



Original Article

When quiet streets are more toxic: The paradox of low-traffic urban canyons

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ARTICLE INFO

Keywords:

Urban canyon effect
Street ventilation
Ginkgo biloba
Leaf morphology
Soil enzyme activity
Heavy metals
Biomonitoring
Urban vegetation resilience

ABSTRACT

In this matched two-street comparison, canyon geometry, used as a proxy for street-level ventilation, was more closely associated with the observed biological stress patterns in trees and soils than traffic intensity alone. Urban air pollution studies often attribute vegetation stress to vehicle emissions, yet the influence of street structure and ventilation remains underexplored. We investigated how canyon-related stagnation may alter coupled plant-soil responses by comparing *Ginkgo biloba* trees of identical age and municipal management along a well-ventilated, high-traffic avenue and a poorly ventilated, low-traffic street in Budapest. Leaf morphology (surface area, stomatal traits), physiology (chlorophyll, peroxidase), and soil enzyme activity (acid/alkaline phosphatase, β -glucosidase) were analysed together with foliar and soil concentrations of Ni, Pb, Cd, Fe, and Li. Across the two sites, trees in the narrow, poorly ventilated canyon exhibited a stronger, integrated response pattern—higher stomatal density, elevated peroxidase activity, and reduced β -glucosidase in soils—while elevated chlorophyll may reflect stress-compensation and/or microclimatic acclimation; this pattern is consistent with the interpretation that constrained air circulation and reduced dispersion (as inferred from canyon geometry) can outweigh emission intensity under certain street configurations. Integrating leaf and soil indicators provided a coherent, low-cost framework for diagnosing urban tree health. Our findings indicate that street ventilation is an important contextual parameter to consider in urban planning. Optimising canopy spacing and maintaining airflow pathways may help reduce pollutant residence time and support vegetation resilience under intensifying urban stagnation and heat stress.

1. Introduction

Urban vegetation responds simultaneously to atmospheric and edaphic stressors, yet few studies integrate these dimensions within a single diagnostic framework. In this study, we explicitly employ a dual leaf-soil diagnostic approach, combining foliar traits with soil enzymatic and elemental indicators to capture how ventilation-driven pollutant dynamics may propagate through the plant-soil system.

Urbanisation intensifies anthropogenic emissions, degrading air quality and exposing urban vegetation to persistent pollutants, among

which potentially toxic elements (PTEs) are of particular concern (Shaddick et al., 2020; Zhang et al., 2020) because of their persistence (Williams, 2019). Although traffic density is often treated as the primary source of these contaminants, growing evidence suggests that street geometry and ventilation more strongly influence local pollutant accumulation (Buccolieri et al., 2018; Ng and Chau et al., 2012). However, there is still limited empirical evidence on how differences in street-scale ventilation translate into biological stress responses in urban vegetation—representing a central gap. In our conceptual framework, canyon geometry and street orientation jointly determine street-scale

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<https://doi.org/10.1016/j.ufug.2026.129445>

Received 31 October 2025; Received in revised form 3 April 2026; Accepted 4 April 2026

Available online 5 April 2026

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ventilation efficiency and pollutant residence time, thereby shaping local exposure conditions for both leaves and soils (An and Park, 2024; Liu et al., 2023). Prolonged pollutant residence may increase particulate deposition and leaf-surface exposure, potentially triggering morphological and physiological stress responses (Soheili et al., 2023; Roy et al., 2025), while washed-off and deposited contaminants may alter soil elemental loads and suppress key enzymatic functions (Korjus, 2014; Kumar et al., 2024; Wróblewska and Jeong, 2021). This process chain underpins the dual leaf–soil diagnostic framework applied here and clarifies how ventilation-related differences may propagate through the plant–soil system (Bhattacharya et al., 2025).

The urban canyon effect restricts air exchange, traps particulate matter, and increases metal concentrations (Voordeckers et al., 2021; Gromke and Ruck, 2009). Vegetation can further modify wind patterns and may either enhance or inhibit ventilation (Liang et al., 2016; Miao et al., 2022).

Morphological and physiological traits—such as leaf area, stomatal density, and chlorophyll content and peroxidase activity, can provide sensitive indicators of pollution-related stress (Khosropour et al., 2019; Shah et al., 2020). Similarly, soil enzyme activity provides complementary information on belowground functioning (Aponte et al., 2020; Adetunji et al., 2017). Together, these indicators form the basis of our dual leaf–soil diagnostic approach, enabling an integrated assessment of vegetation health under contrasting ventilation regimes while explicitly accounting for airflow constraints imposed by street design.

Urban street configuration is increasingly recognised as an important factor shaping local ecosystem services, including air circulation, thermal comfort, and pollutant dispersion (Diener and Mudu, 2021; Linden et al., 2023). From a planning perspective, the geometry of streets and building heights co-define the effectiveness of vegetation-based mitigation strategies. Yet, biological evidence directly linking street-scale ventilation to plant stress and soil functioning remains scarce, even though such evidence is needed to connect environmental physiology with urban form design.

Ginkgo biloba L. is a widely planted urban tree that is generally regarded as tolerant of pollution and drought (Crane, 2019; Kiyomizu et al., 2019). However, recent work suggests that its morphological and enzymatic responses vary with local microclimatic conditions and the degree of air stagnation (Kisvarga et al., 2024). This makes *G. biloba* a suitable model for testing how street ventilation, relative to traffic intensity, shapes plant–soil stress dynamics in real urban environments.

In this study, we conducted a matched-site comparison in Budapest using *G. biloba* populations growing along two contrasting streets—a wide, high-traffic avenue and a narrow, low-traffic canyon—under identical management conditions. We combined analyses of leaf morphology, stomatal traits, chlorophyll and peroxidase activity with soil enzyme assays (acid and alkaline phosphatase, β -glucosidase) and elemental concentrations (Ni, Pb, Fe, Cd, Li) in both leaves and soils. Because the *G. biloba* individuals in the two streets are identical in age, species, and municipal management—and share the same orientation relative to prevailing winds—the comparison reduced confounding related to biological background and street orientation. This design allowed ventilation proxies to be evaluated alongside traffic intensity, while recognising that co-varying microclimatic differences could not be fully excluded. Within this methodologically controlled framework, the pronounced and systematic differences in canyon geometry—and the associated contrasts in ventilation performance—provide the basis for interpreting ventilation-related differences as a plausible contributor to between-street contrasts alongside traffic intensity, rather than as an isolated causal driver. We tested the following hypotheses:

- (I) restricted street-scale ventilation is associated with a stronger stress-related response pattern in *G. biloba*, expressed through shifts in stomatal traits, antioxidative activity and soil enzymatic functioning, beyond what would be expected from traffic intensity alone; and

- (II) combining foliar and soil biochemical indicators provides a sensitive and integrative framework for detecting urban vegetation stress under contrasting street-canyon conditions.

Understanding how ventilation modulates vegetation stress is essential for evidence-based green-infrastructure planning. Such knowledge can help planners prioritise canyon segments for intervention, optimise tree spacing and canopy porosity, and anticipate where vegetation is more likely to function as a sink or a secondary source of pollutants under future urban warming scenarios.

2. Materials and methods

2.1. Study area and sampling sites

The study was conducted in Budapest, Hungary (1.62 million inhabitants; <https://simplemaps.com/data/hu-cities>), which experiences mixed continental and Atlantic climatic influences (Ács et al., 2020). Weather is highly variable due to the combined influence of continental, oceanic, and Mediterranean air masses (Dezső et al., 2024).

Budapest experiences heavy congestion from residents, ~26,000 daily commuters, and tourism (Farkas et al., 2022). This contributes to road congestion and may reduce the effectiveness of urban ecosystem service provision (Kabisch et al., 2016). Air pollution is significant: urban green spaces capture ~38.17 tonnes of particulate matter per year (Chen et al., 2024). The city's rapid urbanisation, heavy traffic, and complex topography make it a representative case for studying Central European air pollution challenges. Average PM_{2.5} levels between 2020–2023 ranged from 13 to 15 $\mu\text{g}\cdot\text{m}^{-3}$, exceeding the WHO guideline of 5 $\mu\text{g}\cdot\text{m}^{-3}$ (Neckel et al., 2023).

Two sampling sites were established on the Pest side of Budapest (Fig. 1):

- Rákóczi avenue (high traffic): a wide, high-traffic, eight-lane road (~35 m width, 1.56 km length);
- Dembinszky street (low traffic): a narrow, low-traffic, two-lane street (~17 m width, 0.76 km length)

Both roads are planted with *G. biloba* L. trees of the same species, comparable age (18–20 years), and identical municipal management, creating a controlled biological background that helps distinguish ventilation-related patterns from traffic-related influences (BKM, Főkert, 2024).

Prevailing wind data from the Global Wind Atlas (2024) indicate a dominant NW direction with an average speed of 2.2 $\text{m}\cdot\text{s}^{-1}$ at 10 m altitude (Szabó Lilla, 2021). Both streets run roughly N–S (~45° to prevailing winds) generally supporting PM dispersion, although coarse particles may accumulate (Chen et al., 2016; Miao et al., 2022; Buccolieri et al., 2018). During the growing season, June and July are low-wind months, and August is nearly windless. Google Earth Pro imagery indicated that Dembinszky street forms a deep, sheltered canyon, whereas Rákóczi avenue is open and likely better ventilated, influenced by airflow and cooling corridors from the Danube and Elisabeth Bridge. To quantify the canyon effect, height-to-width (H/W) ratios were calculated using the maximum continuous façade heights along the tree-lined sections of each street (Chan et al., 2001). Along Rákóczi avenue, the tallest uninterrupted façades reach approximately 24 m above a 35 m road width, yielding an H/W ratio of 0.69, characteristic of a shallow, well-ventilated canyon. In contrast, Dembinszky street presents maximum façade heights of roughly 19 m over a 17 m wide roadway, resulting in an H/W ratio of 1.12, indicative of a deep, ventilation-restricted canyon. These quantified geometric differences follow standard urban canyon classifications and underpin the distinct ventilation regimes analysed in this study (Muniz-Gaal et al., 2020).

Climatological records for central Budapest provide the environmental context in which the study was conducted. Summer



Fig. 1. The location of sampling sites with prevailing wind directions is indicated. A - Low traffic road (Dembinszky) marked in blue; High traffic avenue (Rákóczi) marked in green, white arrows indicate prevailing NW wind direction; B - Street plan of Dembinszky road; C - Street plan of High traffic avenue (Rákóczi); D - *G. biloba* specimen from the same age stand forming the tree (Source of satellite images: Google Earth Pro; photo by László Orlóci, 2024).

(June–August) mean temperatures range between 21–22 °C, with daily maxima of 26–28 °C and minima of 15–17 °C; mean relative humidity is 66–68%, and wind speeds at 10 m height typically reach 5–6 m s⁻¹ (Pongrácz et al., 2016; Dian et al., 2020; Tóth-Ronkay et al., 2015). Annual global horizontal irradiance averages 4200–4400 MJ m⁻², peaking in June–July (Mezősi, 2016). Within this regional climate, local shading and turbulence are expected to be strongly influenced by canyon geometry, alongside short-term meteorological variation.

To ensure reproducibility, we quantified all geometric parameters governing canyon aerodynamics and pollutant residence. Maximum continuous façade heights were 24 m along Rákóczi avenue and 19 m along Dembinszky street. Combined with street widths (35 m and 17 m, respectively), this yielded H/W ratios of 0.69 and 1.12. Canyon depth, defined as the vertical distance from road surface to roofline (Hubay et al., 2025), was ~26 m for Rákóczi avenue and ~21 m for Dembinszky street. Both streets run approximately N–S, oriented ~45° relative to the prevailing NW winds.

Key site descriptors (street width, façade height, H/W ratio, orientation, and tree spacing) are summarised in Table 1 for quick reference.

G. biloba individuals were spaced at regular 10 m intervals, forming structurally consistent rows at both sites. Trees exhibited similar total height (8–10 m), crown-base height (3–4 m), and crown architecture. Crown volume was computed using an ellipsoidal model,

$$V = 4/3 \pi \times (d/2)^2 \times h,$$

where *d* is mean horizontal crown diameter (m; here 4.0–5.5 m) and *h* is

crown depth (m; here 3–4 m).

Trees were positioned 1.5–2.0 m from building façades and 0.8–1.2 m from the curb. Sampling was restricted to a uniform 150–200 m street segment at each site, avoiding intersections to maintain consistent geometry and traffic influence.

2.2. Leaf sampling

Leaf samples were collected on July 30, August 15, and August 25, 2024, under rain-free conditions. Fifteen trees per street (sampling site) were sampled (n = 15 trees per street), and the same trees were resampled on each date. For each tree on each sampling date, fifteen leaves per tree (15 leaves tree⁻¹) were collected from the traffic-facing crown sector at ~2 m height. Leaves were immediately frozen in liquid nitrogen and stored at -70 °C until analysis (Dembinszky: 47.50583 N, 19.07912 E; Rákóczi: 47.49711 N, 19.06993 E).

To standardise light exposure, leaves were collected from the west-facing, road-oriented crown sector at both sites. Sampling was limited to the mid-canopy at ~2 m, avoiding upper sun-exposed and lower heavily shaded foliage to minimise within-tree variation in irradiance.

2.3. Soil sampling

Soil was sampled at each tree on each sampling date in parallel with leaf collection. For each tree, five subsamples were collected to a depth of 20 cm around the trunk and pooled into a 100 g composite sample; adjacent unvegetated control soil was also collected in parallel. Samples were homogenised, air-dried at 40 °C for chemical analyses, and stored at -20 °C for microbial assays.

To minimise environmental variability, we standardised tree species, age class, management regime, sampling depth, sampling period, and crown-sector orientation between the two streets, and conducted sampling under rain-free, broadly comparable meteorological conditions. Because soil enzyme activities and metal mobility can respond to short-term variation in temperature and moisture, microclimate remains a potential confounder; street-level microclimate (e.g., temperature, humidity, irradiance) was not directly measured and therefore cannot be fully controlled in this study.

Table 1

Street-canyon geometry and tree-row layout of the two sampling streets. The table defines the geometric exposure context of the two sampling streets by reporting canyon scale (width, façade height, H/W), wind-facing orientation, and the standardised tree-row spacing used for the matched-site comparison.

Descriptor	Rákóczi avenue (high traffic)	Dembinszky street (low traffic)
Street width (m)	35	17
Maximum continuous façade height (m)	24	19
H/W ratio	0.69	1.12
Street orientation	approximately N-S	approximately N-S
Orientation relative to prevailing NW winds	~45°	~45°
Tree spacing along rows (m)	10	10

2.4. Morphological analyses: leaf area and stomatal traits

Leaf surface area was determined from scanned images using digital image analysis in ImageJ v1.54 (National Institutes of Health, USA). Individual leaves were digitised with a flatbed scanner as two-dimensional images and calibrated to image scale before analysis. The projected lamina area of each leaf was then quantified digitally in ImageJ. Leaf-level values were averaged to obtain one tree-date mean and subsequently one tree-level value for statistical analysis. Stomatal traits were quantified from abaxial epidermal impressions prepared with clear nail varnish. For each tree-date, impressions were prepared from the 15 leaves tree⁻¹; multiple peels and microscopic fields were treated as technical subsamples and averaged to the tree level prior to statistical analysis. Imprints were examined under a Euromex bScope BS.1153-PLi microscope at 40 × magnification equipped with a Levenhuk M1400 digital camera. Digital images (4096 × 3288 px) were calibrated prior to analysis using a stage micrometer, resulting in a pixel-to-micrometre conversion factor of 0.243 μm px⁻¹. On each peel, five non-overlapping 5 × 5 mm counting windows were marked (within the available peel area) following strict criteria to avoid geometric distortion: frames were placed in the central lamina region, at least 200–300 μm from primary veins and away from the leaf margin, ensuring homogenous epidermal structure. Because the entire 5 × 5 mm frame exceeded a single microscope field of view at 40 ×, stomata within the marked area were counted by systematically scanning the frame row-by-row (top-to-bottom) and column-by-column (left-to-right) across adjacent fields of view. Calibrated images were processed in ImageJ to determine stomatal length and density (no. cm⁻²).

All values were averaged per tree before statistical analyses. The stomatal index (ratio of stomata to total epidermal cells) was calculated only in those counting windows where epidermal cell boundaries were clearly distinguishable across the evaluated area, using the ratio of stomata to the total number of stomata plus epidermal cells. Procedures followed Khosropour et al. (2019) and Yan et al. (2024). This combined analysis of leaf surface area and stomatal anatomy provided a morphological indicator of pollution-induced stress, as reduced leaf area and increased stomatal density are established markers of microclimatic and gas-exchange perturbation in urban environments (Bahrul Ulum et al., 2023; Abbasi et al., 2018).

All stomatal and leaf area measurements were treated at the tree level. For each street, tree-level mean values were used as the statistical unit, and differences between streets were evaluated using one-way ANOVA with street as the fixed factor. Effect sizes were quantified as η², calculated as SS_{effect} / SS_{total}.

2.5. Physiological and biochemical analyses

Analytical-grade reagents (VWR International, Belgium; Merck KGaA, Germany) and ultrapure water produced by a Millipore Elix system (Merck Millipore, Darmstadt, Germany) were used for all measurements. All instruments were calibrated according to manufacturer specifications before each analytical series.

2.5.1. Assessment of chlorophyll concentration as a photosynthetic indicator

Chlorophyll concentration (Chl a + b) was calculated following Helrich (1971). For each measurement, 0.1 g of fresh leaf tissue was extracted in 80% acetone. The concentration was computed as:

Chlorophyll (a + b) (μg g⁻¹) = (20.2 × A₆₄₄ + 8.02 × A₆₆₃) × V / w
where A₆₄₄ is absorbance at 644 nm, A₆₆₃ is absorbance at 663 nm, V is final extract volume (mL), w is fresh tissue mass (g; here 0.1 g).

Chlorophyll concentration is expressed in μg g⁻¹ fresh weight.

2.5.2. Activity determination of peroxidase (POD) as oxidative stress marker

Following Shannon et al. (1971), 100 mg frozen leaf tissue (five

replicates) was homogenised in phosphate buffer, centrifuged (13,500 rpm, 20 min, 4 °C), and assayed using H₂O₂ and orthodiansidine. Absorbance at 405 nm was recorded every 10 s. Enzyme activity was calculated as:

$$\text{POD enzyme activity} = (\Delta A1 \times D) / \epsilon \text{ [units/mL, U/mL]}$$

where ΔA1 is the change in absorbance in 405 nm; ε is 11.3 mM⁻¹ cm⁻¹ (extinction coefficient of orthodiansidine, which characterizes the extent of color change), D is dilution factor applied to the extract.

Activity was expressed as units per millilitre (U mL⁻¹), and subsequently normalised to sample mass using:

$$\text{POD(mg}^{-1}\text{)} = \text{POD} \times (V / w)$$

where V is volume of tissue extract (mL); w is mass of leaf tissue (g; 0.1 g in this study).

2.6. Elemental composition of leaves and soils

To distinguish between atmospheric deposition and root uptake, elemental analyses were performed on both washed and unwashed *G. biloba* leaves and on corresponding soil samples. This approach enabled the separation of foliar surface contamination from internal accumulation, allowing direct comparison between above- and below-ground pollutant loads (Norouzi et al., 2015; Nadgórska-Socha et al., 2016).

2.6.1. Foliar samples

Unwashed and washed leaf subsamples were analysed to operationally contrast surface-associated atmospheric deposition with more strongly retained (internal and/or tightly bound) foliar pools. For the washed treatment, leaf samples were rinsed twice with deionized water prior to elemental analysis to remove the operationally detachable surface-associated fraction; the first rinse used 250 mL DIW with 10 min agitation on an orbital shaker, followed by a second rinse with 50 mL DIW (Simon et al., 2014; Abriha Molnár et al., 2024; Zuluaga Gómez et al., 2025). Because this step is a physical surface-cleaning treatment rather than a chemically selective extraction, washed–unwashed differences should be interpreted as an operational estimate of the DIW-detachable surface fraction; more intensive cleaning (e.g., brushing and/or ultrasonication) can elute additional, more tightly adhered particles (Vigevani et al., 2024; Liu et al., 2018). For total foliar element concentrations, 0.2 g dried leaf tissue was digested in Teflon vessels using the standard program of the ETHOS Plus microwave digestion system (Milestone, Italy) with 4.5 mL HNO₃ and 0.5 mL H₂O₂ at 200 °C. Foliar dust was collected following published wash-off approaches (Simon et al., 2016) and digested with 5 mL HNO₃ + 2 mL H₂O₂ prior to elemental determination.

2.6.2. Soils

Plant residues were removed, samples air-dried (40 °C), ground with a RETSCH BB100 crusher. Then, 0.5 g subsamples were digested using the standard program of the ETHOS Plus microwave digestion system (Milestone, Italy) with 5 mL HNO₃ and 2 mL H₂O₂ at 200 °C.

Concentrations of Cd, Fe, Li, Ni, and Pb were measured using ICP-OES iCAP™ 7400 (Thermo Fisher Scientific, USA). Wavelengths: Cd 228.802, Fe 238.204, Li 670.784, Ni 221.647, Pb 220.353 nm. RSD < 5%. Standards from Scharlab (Spain). QA was ensured using WEPAL-QUASIMEME reference materials (Wageningen, The Netherlands).

2.6.3. Soil enzyme assays

Soil samples were sieved (2 mm), plant residues were removed, and the material was stored at –20 °C until analysis. β-glucosidase activity was measured using p-nitrophenyl-β-D-glucoside (Sigma-Aldrich, Switzerland) as substrate, and the released p-nitrophenol (PNP) was

quantified after one hour of incubation (Eivazi and Tabatabai, 1988). Acid phosphatase (ACP) and alkaline phosphatase (ALP) activities were measured at pH 6.5 and 11, respectively, using p-nitrophenyl phosphate substrate (Sigma-Aldrich, Switzerland) following Eivazi and Tabatabai (1977). Absorbance was measured at 405 nm with a UV-6300PC spectrophotometer (VWR International Ltd., Hungary), and enzyme activities were expressed as $\mu\text{g PNP}\cdot\text{kg}^{-1}\text{ dry soil}\cdot\text{h}^{-1}$. The sensitivity of these enzymes to toxic elements has been widely reported in the literature (Pascual et al., 1998; Moscatelli et al., 2012; Wang et al., 2019; Chae et al., 2017; Majumder et al., 2022; Karaca et al., 2010; Renella et al., 2003).

2.7. Statistical evaluation

Statistical analyses were designed to ensure inference from independent biological replicates. Trees were treated as the statistical unit throughout. Individual leaves, epidermal peels, microscopic fields, assay replicates, and soil subsamples were considered technical or within-tree subsamples and were not analysed as independent replicates.

For each tree on each sampling date, leaf traits (leaf area, stomatal traits, chlorophyll, POD activity) were averaged across the 15 leaves tree⁻¹ (and associated technical subsamples). Soil variables were summarised per tree and date using a single composite sample generated by pooling five subsamples (20 cm depth). Because sampling was repeated on July 30, August 15, and August 25, 2024, one value per tree was obtained for each response variable by averaging the three tree-date means; this yielded $n = 15$ independent trees per street for primary between-street comparisons. This date-averaged tree-level approach was chosen to evaluate the seasonal (summer) between-street contrast while avoiding pseudoreplication from repeated sampling of the same individuals. Primary between-street inference was based on date-averaged tree-level values, so Date was not included as a separate factor in the corresponding ANOVA models. As a robustness check, we fitted linear mixed-effects models to the unaveraged tree-date dataset with Street as a fixed effect and random intercepts for Tree and Date ((1|Tree) + (1|Date)) in R using the lme4 and lmerTest packages; the mixed-model results were consistent with the date-averaged ANOVA results and yielded the same direction and significance pattern for the key fixed effects.

For responses with one value per tree (morphology, chlorophyll, POD), between-street differences were tested using one-way ANOVA with Street as a fixed factor; the species-level models were based on $n = 15$ trees per street (30 trees in total), and we report $F(1, 28)$, p -values, and η^2 ($\eta^2 = \text{SS}_{\text{Street}} / \text{SS}_{\text{Total}}$). For paired within-tree comparisons (washed vs. unwashed leaves; under-canopy vs. open soil), we used two-way mixed (split-plot) ANOVA with Street as a between-tree factor and Washing/Position as a within-tree factor (paired design). Trees were treated as subjects, and the within-tree error terms were used to test repeated effects and interactions, thereby avoiding pseudoreplication. These split-plot analyses were likewise performed on date-averaged tree-level values; robustness of the main fixed-effect inferences was verified using the mixed-effects approach described above. Because within-tree factors had two levels, planned contrasts were reported directly and Tukey lettering was not applied.

Residual normality and variance homogeneity were assessed on model residuals (Q-Q plots; Shapiro-Wilk on residuals; Levene tests). Where required, responses were log-transformed and estimates were back-transformed for presentation. All tests used $\alpha = 0.05$.

We interpreted η^2 using conventional benchmarks (small ≈ 0.01 , medium ≈ 0.06 , large ≈ 0.14) to contextualise the magnitude of street- and treatment-related effects. Because the study contrasts two deliberately distinct canyon typologies, effect sizes should be interpreted as quantifying a discrete site contrast rather than variation along a continuous urban gradient.

2.8. Quality assurance

Analyses were repeated five times to assess precision (SD calculated). Instruments and reagents were calibrated using Merck Life Science standards (Budapest, Hungary). pH electrodes were calibrated with NIST-traceable buffers (pH 4 and 7). Spectrophotometer accuracy was validated with calibration curves of p-nitrophenol. Laboratory control samples (LCS) were included for method validation.

3. Results

3.1. Leaf parameters

3.1.1. Morphology

All morphological traits showed between-street differences when analysed at the tree level ($n = 15$ trees per street) (Fig. 2). Stomatal length was higher in Dembinszky street ($F(1,28) = 36.02$, $p = 1.82 \times 10^{-6}$, $\eta^2 = 0.563$). Stomatal density also differed between streets ($F(1,28) = 14.97$, $p = 5.96 \times 10^{-4}$, $\eta^2 = 0.348$), and leaf area was larger in Dembinszky street ($F(1,28) = 9.17$, $p = 0.00524$, $\eta^2 = 0.247$) (Fig. 3).

Overall, the results indicate that street configuration, as captured by canyon geometry, is associated with consistent shifts in leaf morphology in *G. biloba* across the two sites.

3.1.2. Physiological indicators

Leaf pigment concentrations differed between the two streets at the tree level ($n = 15$ trees per street). Total chlorophyll (a + b) was higher in Dembinszky street ($F(1,28) = 48.73$, $p = 1.37 \times 10^{-7}$, $\eta^2 = 0.635$). POD activity also differed between streets ($F(1,28) = 7.62$, $p = 0.0101$, $\eta^2 = 0.214$) (Fig. 4).

Overall, these physiological shifts are consistent with stronger stress-associated biochemical responses in the more enclosed street canyon, while recognising that unmeasured microclimatic factors may also contribute to between-site differences.

3.1.3. Element content of leaf dust

Paired washed and unwashed leaf samples were analysed using within-tree inference (Table 2). Street and Washing effects (and their interaction) were evaluated on tree-level observations derived from within-tree aggregation of leaf subsamples, thereby avoiding pseudoreplication.

Street effects were evident for several elements, with higher foliar concentrations on the high-traffic Rákóczi avenue than on Dembinszky street. Washing also affected concentrations for multiple elements, consistent with a substantial surface-associated fraction that is removable by rinsing, although internal uptake cannot be excluded. Street $\times$ Washing interactions were limited for most elements; however, Fe showed evidence for an interaction, indicating that the magnitude of the washed–unwashed contrast differed between streets, consistent with street-specific differences in the surface-associated Fe fraction. Collectively, these results indicate a street-specific elemental signature on *G. biloba* foliage that is consistent with differences in local deposition conditions between the sampling sites.

3.2. Soil

3.2.1. Potentially toxic elements

In contrast to Table 2, which summarises foliar washed–unwashed comparisons, Table 3 presents soil metal concentrations by sampling position (under-canopy vs. open soil), which also varied by street. Street effects were significant for Cd, Fe, Li, Ni, and Pb, indicating consistent between-site differences in soil metal loads. For example, Li and Pb differed strongly between streets (Li: $F(1,28) = 10.13$, $p = 0.0036$; Pb: $F(1,28) = 11.45$, $p = 0.0021$).

Position effects were significant for Cd, Fe, and Pb (Cd: $F(1,28)$

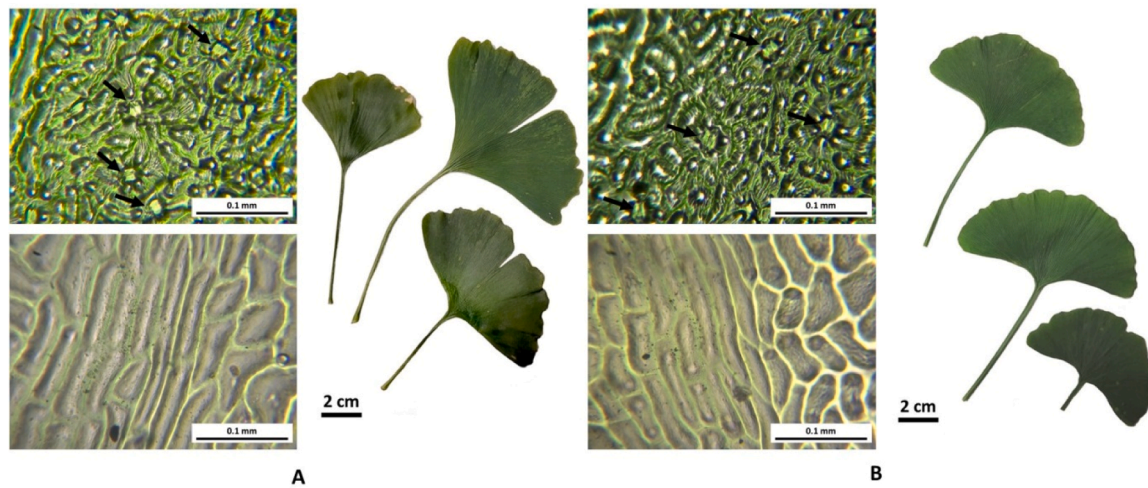


Fig. 2. Tree-level leaf and stomatal morphology of *G. biloba* in the two street canyons. Panels show representative stomatal impressions, epidermal surfaces and whole leaves from Dembinszky street (A) and Rákóczi avenue (B). Images illustrate typical stomatal patterning and lamina morphology, providing qualitative anatomical context for the tree-level quantitative results.

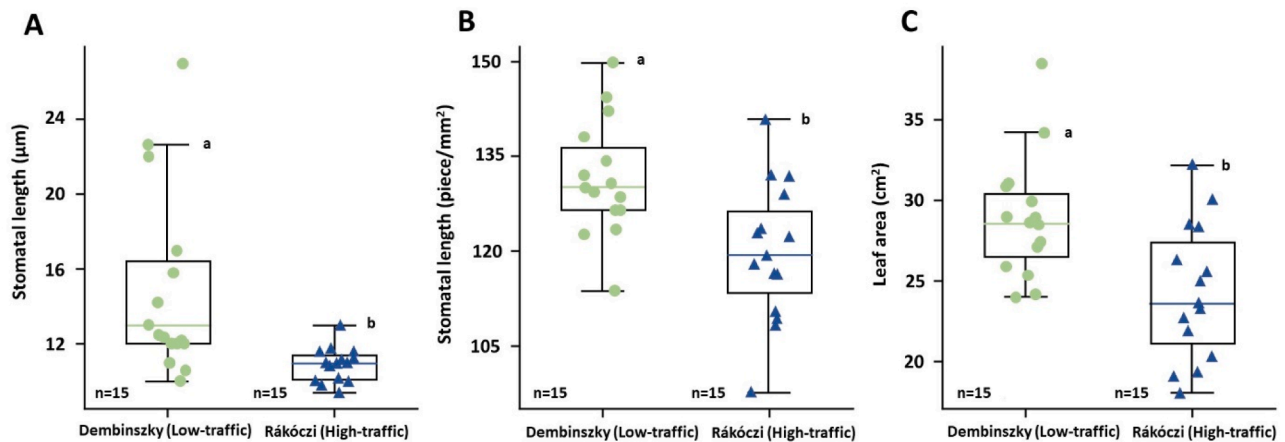


Fig. 3. Tree-level leaf morphological traits of *G. biloba* in the two street canyons. Boxplots show the distribution of tree-level means for (A) stomatal length, (B) stomatal density and (C) leaf area. All subsample measurements (microscopic fields or individual leaves) were averaged per tree prior to analysis ($n = 15$ trees per street). Group differences were tested at the tree level using one-way ANOVA, and effect sizes (η^2) are reported in the Results. Significance codes: ns - not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$.

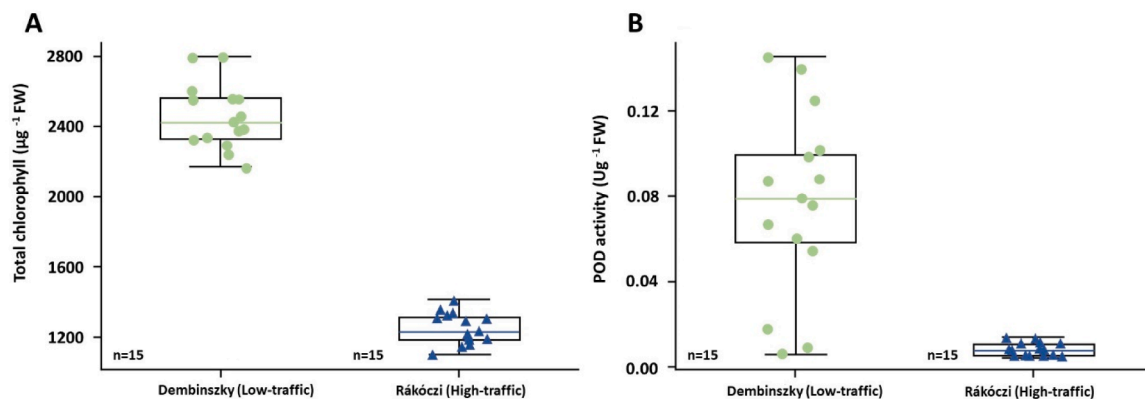


Fig. 4. Pigment concentrations and antioxidative enzyme activity in *G. biloba* leaves from the two street canyons. Boxplots show tree-level values for (A) total chlorophyll (a + b) concentration and (B) peroxidase (POD) activity. Each point represents one tree ($n = 15$ trees per street). Boxplots display the distribution of tree-level means (within-tree subsamples and dates averaged prior to analysis). Between-street comparisons were performed using one-way ANOVA (Street fixed effect; $F(1,28)$); effect sizes (η^2) are reported in the Results. Significance codes: ns - not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$.

Table 2

Two-way mixed (split-plot) ANOVA results for washed versus unwashed foliar element concentrations (Cd, Fe, Li, Ni, Pb) in *G. biloba* leaves. Street (between-tree factor) and Washing (within-tree paired factor: washed vs. unwashed aliquots from the same trees) and their interaction were tested as F(1, 28) under a split-plot framework (trees as biological replicates; n = 15 trees per street). Values are based on tree-level observations obtained by aggregating leaf subsamples within trees (and across sampling dates as described in 2.7).

Element	Street F	Street p	Washing F	Washing p	Interaction F	Interaction p
Cd	12.05	0.0017	18.44	0.0002	2.23	0.1470
Fe	24.67	< 0.0001	31.55	< 0.0001	11.17	0.0024
Li	17.80	0.0002	14.32	0.0007	3.44	0.0742
Ni	4.56	0.0416	12.91	0.0012	0.88	0.3560
Pb	9.77	0.0041	22.48	0.0001	1.66	0.2080

Table 3

Two-way mixed (split-plot) ANOVA results for soil metal concentrations (Cd, Fe, Li, Ni, Pb) in under-canopy and adjacent open-soil compartments associated with *G. biloba* trees across two streets. Factors were Street (Dembinszky vs. Rákóczi) and Position (under-canopy vs. adjacent open soil). Position represents a within-tree (paired) contrast; values are based on tree-level observations derived from pooled subsamples per tree and sampling date and then averaged across dates as described in 2.7. The table reports F- and p-values for main effects and their interaction ($\alpha = 0.05$). Model assumptions were assessed using residual diagnostics (Q-Q plots; Shapiro-Wilk on residuals; Levene tests).

Element	Street F	p	Position F	p	Street×Position F	p
Cd	6.12	0.0197	4.44	0.039	0.92	0.3457
Fe	5.01	0.0333	7.88	0.007	1.55	0.2235
Li	10.13	0.0036	2.90	0.094	1.21	0.2807
Ni	4.33	0.0467	3.56	0.064	0.77	0.3877
Pb	11.45	0.0021	8.66	0.005	2.22	0.1474

= 4.44, $p = 0.039$; Fe: F (1,28) = 7.88, $p = 0.007$; Pb: F (1,28) = 8.66, $p = 0.005$, with lower concentrations under tree canopies than in adjacent open soil. Street × Position interactions were not significant (all F(1,28); $p > 0.05$), suggesting that position-related contrasts were broadly similar at both sites.

Overall, the results indicate that canopy-associated microhabitats are linked to systematically lower soil concentrations for several metals, while street-level conditions are associated with broader differences in soil metal loads between the two canyons.

Comparison with the leaf-washing results (Table 4) suggests that a substantial fraction of the foliar element signal is surface-associated and removable by rinsing (27–41% across elements and sites, with similar values for some elements reflecting rounding). This proportion should be interpreted as an operational estimate of detachable surface deposition rather than as a direct measure of natural wash-off to soils.

3.2.2. Enzyme activity

Soil enzyme activities varied primarily by microhabitat (Position) and, for some enzymes, by street-level conditions (Fig. 5, A–C). Acid phosphatase (ACP) activity was lower under canopies than in adjacent open soils (Position: F (1,28) = 60.42, $p < 0.001$), while the Street main effect was small (F(1,28) = 0.68, $p = 0.43$). The Street × Position interaction was significant (F(1,28) = 6.89, $p = 0.030$), indicating that the magnitude of the position effect differed between streets.

Alkaline phosphatase (ALP) activity differed between streets (Street: F (1,28) = 16.83, $p = 0.003$), whereas Position and the interaction were not significant (both $p > 0.5$). β -glucosidase (GLUC) showed a strong

street effect (Street: F (1,28) = 57.59, $p < 0.001$), with no evidence for Position or interaction effects (both $p > 0.15$).

Together, these patterns indicate that potential enzyme activities related to P and C cycling differ between the two street environments, while ACP additionally shows a consistent within-tree microhabitat contrast. Given that enzyme activities were contrasted between two deliberately distinct street-canyon settings, large to very large effect sizes (η^2), where observed, primarily reflect this matched site contrast between the selected canyon types. Because these assays quantify potential activities in surface soil, they should be interpreted as indicators of altered microbial functioning rather than direct measures of in situ process rates.

4. Discussion

4.1. Factors controlling urban air pollution and plant exposure

Urban populations are rapidly increasing, intensifying human and ecosystem exposure to persistent air pollution (UN, 2024). The accumulation of airborne toxicants, such as heavy metals, is influenced by traffic intensity, street geometry, and ventilation efficiency (Liang et al., 2016; Ng and Chau, 2012). To examine how ventilation-related street structure may modulate plant–soil responses under contrasting traffic settings, we compared two streets in Budapest hosting *G. biloba* under comparable age and management conditions; their markedly different height-to-width (H/W) ratios distinguish a wide, better-ventilated, high-traffic avenue from a narrow, poorly ventilated, low-traffic canyon street.

The systematic divergence between sites is consistent with the interpretation that canyon geometry and associated differences in ventilation may influence local pollutant retention and exposure, and are reflected in plant–soil stress signatures. This pattern is captured by our dual leaf–soil diagnostic framework and the washed–versus–unwashed leaf comparisons (Fig. 6).

This interpretation is strengthened when washed and unwashed leaves are compared, because this approach helps distinguish surface-associated deposition from internal accumulation and may provide higher spatial sensitivity than mosses or lichens. In *G. biloba*, foliar PTEs offer a snapshot of current exposure, making the species a sensitive tool for cross-site comparisons (Werdell et al., 2021).

Table 4

Proportion (%) of foliar element loads removed by washing in *G. biloba* leaves at the two sites. Values represent the percentage reduction in measured concentrations after washing relative to total (unwashed) foliar concentrations, serving as an operational indicator of detachable surface-associated deposition. Similar percentages across some elements reflect rounded values rather than exact identity.

Sampling sites	Cd	Fe	Li	Ni	Pb
Dembinszky (low traffic): % removed by washing	33.33	27.22	27.21	27.22	27.21
Rákóczi (high traffic): % removed by washing	40.94	40.08	40.23	40.05	40.07

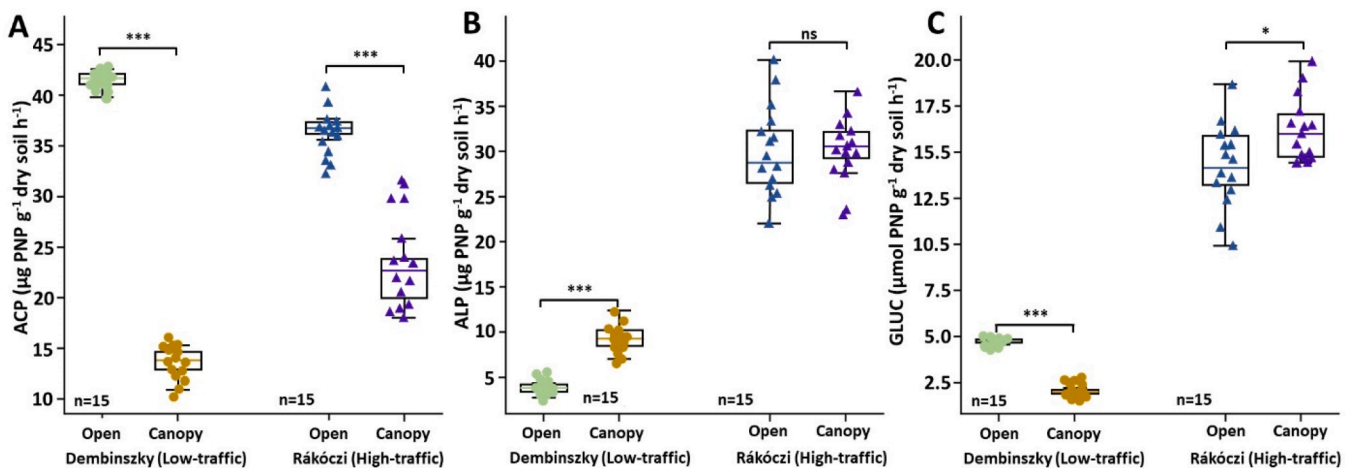


Fig. 5. Soil enzyme activities associated with *G. biloba* trees in the two street environments. Panels show potential activities of (A) acid phosphatase (ACP), (B) alkaline phosphatase (ALP), and (C) β -glucosidase (GLUC) in paired under-canopy versus adjacent open soils at Dembinszky street and Rákóczi avenue. Boxplots summarise the distribution of tree-level values ($n = 15$ trees per street). Position is a within-tree (paired) factor and Street is a between-tree factor; Street, Position, and their interaction were evaluated using a two-way mixed ANOVA framework as described in 2.7. Brackets and significance codes indicate the paired Open vs. Canopy contrast within each street: ns, not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$.

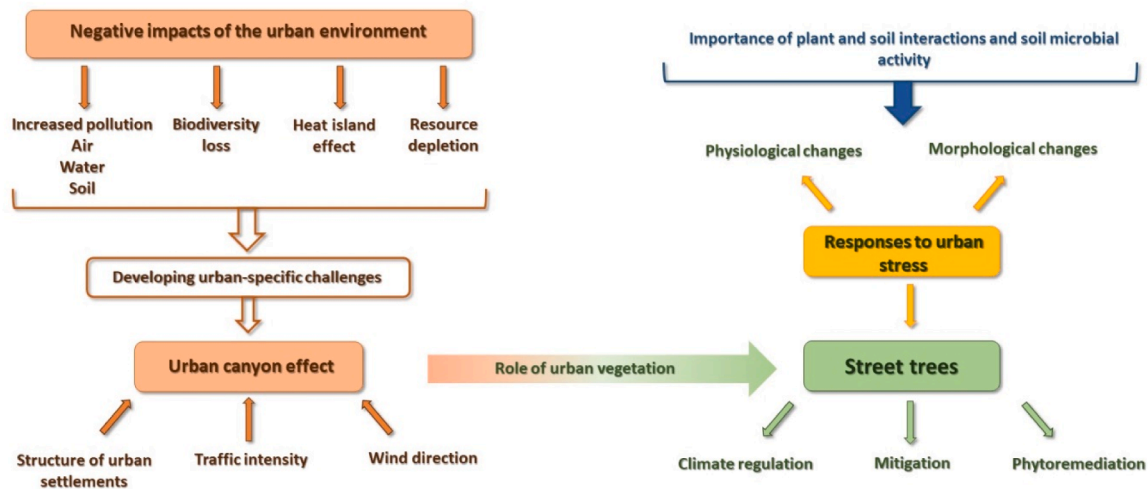


Fig. 6. Schematic summary of relationships between urban canyon geometry, ventilation, and vegetation responses. Diagram integrating leaf-level (morphological and physiological) and soil-level (elemental and enzymatic) indicators.

4.2. Morphological and physiological state of plants

Airborne toxicants also shape plant morphology and physiology (Paull et al., 2021), with leaves—via stomata—serving as primary interfaces for uptake and exchange (Shahid et al., 2017). These interfaces therefore play a central role in the response of how *G. biloba* to atmospheric stress.

Contrary to our initial assumption that reduced ventilation would suppress leaf development, mean leaf area was larger in the poorly ventilated Dembinszky street, suggesting that leaf expansion may be more closely associated with microclimatic differences than with traffic intensity (Figs. 2–3). Because both streets run at $\sim 45^\circ$ to prevailing winds, these differences are consistent with the interpretation that local ventilation and canyon depth may be important correlates of the observed stress patterns (Miao et al., 2022; Buccolieri et al., 2018).

This interpretation is consistent with urban-form and dispersion studies indicating that H/W ratios and building geometry can strongly influence pollutant residence times and near-canopy turbulence (Cai, 2021; Li et al., 2025). Because smaller leaves often accompany stress

(Parkhurst et al., 1972) and may retain less surface PM (Marchini et al., 2019), the larger leaf area in the poorly ventilated street suggests that leaf expansion was more strongly shaped by microclimatic co-variation (e.g., shading, humidity, thermal regime) than by traffic intensity per se. These patterns highlight substantial morphological plasticity in *G. biloba*, consistent with acclimation to contrasting microclimatic and deposition regimes associated with canyon geometry.

G. biloba stomata are haplocheilic and irregularly distributed across the lamina (Šmarda et al., 2018). We observed higher stomatal length and density in the low-traffic but poorly ventilated street, consistent with a response that may be associated with reduced ventilation conditions and/or co-varying microclimatic factors. These patterns align with the effect sizes in our dataset ($\eta^2 = 0.563$ for stomatal length; $\eta^2 = 0.348$ for stomatal density). Although larger leaves are often associated with greater stomatal size or density, the site with larger leaves also showed higher stomatal values in our study, suggesting a combined structural acclimation and micromorphological adjustment. This pattern appears consistent with observations in mature *G. biloba*, yet contrasts with reports of stomatal reduction under contaminant stress (Kiyomizu

et al., 2019; Kisvarga et al., 2024), indicating strong context dependence.

In our dataset, the deeper street canyon (higher H/W, used as a ventilation proxy) coincided with elevated chlorophyll and POD activity. However, as microclimate was not monitored within the canyons, microclimatic co-variation (e.g., irradiance, humidity and thermal regime) cannot be ruled out as a contributing driver of these physiological differences. This contrasts with the common expectations of chlorophyll loss under pollution due to ROS-driven chloroplast damage (Kaur and Nagpal, 2017; Honour et al., 2009; Woo et al., 2007; Dhir, 2016; Anthony, 2001; Spedding and Thomas, 1973; Tiwari et al., 2006). The concurrent rise in POD activity is consistent with a short-term compensatory response rather than pigment degradation, a pattern also visible in Fig. 7, where the more enclosed street combines elevated chlorophyll with higher POD activity relative to the more open avenue.

Although elevated POD activity is commonly interpreted as a marker of oxidative stress (Mishra et al., 2005), POD is also modulated by leaf age, microclimate (temperature, humidity, irradiance), and nutrient status (Ruuhola et al., 2018; Danielsson et al., 2013; Abdi et al., 2025); thus, it should be interpreted as a multifunctional physiological marker rather than a stress-specific response. In our study, the concurrent increase in chlorophyll and POD in the more enclosed street is consistent with oxidative adjustment under constrained canyon conditions, but alternative mechanisms—particularly shade-driven chlorophyll acclimation and other unmeasured microenvironmental differences—cannot be excluded. Accordingly, the pigment–POD pattern is best interpreted as an integrated site-level response plausibly linked to canyon structure and inferred pollutant residence conditions, while recognising the observational design and the absence of direct in-canyon microclimate/airflow measurements. This cautious interpretation remains consistent with the strong between-street contrasts observed for both traits and with established evidence that H/W ratios and street geometry shape dispersion and physiological exposure in urban canyons (Chen et al., 2016; Cai, 2021).

4.3. Leaf-surface deposition and patterns of potentially toxic elements

The PTEs examined here cover transition metals (Fe, Ni), post-transition elements (Pb, Cd) and an alkali-group element (Li) (Pourret and Hursthouse, 2019). Leaf-surface dust provides a sensitive proxy for local elemental composition and can capture short-term exposure signals more directly than bulk leaf tissue or soil (Li et al., 2022), particularly when washed and unwashed leaves are evaluated together to operationally separate detachable surface deposition from internal/strongly bound fractions. Because higher stomatal density and larger

stomata can increase surface roughness and particle adhesion (Sgrigna et al., 2020), we hypothesised that the low-traffic street—where stomatal density and length were higher—would exhibit higher foliar PTE loads. Instead, Cd, Fe, Ni and Pb concentrations were higher on the high-traffic, better ventilated avenue, whereas Li showed the opposite pattern and was higher on the low-traffic, poorly ventilated canyon.

The washed-versus-unwashed design further supports source interpretation. Significant Washing effects for multiple elements indicate that a substantial fraction of foliar loads was detachable and therefore consistent with surface-associated deposition. Moreover, the Street $\times$ Washing term was generally weak, suggesting broadly similar relative wash-off contrasts between streets, with the main exception of Fe, where the interaction indicates that the washing contrast differed between sites. These results support the view that the two streets impose distinct deposition regimes that are only partly captured by simple morphological predictors.

Cross-compartment comparisons further highlight element-specific behaviour. Pb concentrations in leaves were orders of magnitude lower than those in soils, consistent with strong Pb sorption to soil colloids and limited translocation to shoots (Nieder et al., 2018). In contrast, Cd and Ni generally exhibit higher mobility and can be more readily taken up into aboveground tissues, which may contribute to their foliar signal alongside surface deposition. However, without isotopic tracing or mass-balance approaches, the relative contributions of uptake versus deposition cannot be fully resolved from concentration data alone.

Lithium differed from the other analysed elements, as its concentration was higher in the low-traffic, poorly ventilated street. Its enrichment in the low-traffic yet poorly ventilated street suggests a site-specific source and/or retention pathway that does not follow the distribution pattern of the more typical traffic-related metals. Although the co-occurrence of elevated Li and higher chlorophyll is noteworthy, this association should be interpreted cautiously and only as hypothesis-generating (Shakoor et al., 2023; Xu et al., 2024).

Finally, the element patterns should be interpreted alongside the physiological results. Although deposition indicators were higher for several metals on the avenue, the leaf-level biochemical profile differed between streets, consistent with ventilation and microenvironmental context modulating realised stress responses. The combined evidence suggests that *G. biloba* foliage carries a street-specific elemental signature associated with local deposition dynamics, and that washed–unwashed comparisons improve interpretability by separating detachable surface-associated fractions from the total foliar load.

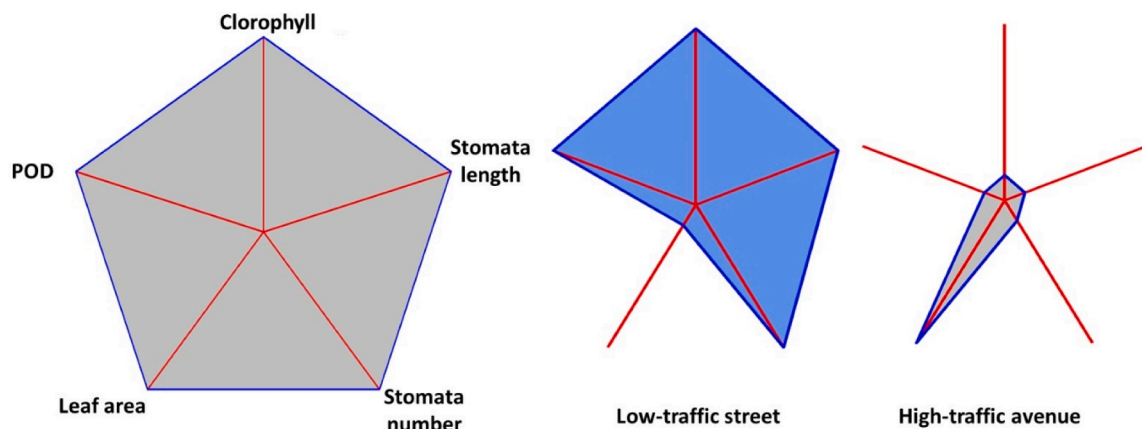


Fig. 7. Star glyph visualisation of the morphological and physiological parameters. Variables were min–max standardised across the dataset (0–1), where larger radii indicate higher values. The figure illustrates that the more enclosed street canyon is characterised by higher chlorophyll and POD values, together with a distinct morphological profile, relative to the more open avenue.

4.4. Soil elemental content and enzyme activity

Soil enzymes—largely microbially derived—are sensitive bio-indicators of soil condition and nutrient cycling, and some enzyme systems also contribute to the transformation of organic pollutants (Rao et al., 2017). Potentially toxic elements such as Cd, Pb, and Ni remain of concern because of their persistence and documented ecological risks (Tóth et al., 2016), even at low concentrations (Singh et al., 2016; Bashir et al., 2016).

Across both streets, all five elements (Cd, Fe, Li, Ni, Pb) were detected in the 0–20 cm layer, consistent with multiple urban inputs including atmospheric deposition, wash-off from aboveground surfaces, and plant- and soil-mediated redistribution processes (Bartkowiak et al., 2020; Nadgórska-Socha et al., 2017; Norouzi et al., 2015). In the mixed (paired) two-factor framework, Street effects were significant for all elements (Table 3), indicating systematic between-site differences in soil metal loads. Position (under-canopy vs. adjacent open soil) effects were significant for Cd, Fe, and Pb, with lower concentrations under canopies than in paired open-soil samples, while Street $\times$ Position interactions were not significant.

This pattern suggests that canopy-associated microhabitats consistently co-vary with reduced concentrations for several metals, whereas broader site conditions appear to drive the dominant between-street contrasts. Because the study did not quantify street-level microclimate, runoff pathways, soil physicochemical properties (e.g., pH, organic matter, texture), or particle size distributions in parallel, the observed street and position effects should be interpreted as integrated outcomes of multiple co-varying processes rather than as evidence for a single controlling mechanism.

The under-canopy reductions for Cd, Fe and Pb are consistent with canopy-mediated interception and altered near-tree deposition or retention pathways, potentially combined with biological uptake and co-varying changes in soil moisture and organic inputs that may influence metal mobility (Nadgórska-Socha et al., 2017; Linde et al., 2007). However, the paired design cannot distinguish whether these differences arise primarily from reduced net inputs under canopies, enhanced immobilisation, or differences in fine-scale soil properties; targeted measurements (e.g., throughfall chemistry, particulate characterisation, soil pH/OM gradients) would be required for attribution.

Soil enzyme activities further indicated strong habitat- and site-associated contrasts. Acid phosphatase (ACP) was dominated by microhabitat effects, with lower activity under canopies than in adjacent open soils, and a significant Street $\times$ Position interaction indicating that the magnitude of this contrast differed between streets. In contrast, alkaline phosphatase (ALP) and β -glucosidase (GLUC) showed strong street-level differences with little evidence for Position effects, implying that broader site conditions were the primary correlate of these potential activities. While such enzyme shifts are often associated with metal stress and altered soil functioning, enzyme activities are also highly responsive to co-varying drivers—including moisture, temperature, organic substrate availability and pH—so the enzyme patterns should be interpreted as indicators of altered microbial functioning rather than direct measures of in situ process rates or metal toxicity alone (Jaworska and Lemanowicz, 2019; Narendrula-Kotha and Nkongolo, 2017; Turner et al., 2002; Nikolova et al., 2023).

Across the two street environments, potential soil enzyme activities—particularly β -glucosidase—differed in a manner consistent with broader contrasts in site conditions and contaminant pressure, suggesting shifts in microbial functioning linked to C and nutrient turnover (Adetunji et al., 2017; Sinsabaugh et al., 1997; Wade et al., 2021). Although street–species systems can respond idiosyncratically to PTE exposure (Rashid et al., 2023), the combined soil enzyme and element patterns support the use of enzyme assays as a practical biodiagnostic component of urban soil health assessments (Gorbov et al., 2021).

4.5. Influence of canyon geometry and ventilation

Debates on roadside ventilation often focus on whether vegetation rows reduce or enhance airflow. It is important to note that no direct measurements of airflow, turbulence intensity or particulate matter concentrations were conducted within the two street canyons. Consequently, our interpretation relies on structural proxies—primarily the measured H/W ratios (Rákóczi avenue: H/W = 0.69; Dembinszky street: H/W = 1.12), street layouts and established urban-form dispersion principles—rather than on site-specific dispersion or ventilation datasets. All conclusions regarding canyon-induced ventilation constraints therefore reflect inferred patterns that are consistent with the literature, rather than direct aerodynamic quantification.

Our findings suggest that vegetation effects may be secondary relative to the apparent influence of canyon geometry and H/W ratio on pollutant retention. Vegetation can mitigate pollution (Vos et al., 2013) while simultaneously altering local wind exposure. In our system, however, the magnitude of these vegetation-mediated effects was exceeded by large canyon-driven differences in physiological and morphological indicators, including between-street contrasts in stomatal traits (stomatal length: $\eta^2 = 0.563$; stomatal density: $\eta^2 = 0.348$) and physiological responses (chlorophyll: $\eta^2 = 0.635$; POD: $\eta^2 = 0.214$) observed at the tree level. These large effect sizes reflect the strong, intentionally paired contrast in this matched-site design and should not be interpreted as typical of more continuous street-canyon gradients. Within street canyons, pollutant dispersion is highly spatially variable (Baldauf et al., 2008). This variability was reflected in our dataset, where the narrow, high-H/W Dembinszky canyon—characterised by the larger H/W ratio reported in the Methods—showed stronger stress signatures, including elevated POD activity ($\eta^2 = 0.214$) and coordinated shifts in leaf morphology and physiology relative to the more open avenue, despite substantially lower traffic emissions.

This pattern is consistent with, but does not prove, an important role for canyon form and ventilation context, as reflected in moderate-to-large effect sizes for stomatal traits (η^2 up to 0.563) and pigment concentrations (η^2 up to 0.635), and should therefore be interpreted as a data-derived hypothesis rather than a directly proven mechanism. Given the proximity and similar orientation of the two sites, the urban canyon effect appears to be a plausible, parsimonious explanatory hypothesis. Nevertheless, without in-canyon airflow or concentration measurements, the relative contributions of ventilation, shading, and other microclimatic covariates cannot be fully separated. This interpretation aligns with CFD-based evidence showing that H/W ratio and canyon openness are widely reported to influence pollutant residence times more strongly than traffic intensity (Yang et al., 2025; Wu and Qiao, 2025). Adequate wind corridors and wider spacing on Rákóczi avenue may be associated with the less stress-associated response pattern observed in *G. biloba* and with differences in pollutant uptake and soil accumulation. Thus, the measured H/W contrasts, together with vegetation placement, represent potentially actionable design parameters for urban environmental planning.

Deciduous canopies can trap pollutants during summer (Diener and Mudu, 2021); therefore, landscape design must jointly integrate street form, canopy structure, and species traits. This is reflected in our soil data, where under-canopy reductions of Cd, Fe and Pb (as indicated by significant Position effects for these elements in the soil analysis) indicate that *G. biloba* modifies deposition patterns but does not override the fundamental constraint imposed by canyon geometry. Well-designed greenery reduces PM exposure for residents and pedestrians (Karttunen et al., 2020) and can be strategically tuned for broader health co-benefits. The substantial removable surface load detected on leaves—particularly Fe and Pb, with washing removing 27–41% of total foliar accumulation—demonstrates that vegetation intercepts large pollutant quantities, although this operational washable fraction should be interpreted cautiously and not as a direct measure of natural wash-off fluxes. Ventilation also moderates temperature and humidity, both of

which are closely linked to street-level pollution dynamics (Kinney, 2018). Consistent with this, our physiological indicators showed that poorly ventilated conditions intensified biochemical stress responses, as evidenced by markedly elevated POD activity ($\eta^2 = 0.214$) and pigment accumulation ($\eta^2 = 0.635$). In many contexts, reduced ventilation and added aerodynamic resistance from trees can outweigh pollutant removal (Buccolieri et al., 2018); because vegetation may obstruct flow, reconfigure eddies, and reduce circulation within canyons (Xue and Li, 2017; Janhäll, 2015). In our study, the washed–unwashed design supports the presence of a substantial surface-associated component, while the mixed ANOVA indicates generally limited Street $\times$ Washing interactions (with the clearest interaction evidence for Fe), consistent with broadly similar washing contrasts across streets for most elements. This provides biological evidence consistent with patterns predicted by CFD modelling studies, which similarly identify H/W ratio and airflow pathways as major determinants of pollutant concentration fields.

The design implication is clear: vegetation must be configured to balance shading with sufficient ventilation (Linden et al., 2023). Pollutant accumulation may be greater on poorly ventilated, low-traffic streets than on breezier, high-traffic avenues, representing an underexplored dimension of urban plant stress. Li et al. (2023) recommend aligning expansive crowns with prevailing winds along long canyons to enhance thermal comfort and pollutant dilution. This aligns with our unexpected finding that Li accumulation—higher in the low-traffic canyon—may indicate localised sources or altered deposition pathways that require further site-specific interpretation. While higher planting density may improve shade, it risks stagnant air and pollutant retention. Because real cities exhibit complex morphologies, most models rely on simplified geometries; critical drivers include local wind patterns, thermal gradients, and building form (Tang et al., 2023). Consequently, field-based, site-specific design is essential for effective ventilation management and resilient urban greening.

4.6. Potential solutions

Street-canyon environments impose tightly coupled constraints on soil–plant systems due to restricted air circulation, thermal gradients, and the prolonged residence time of airborne pollutants. In our study, these constraints were associated with between-street differences in soil PTE signatures and depressed enzyme activities in the poorly ventilated street, suggesting reduced microbial functioning and edaphic resilience.

In deep, low-ventilation canyons—where significant street-level contrasts were detected for multiple soil metals—species capable of effective metal stabilisation offer immediate functional value. *Ricinus communis* and *Tagetes spp.* are particularly promising for phytostabilisation (Cui et al., 2023), while spontaneous or intentionally retained *Plantago lanceolata*—owing to its high bioaccumulation factor (Li et al., 2023)—may be considered as part of a broader risk-reduction planting palette, subject to local regulatory, maintenance, and invasiveness constraints. Because we did not quantify metal speciation or bioavailable fractions, these suggestions should be interpreted as plausible management options rather than as demonstrated remediation outcomes in this system.

A different functional role may be needed to address the aerodynamic limitations of narrow canyons, which may be associated with greater leaf-surface deposition and oxidative stress. Species forming lighter, more open canopies—such as *Amorpha fruticosa* and *Photinia fraseri* (Mori et al., 2015)—could be explored to enhance near-surface ventilation by creating micro-scale airflow channels, thereby potentially reducing pollutant residence time and moderating the stress signatures that characterised the poorly ventilated street. These species can operate synergistically with *G. biloba*, which in our dataset showed strong between-street responses in stomatal traits ($\eta^2 = 0.563$ and 0.348) and pigments/enzymes (chlorophyll $\eta^2 = 0.635$; POD $\eta^2 = 0.214$), consistent with sensitivity to site microenvironment and ventilation context.

In wider, better ventilated settings—such as the Rákóczi avenue—*G. biloba* performed robustly, indicating that with appropriate spacing and preserved airflow pathways, it remains well suited for high-traffic yet breezy corridors. Thus, by adjusting species composition and planting structure, it is possible to target soil contaminants, restore microbial functioning, while recognising that causal attribution to ventilation cannot be confirmed without in-canyon airflow and concentration measurements.

An intervention strategy that integrates targeted phytostabilisation with canopy architectures that maintain or enhance ventilation may offer a hypothesis-driven pathway to reduce soil PTE accumulation, support enzymatic functioning, and moderate plant stress in canyon environments similar to those examined in this study.

4.7. Concluding perspective and future directions

Our results suggest that street-canyon geometry—expressed through contrasting H/W ratios—and associated differences in ventilation are linked to contrasting plant and soil response patterns in this matched two-street comparison, supporting the utility of our dual leaf–soil diagnostic framework for identifying ventilation-related stress signatures. In the poorly ventilated, deeper canyon we observed between-street differences consistent with stronger stress-associated signatures, including shifts in stomatal traits and elevated chlorophyll and POD activity, together with strong street effects in soil enzyme activities (e.g., GLUC: Street F (1,28) = 57.59, $p < 0.001$), consistent with compounded oxidative and edaphic stress. Because in-canyon microclimate and airflow were not measured, co-varying factors such as shading, temperature and humidity cannot be excluded as contributors to the observed chlorophyll and POD patterns. By contrast, on the well-ventilated, high-traffic avenue, multiple indicators showed patterns consistent with reduced stress-associated responses and higher soil enzymatic functioning, although direct inference about pollutant residence times cannot be made without in-canyon airflow and concentration measurements. These findings indicate that ventilation should be considered an important design parameter in urban tree-corridor planning.

This is an observational study restricted to two streets and a single species during summer, therefore generalisation across seasons, cities, and taxa is limited. Practically, we recommend incorporating ventilation performance into street-tree corridor planning by tuning tree spacing, crown architecture, and street orientation relative to prevailing winds, as a manageable design parameter that is consistent with the integrated leaf–soil patterns documented here. Ultimately, linking biological stress diagnostics with urban morphology metrics—particularly canyon H/W ratios and local wind corridors—offers a promising framework for evidence-based climate-adaptive street design.

4.8. Limitations and directions for future

Although the two-street comparison provided a rare opportunity to examine ventilation-related stress under tightly controlled biological and management conditions, several limitations should be acknowledged. The study is necessarily bounded by the geometry and microclimate of two specific canyon types, which restricts the breadth of urban forms represented here. Likewise, the focus on a single, widely planted species, *G. biloba*, strengthens internal consistency but limits taxonomic generalisability. Because sampling was carried out during one summer season, the results capture a physiologically active yet seasonally narrow window of plant response, and cannot resolve potential shifts across spring leaf-out or autumnal senescence.

A further constraint is that no in-canyon measurements of airflow, turbulence or particulate concentrations were performed. This also means that the study design cannot disentangle the effects of reduced ventilation from co-varying microclimatic factors within the deeper canyon, particularly increased shading and altered humidity, both of

which may influence chlorophyll content and stomatal morphology. These traits should therefore be interpreted as integrated responses to canyon-associated environmental conditions rather than as specific responses to ventilation alone. Our inferences therefore rely on well-established dispersion principles and on the quantified H/W contrasts, rather than on direct aerodynamic datasets. Accordingly, mechanistic interpretations (e.g., residence-time effects) should be treated as inferred from geometry-based proxies rather than directly verified on site. Finally, despite standardised protocols, urban soils exhibit fine-scale heterogeneity, and the number of age- and management-matched *G. biloba* individuals available for sampling necessarily limited replication.

These constraints do not negate the overall pattern that street form and ventilation proxies were consistently associated with plant–soil stress signatures; rather, they clarify the scope within which the interpretations are robust. Expanding future work across additional canyon typologies, multiple seasons and a broader set of urban tree species would enable a more generalisable understanding of ventilation-driven ecological processes. Integrating continuous microclimate and airflow monitoring—together with real-time particle characterisation—would also allow direct testing of the aerodynamic mechanisms hypothesised here. Finally, field experiments involving canopy architecture, tree spacing or orientation relative to prevailing winds could quantify the practical gains achievable through ventilation-informed street design.

Overall, linking biological stress diagnostics with urban morphology metrics—particularly canyon H/W ratios and local wind corridors—remains a promising framework for evidence-based climate-adaptive street design, but should be strengthened by direct in-canyon measurements in future studies.

4.9. Evaluation of hypotheses

The findings of this study provide overall support for both initial hypotheses. For the first hypothesis, the combined leaf-level and soil-level indicators showed clear and repeatable differences between the two streets. Stomatal traits, POD activity and soil enzyme patterns were consistently different between sites and were compatible with higher stress levels in the more enclosed canyon, whereas the well-ventilated avenue showed more moderate values across the same parameters. Chlorophyll content also differed between the sites; this trait can reflect stress-compensation and/or microclimatic acclimation, and its pattern here followed the same between-street contrast as other indicators. Taken together, these results are consistent with the interpretation that street-scale ventilation proxies are associated with contrasting plant–soil responses, while recognising that multiple environmental drivers may operate simultaneously in real urban settings and that ventilation was not measured directly.

The second hypothesis—that combined foliar and soil indicators form a sensitive integrative diagnostic framework—is supported by the coherence of responses across compartments. The multi-compartment approach (washed vs. unwashed leaves, foliar morphology and physiology, and soil enzyme activity) revealed a coherent pattern that would have been less detectable through any single metric alone. While the underlying mechanisms cannot be fully separated without direct airflow measurements, the dataset demonstrates that a dual leaf–soil framework is a practical approach for identifying environmental contrasts that covary with street-scale ventilation.

5. Conclusions

At street scale, the observed biological response pattern in this matched two-street comparison was more consistent with differences in ventilation, as approximated by canyon geometry, than with traffic volume alone. This inference was strengthened by the dual leaf–soil diagnostic framework and by the matched-site design, which reduced

variation in tree age and municipal management between the two streets. The concordant signal, reflected in systematic differences between the more enclosed and the more open street environment, including shifts in stomatal traits and POD activity, is consistent with the interpretation that ventilation-related street configuration may be associated with plant–soil response patterns under otherwise comparable management conditions. Elevated chlorophyll may reflect stress compensation and/or microclimatic acclimation rather than a single stress signature. Including lithium as an emergent contaminant further extends ornamental-tree research beyond the usual traffic metals and highlights a pattern that differs from that of Pb, Ni, Cd and Fe. From a practical perspective, this combined leaf-wash and soil enzyme approach provides a low-cost, field-ready diagnostic option that can be implemented without specialised instrumentation, making it suitable for routine municipal tree health monitoring.

The contribution is practical as well as conceptual, grounded in the explicit use of a dual leaf–soil diagnostic approach. By pairing leaf-dust composition with soil enzyme activity, the dual diagnostic offers a low-cost, minimally invasive tool that cities can apply across streets and seasons to identify exposure hot spots and monitor spatial contrasts and temporal variability. In a warming, increasingly stagnant urban atmosphere, with more heatwaves and more calm, inversion-prone episodes, this ventilation-first perspective may also support climate-adaptive urban tree management: tuning tree spacing, crown porosity and depth, and street orientation relative to prevailing winds may help reduce pollutant accumulation and safeguard soil function even where traffic remains high. Because the evidence comes from a globally used ornamental species, the approach may be transferable to other cities and planting palettes, potentially helping urban planners prioritise canyon segments for intervention, integrate ventilation performance into planting and maintenance specifications, and track biological responses through the parallel evaluation of leaf-surface metal loads, particularly Pb, Fe, Ni, Cd, together with soil β -glucosidase activity. Within the scope of the present study, these variables are best interpreted as complementary indicators rather than as components of a formally validated composite municipal index.

Author Contributions

All authors contributed to the concept and design of the study. The collection and analysis was coordinated by László Orlóci and Szilvia Kisvarga. Sample collection was carried out by László Orlóci and Zsanett Istvánfi. Material preparation, data collection and analysis were carried out by Tünde Pusztahelyi, Viktória Orosz and Csilla Almási, Katalin Horotán and Gábor Boronkay. The first draft of the manuscript was written by Szilvia Kisvarga and Katalin Horotán, and checked by László Orlóci. Earlier versions of the manuscript were reviewed by all authors. The final manuscript was read and approved by all authors.

CRediT authorship contribution statement

Szilvia Kisvarga: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Katalin Horotán:** Writing – review & editing, Visualization, Software, Investigation. **Tünde Pusztahelyi:** Validation, Investigation, Data curation. **Gábor Boronkay:** Software, Data curation. **Zsanett Istvánfi:** Project administration. **Viktória Orosz:** Methodology, Investigation. **Csilla Almási:** Methodology, Investigation. **László Orlóci:** Validation, Supervision, Resources, Conceptualization.

Funding

The authors have no relevant financial or non-financial interests to disclose.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are grateful to Györgyné Gondos for her help during the sample collecting process and for technical assistance, and to Bertold Sz. H. for the support during the writing process.

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