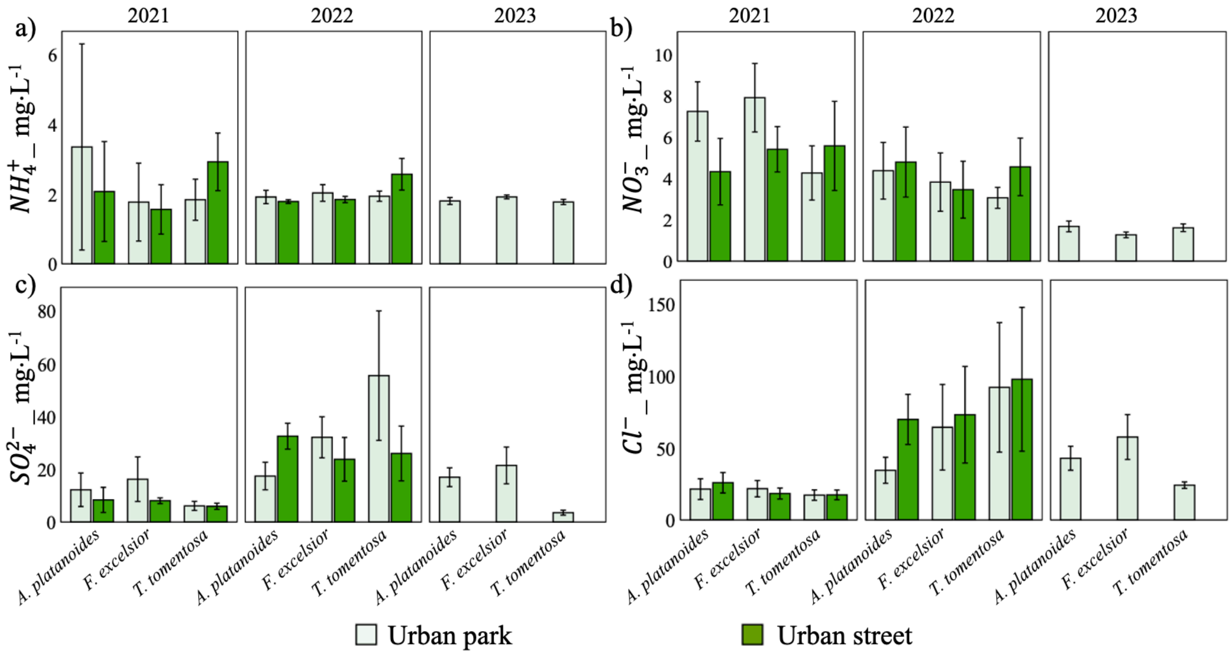

Fig. 19. Comparison of major ions of fine PM deposition between two different locations in 2021 to 2023. (a) NH_4^+_ mg·L-1, (b) NO_3^-_ mg·L-1, (c) SO_4^{2-}_ mg·L-1, and (d) Cl^-_ mg·L-1. T-bars represent SDs at the confidence interval of 95%.

5.5.2 Chemical Properties of Soil

Soil plays a crucial role as a medium for plant growth and acts as a sink for ambient PM, making it a key component in the sustainable development of urban environments. Urban soils undergo substantial alterations in their physical, chemical, and biological properties, which can significantly influence the growth and health of urban trees (Kumar and Hundal, 2016;

Scharenbroch et al., 2005). Therefore, it is essential to accurately assess the characteristics of urban soils to better understand their impact on urban ecosystems.

The soil samples (*n*=69) from 2021 to 2023 from urban trees plantations are listed in **Table 15**. The overall pH_1 and pH_2 values 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 higher pH in urban soil can be explained by the presence of artefacts, particularly alkaline construction waste with high limestone content (Mónok et al., 2021). The EC values also elevated, with average of 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. Ammonium (NH_4^+) and nitrate (NO_3^-) were all in a similar range among all species. Phytoavailable potassium (K_2O) and phosphorus (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. This indicates high spatial variability of K_2O and P_2O_5, and large local differences in availability (Della Chiesa et al., 2019). It also agrees with that parks and street sites might found higher potassium and phosphorus concentration (Mónok et al., 2021; Scharenbroch et al., 2005).

Table 15. Descriptive statistics of the chemical properties of soil from urban tree plantations. The pH was measured using two different solvents: pH_1 was determined using water, while pH_2 was measured using KCl solution; EC_ µs·cm^{-1}; humus_%; NH_4^+_mg·L^{-1}; NO_3^-_ mg·L^{-1}; K_2O _mg·kg^{-1};and P_2O_5_ mg·kg^{-1}.

Species	*A. platanoides*	*F. excelsior*	*T. tomentosa*
pH_1	8.04±0.65	7.95±0.53	8.08±0.41
pH_2	7.46±0.49	7.44±0.45	7.44±0.40
EC	166.90±64.94	180.95±74.00	176.67±66.61
Humus	4.15±1.88	3.22±1.04	4.68±1.40
NH_4^+	2.19±2.14	1.94±1.79	1.96±1.68
NO_3^-	3.86±4.54	3.80±4.64	3.29±3.51
K_2O	721.89±440.06	496.61±185.87	927.45±556.81
P_2O_5	550.82±165.24	578.41±218.83	620.72±170.16

Table 16 shows the chemical properties of the urban park and the urban street from 2021 to 2023. The pH value and EC were similar at both locations. The humus content, phytoavailable potassium

(K_2O) and phosphorus (P_2O_5) were higher at the urban park. In contrast, the ammonium (NH_4^+) and nitrate (NO_3^-) were higher at the urban street. This shows a slight better soil nutrient from the urban park than the urban street. Since anthropogenic activities can contribute to higher pH of soils, the modifications can adversely affect many chemical and biological processes in soil (Mónok et al., 2021). It is understandable that the urban trees are experiencing poorer soil conditions at streets than at parks.

Table 16. Descriptive statistics of the chemical properties of soil from Budai Arborétum (urban park) and Deák Ferenc tér (urban street). The pH was measured using two different solvents: pH_1 was determined using water, while pH_2 was measured using a KCl solution; EC_ us·cm^{-1}; humus_%; NH_4^+ _mg·L^{-1}; NO_3^- _ mg·L^{-1}; K_2O _mg·kg^{-1};and P_2O_5_ mg·kg^{-1}.

Species	Urban park	Urban street
pH_1	8.16±0.43	7.82±0.62
pH_2	7.39±0.39	7.54±0.50
EC	169.74±69.15	182.78±66.33
Humus	4.51±1.72	3.24±0.93
NH_4^+	1.91±1.52	2.21±2.27
NO_3^-	2.88±3.43	4.85±5.02
K_2O	875.93±506.24	465.47±164.20
P_2O_5	634.43±196.26	503.80±137.08

5.6 Translocation of Trace Elements in Urban Trees

TE, which TE pollution has the potential to become a persistent problem globally, with its prevalence increasing (Aksu, 2015). The elemental analysis of leaf tissues also provides data on elemental concentrations in the environment (Simon et al., 2011). In this study, we measured the elemental concentration from fine PM wash-off, soil, and different tissues of urban tree to access the anthropogenic impact along the urbanization gradient. Environmental pollution has no effect on the distribution of structural wood components (lignin, cellulose, and hemicelluloses) on the trunk's cross- and longitudinal sections, as well as in the bark. Apart from the species, it influences the content and distribution of elements classified as macro-, micro-, and TE (Krutul et al., 2014; Watmough and Hutchinson, 2002). Raised concentrations of Pb (24 mg·kg^{-1}) and Sr (158 mg·kg^{-1}) were specified in Norway maple bark from polluted areas, high contents of Fe (455 mg·kg^{-1} in bark and 330 mg·kg^{-1} in roots), and Al (300 mg·kg^{-1} in bark and 290-376 mg·kg^{-1} in roots) were also stated (Krutul et al., 2014).

The structure of each tissue and the contamination of ambient air significantly influence the quantity of TE in these tree tissues (Kosiorek et al., 2016). The mineral substance content of bark is always greater than that of wood; polluted trunk sapwood and bark contain more mineral substances than unpolluted trunk sapwood and bark (Krutul et al., 2014).

5.6.1 Trace Elements in the Environment and the Urban Trees

The concentration of TE in the environment can significantly influence the translocation and accumulation of TE in urban tree. The measured concentration of TE in the fine PM suspension and soil are listed in **Table 17** and **18**. 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.

Table 17. Descriptive of TE contents (mg·kg^{-1}) in the fine PM of urban trees in Budapest.

Species	Cu	Fe	Ni	Pb	Zn
A. platanoides	19.49±23.16	21.04±15.57	20.19±19.35	18.38±36.68	5.11±4.96
F. excelsior	10.46±8.95	19.58±22.62	12.33±12.02	13.56±24.42	3.09±3.01
T. tomentosa	46.64±37.94	31.25±24.47	45.29±29.18	14.33±32.57	11.46±9.00

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. Their descriptive statistics and geo-accumulation are listed in **Table 18**. 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. In addition, the content of Ni and Zn were higher the Hungarian soil background values, 27 mg·kg^{-1} and 53 mg·kg^{-1}, respectively (Rékási and Filep, 2012). The Zn level varied significantly among the samples, perhaps due to the absence of homogeneous mixing and stratification in urban soil. Consequently, certain regions have elevated concentrations of Zn, while others display markedly low concentrations.

Compared to the study of Mónok et al., (2021), who had examined soil samples from urban sties and green-urban sites in Budapest, our results showed lower concentration of Cu and Pb, but higher contents of Fe, Ni, and Zn. The decreased of Pb can be attribute to the banned of leaded petrol (Simon et al., 2014).

Table 18. Descriptive of TE contents ($mg \cdot kg^{-1}$) in soil and geo-accumulation in Budapest.

Species	Cu	Fe	Ni	Pb	Zn
A. platanoides	19.05±0.18	1382.48±43.04	131.94±37.60	37.59±14.24	363.11±406.26
F. excelsior	19.14 ±0.16	1355.37±46.99	149.53±31.92	40.76±10.38	183.20±232.83
T. tomentosa	19.19±0.15	1387.10±65.71	155.48±22.11	32.42±17.07	300±334.72
I_{geo}	-0.57±0.01	-3.71±0.05	1.80±0.36	0.10±0.65	-1.07±4.14
Range of I_{geo}	< 0	< 0	1-2	0-1	< 0

TE, which constitute a minor proportion of the PM with V, Cr, Mn, Ni, Cu, As, Cd, and Pb, were predominantly released from industrial activities (H. Xu et al., 2019). We processed an MANOVA test to evaluate the effects of factors (location, species, year, and season) on the TE concentrations. The MANOVA revealed significant effects for year was significant (Wilks' lambda=0.019, F(10, 766)=480.25, p=0.000, η2=0.86), indicating a strong group-level influence on the dependent variables. The effect of the season (Wilks' lambda=0.363, F(10, 766)=50.53, p=0.002, η2=0.39) and species (Wilks' lambda=0.434, F(10, 766)=39.67, p=0.002, η2=0.34) were significant too, suggesting that the influence of species varied across species and seasons. Additionally, the effects of location (Wilks' lambda=0.828, F(5, 383)=15.95, p<0.001, η2=0.17) was significant, though the effect size was moderate. Since year is the most significant factor affect the TE content from the fine PM suspension, suggests that the source is the most important factor that determine the differences of the TE in the ambient PM pollution.

We compared the differences of TE content from wash-off fine PM at different locations, the results as shown in **Fig. 20**. 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. It agrees with the finding of other studies that in the urban environment of Budapest, the pollution sources between urban parks and urban streets exhibited no significant difference for the TE content from PM wash-off from urban trees (Hrotkó et al., 2021).

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*.

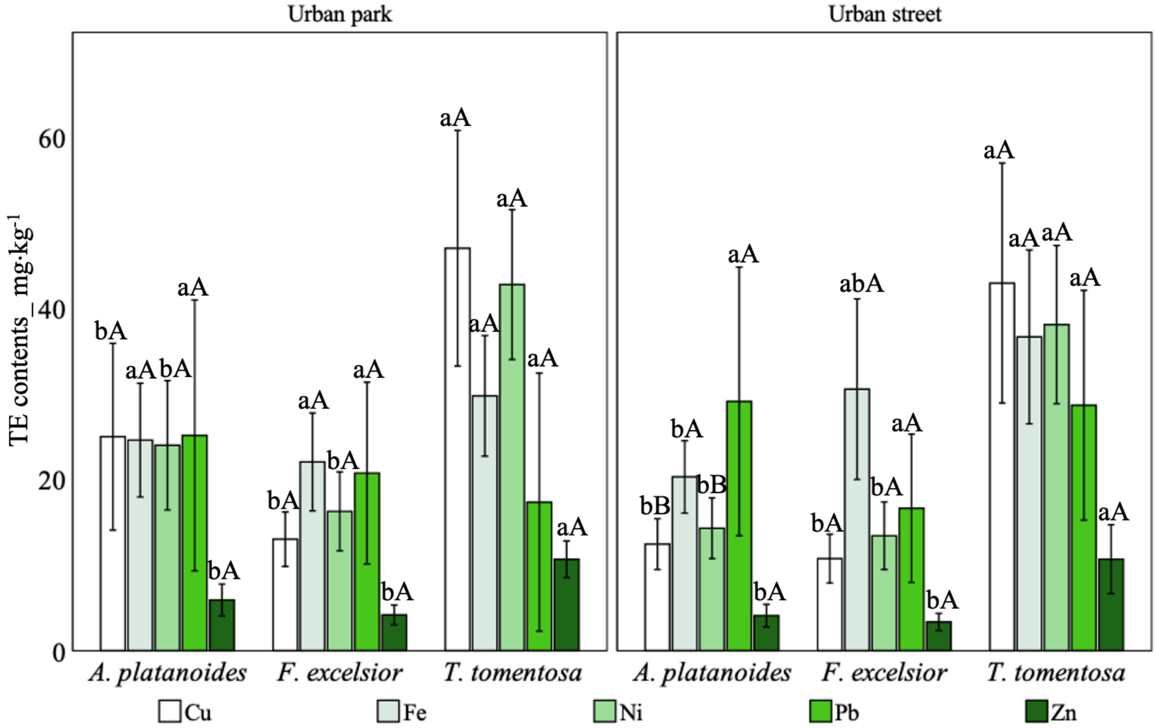

Fig. 20. TE contents of fine PM of urban trees in Budapest from different locations. Lower case letters indicate the results of Tukey HSD post-hoc test between species at the same location; capital letters indicate results of independent T-test of location from same species; both at the level of $p<0.05$.

The seasonal changes of TE concentrations in different species from 2021 to 2023 are shown in **Fig. 21**. 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 variation in TE concentrations across different seasons can largely be attributed to unfavorable meteorological conditions that limit the dispersion of air pollution, assuming industrial activities or traffic remain consistent throughout the year (Popek et al., 2018; H. Xu et al., 2019). 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 (H. Xu et al., 2019). In another study, Muhammad et al., (2020) examined the immobilization of atmospheric particulate matter on leaves of 96 urban plant species, noting that lead concentrations were significantly higher in areas with heavy traffic, which correlates with increased deposition of PM. Thus, the unpreferable meteorological conditions couple with heavy traffic resulting in elevated Pb concentration.

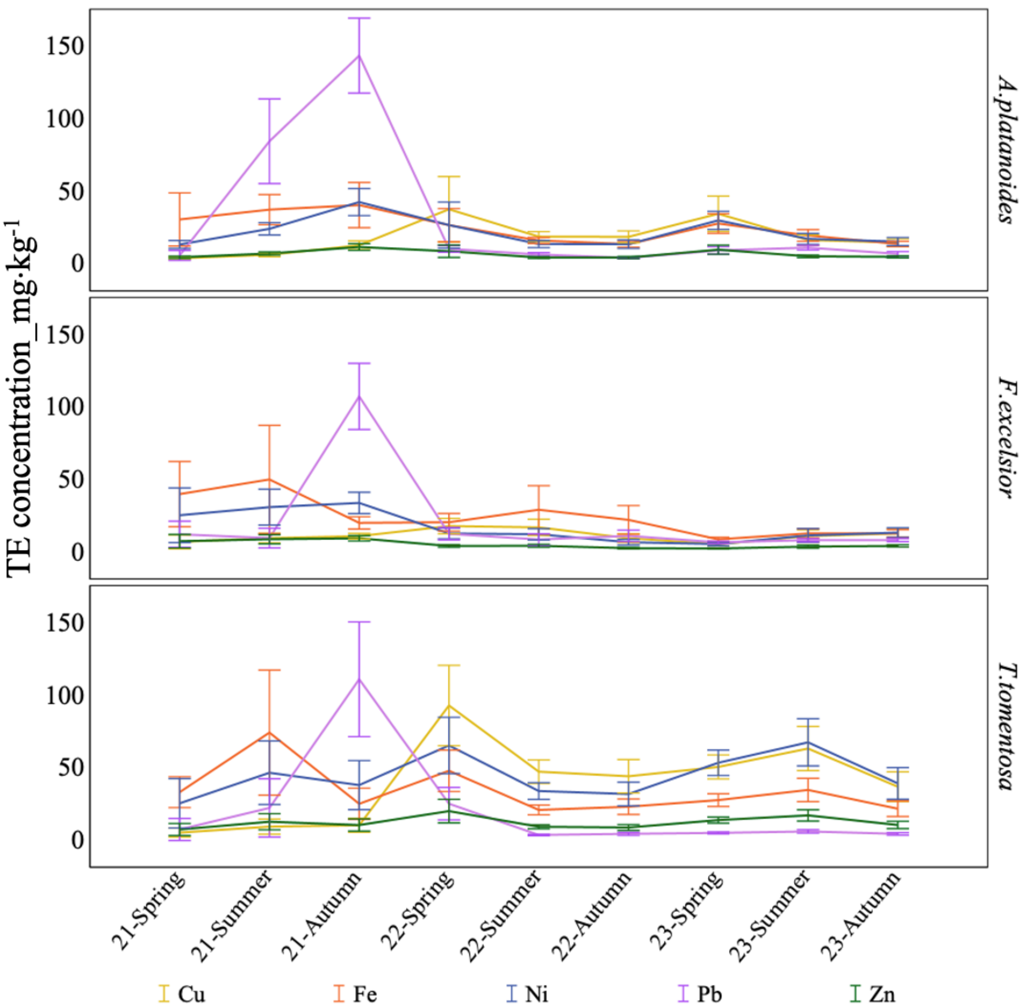

Fig. 21. TE concentration of urban trees' leaf surface wash-off in Budapest from 2021 to 2023. T-bars represent a 95% of confident interval.

In terms of the concentration of TE in urban tree, the measured TE contents of leaves and branches are listed in **Table 19**. The concentration of Cu, Fe, Ni, Pb, and Zn in leaf ranged 0.04 to 16.27 $mg \cdot kg^{-1}$, 2.37 to 136.61 $mg \cdot kg^{-1}$, 3.25 to 19.28 $mg \cdot kg^{-1}$, 0.05 to 44.15 $mg \cdot kg^{-1}$, 3.02 to 6.54 $mg \cdot kg^{-1}$, respectively. While they were ranged in the branch 8.55 to 20.00 $mg \cdot kg^{-1}$, 26.62 to 369.1 $mg \cdot kg^{-1}$, 8.42 to 30.64 $mg \cdot kg^{-1}$, 0.43 to 38.3 $mg \cdot kg^{-1}$, 3.30 to 9.84 $mg \cdot kg^{-1}$, respectively. 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*, which Fe>Ni>Cu>Fb>Zn in *A. platanoides*. Different from the study of Rehman et al., (2023), they found Fe>Pb>Cu>Ni in the wet season and Fe>Cu>Pb>Ni in dry season. This highlights the high concentration of Ni in our study.

Table 19. Descriptive of TE contents ($mg \cdot kg^{-1}$) in the leaf and branch of urban trees.

	Species	Cu	Fe	Ni	Pb	Zn
Leaf	*A. platanoides*	8.85±3.31	56.58±27.22	13.71±3.52	4.94±9.03	3.35±0.14
	F. excelsior	7.63±3.36	67.41±24.74	12.57±3.68	9.92±12.66	3.47±0.46
	T. tomentosa	7.63±2.92	60.27±19.19	12.58±2.85	8.75±10.67	3.41±0.39
Branch	*A. platanoides*	13.13±5.41	104.91±46.08	19.96±4.09	15.88±10.36	5.43±2.36
	F. excelsior	13.06±5.43	109.25±33.27	20.62±3.30	17.45±9.63	5.54±2.51
	T. tomentosa	12.93±5.41	111.98±25.24	21.29±3.46	17.97±9.10	5.50±2.45

When compared between different locations. The results of TE content in urban trees from urban park and urban street are shown in **Fig. 22**. 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.

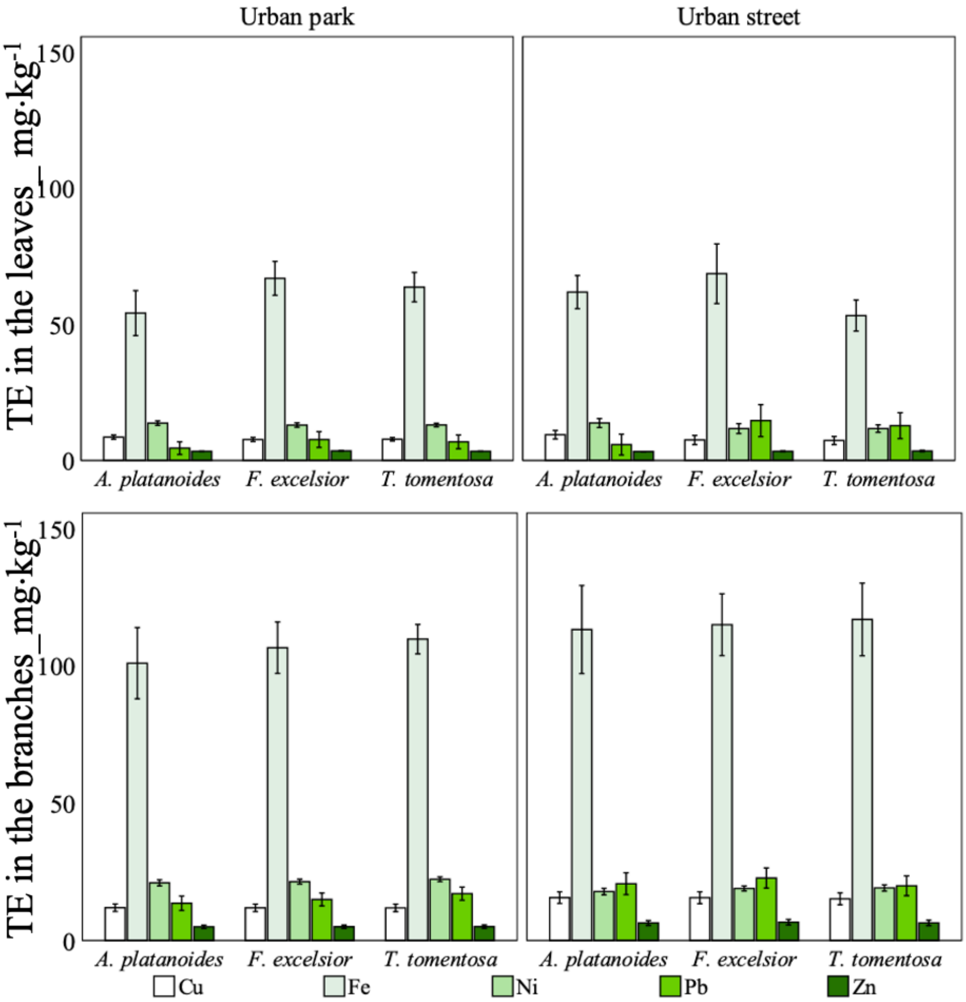

Fig. 22. TE concentration of urban trees' leaf and branch in urban park and urban street in Budapest from 2021 to 2023.

5.6.2 Translocation of Trace Elements

The BCF and BCBI of urban trees are presented in **Table 20**. 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 similarities in the translocation of trace elements from soil to branch.

Table 20. BCF and BCBI of urban trees from environment.

	Species	BCF					BCBI
		Cu	Fe	Ni	Pb	Zn	
Dust-Leaf	*A. platanoides*	0.77	3.01	0.79	1.35	0.77	0.19
	F. excelsior	0.88	4.68	1.40	2.35	1.46	0.31
	T. tomentosa	0.45	2.19	0.43	3.33	0.41	0.11
Soil-Branch	*A. platanoides*	0.70	0.07	0.15	0.44	0.01	0.44
	F. excelsior	0.70	0.08	0.13	0.44	0.03	0.53
	T. tomentosa	0.69	0.08	0.13	0.57	0.01	0.47

The concentration of Cu in *A. platanoides, F. excelsior*, and *T. tomentosa* follows the order of leaf<branch<soil/dust, leaf<dust<branch<soil, and leaf<branch<soil<dust, respectively. As the concentration in the dust varied, suggests the different interactions of urban trees and the ambient PM pollution. Which agree with that soil is not the primary source of Cu in urban areas (Aksu, 2015). The concentration of Fe in *A. platanoides, F. excelsior*, and *T. tomentosa* follows dust<leaf<branch<soil constantly, which indicates the source of Fe are mainly contributes from soil. The concentration of Ni in *A. platanoides* and *T. tomentosa* were leaf<branch<dust<soil, while dust/leaf<branch<soil. The concentration of Pb in *F. excelsior* and *T. tomentosa* followed leaf<dust<branch<soil, whereas followed leaf<branch<dust<leaf in *A. platanoides.* The concentration of Zn in all species followed dust/leaf/branch<soil.

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 known role in plant growth, leading to less active accumulation.

5.7 Sources Appropriation of Trace Elements

The PM deposition on urban trees allows for a closer analysis of the chemical properties of ambient particulate matter, providing insights into the potential sources of its chemical components. Anthropogenic activities, such as burning of fossil fuels in vehicles, domestic heating, power plants, construction activities, and industrial processes, have increased the amount and types of PM in the environment (Al-Thani et al., 2018). According to their major sources, chemical components of PM can be categorized to three groups: natural sources (Na, K, Ca, Al, Mg, Fe), traffic sources (Cr, Mn, Ni, V, and Zn), and industrial sources (Cu, Cd, Pb) (Ventura et al., 2017).

5.7.1 The Sources of Water Soluble Ions

The Spearman correlation coefficients (*n*=432) performed on pH, EC, and major ionic concentrations are shown in **Table 20.** 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^-, the accumulation of these ion related compounds resulted in a higher EC value. NH_4^+ was positive correlated with SO_4^{2-} and Cl^- at *p*=0.01 level, and NO_3^- at *p*=0.05 level. Whereas NO_3^- was negative correlated with Cl^-.

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. This is similar as to NO_3^- , because NH_4^+ is predominantly present as NH_4HSO_4 , $(NH_4)_2SO_4$, or NH_4HNO_3 in the fine fraction in the air (Szigeti et al., 2015; Y. Wang et al., 2019).

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. Furthermore, Cl^- may originate from natural and anthropogenic sources, whereas SO_4^{2-} and its precursor SO_2 release into the atmosphere from anthropogenic activities, such as fossil fuel combustion, biomass burning, and long-distance transport sources (Juda-Rezler et al., 2020). The sources of Cl^- mainly generate from sea salt and coal combustion (Huang et al., 2017; H. Xu et al., 2019) and this is not the situation in Budapest. 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. Since NH_4^+, NO_3^- , SO_4^{2-} in the atmosphere usually form through the gas-to-particle process as the result of chemical reactions precursors and considered as secondary inorganic ions, such as traffic and industrial emissions (Correa et al., 2023; Song et al., 2022; Y. Wang et al., 2019). The large variability SO_4^{2-} and Cl^- in the wash-off solutions, can be the result of the urban trees adsorption and translocation effects for other ions, such as NH_4^+ and NO_3^-. The enrichment of Cl^- and SO_4^{2-} were extreme high due to de-icing agent and traffic emission sources, respectively. Lastly, SO_4^{2-} is also used to evaluate the level of anthropogenic activities, therefore the evaluated SO_4^{2-} concentration indicates a high level of anthropogenic interferences in the air in Budapest.

Table. 20 Spearman's correlation coefficients between different water-soluble ions. ** indicates a correlation is significant at a 2-tailed 0.001 level, * indicates a correlation is significant at a 2-tailed 0.05 level.

	EC	NH_4^+	NO_3^-	SO_4^{2-}	Cl^-
pH	-0.307**	-	0.471**	-0.144**	-0.223**
	EC	0.101*	-0.130*	0.628**	0.539**
		NH_4^+	0.107*	0.252**	0.129**
			NO_3^-	-	-0.287**
				SO_4^{2-}	-0.549**

5.7.2 The Sources of Trace Elements

The CDA results (Gradient length 0.84 and 0.68) indicate suitable of RDA analysis. RDA results (**Fig. 22**) 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.

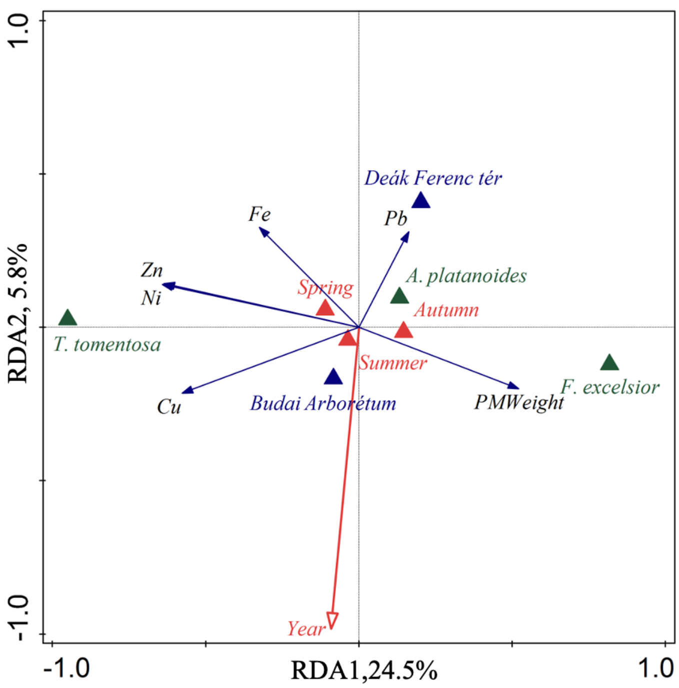

Fig. 22. Biplot of RDA analysis ordination plot of TE contents of the fine PM wash off from urban trees (n=432). Environment factors: Species (*A. platanoides*, *F. excelsior*, and *T. tomentose*), location (Budai Arborétum - urban park and Deák Ferenc tér - urban street), and season (spring, summer, and autumn). Arrows indicate different TE content of fine PM wash-off. RDA1 and RDA2 axis accounted for 24.5% and 5.8% of the total explained variation in PM deposition, respectively (F=32, p=0.002).

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. Note the significant impact of the factor of year, indicates the impact of changes in different years of PM sources and deposition.

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. Thus, historical source. 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.

6. CONCLUSIONS 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. Future research could, for example, attempt to quantify whether the same tree species provide different benefits in different parts of the world. It would also be useful to know what information would be needed to modify the algorithms of urban tree assessment tools so that the same tool could accurately quantify tree benefits in different cities in different countries with both similar and different climates (Roy et al., 2012).

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 endeavors, 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 Modeling 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.

7. 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.

8. SUMMARY

With the urbanization increase, air pollution has become a global issue, significantly affecting most of countries. This problem extends not only in terms of human health but also in several other areas, such as climate change and biodiversity loss. Urban trees growing in built environment must contend with limited sunlight in the shade buildings, increased air pollution, and limited space for crown growth due to the presence of buildings and utilizes. Additionally, climate change and the UHI effect exacerbate these challenges, increasing the pressures trees face from pests, disease, and human interference.

Using nature-based solutions like phytoremediation, which involves using plants to absorb, degrade, or immobilize pollutants, has gained attention worldwide as an effective method for reducing ambient particulate matter. By continuously interacting with and adapting to urban pollution, urban green infrastructures provide a valuable solution to mitigate the effects of particulate matter and contribute to healthier living environments. In contrast, urban trees in cities like Budapest are exposed to multiple environmental stressors, including drought, soil salinity, and air pollution. The urban environment also alters leaf light absorption and radiation reflection, affecting trees' photosynthetic activity. Studies focusing on individual leaf-level responses offer valuable insights into broader ecosystem productivity, as photosynthesis is a fundamental process driving carbon uptake and overall ecosystem functioning. However, there remains a knowledge gap regarding the dual relationship between urban environments' impact on trees and trees' ecological benefits.

This dissertation opens with the physiological performance and growth of three commonly planted urban tree species - *Acer platanoides*, *Fraxinus excelsior*, and *Tilia tomentosa* - from two locations (represent urban park and urban street settings) in Budapest. During their vegetative phase, we examined their canopy volume through paramenter calculation and leaf area index methods. We also analyzed their photosynthetic activity parameters, including net photosynthesis rate, transpiration rate, internal CO_2 concentration, water use efficiency, stomatal conductance, surface temperature, and photosynthetically active radiation. Our findings reveal that *T. tomentosa* exhibited densest canopy and demonstrated the highest net photosynthesis rates compared to the other species. However, the better of photosynthetic activities only observed at urban parks in spring. Notably, stomatal conductance emerged as the most influential parameter, accounting for

84% of the predictive power for net photosynthesis, highlighting drought as a key growth-limiting factor across all species. This observation aligns with moderate drought conditions identified in Budapest. Furthermore, all species showed a decline in leaf area index throughout the summer, indicating that heat stress is becoming an issue for urban trees in Budapest.

We followed up with examination of urban trees potential in fine particulate matter accumulation and assessed the physiochemical properties of particulate matter on the tree leaves. A higher concentration of fine particulate matter concentrations on *F. excelsior* compared to *A. platanoides* and *T. tomentosa*. Our analysis showed that variables such as precipitation, maximum wind speed, and ambient particulate matter levels had minimal direct impact on particulate matter wash-off, suggesting a complex and dynamic interaction between particulate matter and tree leaves. This was confirmed by redundancy analysis, which further indicated that while environmental factors, species type, location, and seasonal variations influenced the trees' fine particulate matter deposition capacities, they were not the primary determinants. The chemical analysis of the particulate matter washed off from the leaves showed elevated sulfate and chloride, indicated to significant anthropogenic influences and secondary pollutant deposition.

In addition, we evaluated the trace elements content of fine particulate matter suspension, soil, leaf, and branch from urban trees. Our results reveal that air pollutant was not different between urban park and the street in Budapest. Nevertheless, trace elements were accumulated higher concentrations in the wash-off of *T. tomentosa* than other two species. Given that *T. tomentosa* exhibited superior net photosynthesis rates and a higher potential for trace element accumulation, we propose it as a more effective species for coping with urban conditions in Budapest. Its ecological benefits, particularly in particulate matter capture, suggest that *T. tomentosa* could play a valuable role in improving air quality and supporting sustainable urban green infrastructure in Hungary's urban areas. However, there were no significant differences between two location of trace elements concentration in leaf and branch, as well as in the soil of urban trees' plantation. Therefore, all mature urban trees could provide significant ecological benefits despite of species.

In the future, several key aspects should be considered in future urban planning. Foremost, species selection must be prioritized, with particular attention to their mortality rates. Because mature urban trees contribute significantly to ecological benefits despite species and abundant biodiversity is crucial for sustainable urban planting. Lastly, urban planning strategies should emphasize the controlling of particulate matter emissions at the first place.

In summary, urban trees growth also under significant stress in Budapest. *A. platanoides* and *F. excelsior* have exhibited declining signs of yellowing leaf in summer and premature leaf fall in autumn, indicating that future conditions are likely to become even more challenging. These will in turn, limiting their ecological providing. Despite the challenges, the importance of urban trees in delivering ecological benefits in urban environment remains critical. To ensure their survival and continued contributions to urban ecology, proactive strategies must be implemented.

First, species selection should take place at an early stage. While young trees struggle to thrive in the hostile urban environment, mature trees, regardless of species, can provide significantly more ecological advantages regardless of species. Thus, species selection should consider its moral rate after planting in an urban setting. Second, ambient PM pollution is typically worse in cold weather, from late autumn to early spring, when deciduous trees are in leaf-off phase. As a result, evergreen plants and cold resilience deciduous or shrub species should be investigated further. Furthermore, because plant interaction with ambient PM pollution is a very complex and dynamic process, long-term modeling and more frequent determination studies of fine PM accumulation would be beneficial in determining potential accumulation limits or the dependence of resuspension from PM storages on leaves. Future research should look at a dynamic wash-off and resuspension model parametrization for PM deposition potential estimation. Finally, most PM pollution, including TE, is caused by anthropogenic activities. Better policies and human actions will help to bring about considerable environmental change.

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2024 The III International Symposium on Greener Cities: Improving Ecosystem Services in a Climate-Changing World (Wisley, UK), Assessing the Photosynthetic Activities of Woody Plants as a Metric of Adaptability to the Urban Environment in Budapest

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