



Integrated tree and soil-based monitoring of vehicular pollution in a megacity

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Abstract

Traffic-related environmental pollution is increasing in developing countries due to deficient pollution prevention methods and a lack of use of sophisticated technology. Increasing urbanization, vehicle use, and inadequate environmental regulations cause health and environmental problems. This study assessed the suitability of *Robinia pseudoacacia* var. *umbraculifera* DC. as a biomonitor of urban metal contamination in Istanbul by quantifying Al, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn in washed and unwashed leaves, branches, and bark, together with paired soils collected from ten localities representing contrasting traffic and background conditions. Spatial patterns across independent matrices revealed a clear contaminated-to-background gradient. The control locality (Buyukada) showed the lowest elemental burdens overall, whereas traffic-impacted districts, particularly Besiktas and Bakirkoy, exhibited the highest loads for several traffic-associated elements in plant tissues and co-located soils. Pronounced washed versus unwashed leaf contrasts, strongest at the most impacted sites, indicated a substantial contribution from surface-deposited particulates, consistent with non-exhaust traffic sources (brake and tire wear), road-surface abrasion, and resuspended road dust. Pb emerged as the most diagnostically informative element for localized contamination, with exceedances of commonly used benchmark ranges at selected localities, while Cd, Cr, Cu, Fe, and Zn in washed leaves were broadly consistent with commonly accepted background ranges reported for comparable contexts. Overall, the coherent site-dependent enrichment in plant compartments, combined with paired-soil correspondence and strong leaf-deposition signals, supports *R. pseudoacacia* var. *umbraculifera* DC. as an effective biomonitor for traffic-influenced urban metal pollution and a practical tool for hotspot screening and spatial risk mapping in megacity environments.

Keywords Bioindicator · Deposition · Metal · Mineral element · Urban area

Introduction

Ambient air quality is a fundamental determinant of biological function, as the atmospheric gas mixture sustains essential physiological and biochemical processes in living organisms (Yang et al. 2024; Atafar et al., 2025). Air

pollution is broadly defined as atmospheric contamination that threatens human health, ecological integrity, and material assets through disruptions in the natural gaseous balance and the introduction of foreign substances (Almetwally et al. 2020; Giordano et al. 2021; Acarer Arat 2025). In rapidly urbanizing and industrializing regions, urban air pollution remains a major public-health and environmental burden. Global assessments consistently associate air-pollution exposure with increased cardiopulmonary morbidity and premature mortality, and indicate that approximately 90% of air-pollution-related deaths occur in developing countries (Kapoor et al. 2024).

At the urban scale, ambient pollution is primarily driven by emissions from transportation, industrial activities, residential heating, and fuel combustion from solid, liquid, and gaseous sources. Within this profile, road traffic is a major contributor and, in some urban settings, may account for a substantial share of the local pollution burden, although

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this contribution varies by pollutant type, season, fleet composition, and traffic dynamics. Global projections suggest that emissions could increase markedly by 2030 under business-as-usual conditions; however, regional trajectories are expected to differ according to policy stringency, fuel characteristics, and the pace of technological adoption (Coelho et al. 2021; Saxena 2025). Vehicle exhaust is a major source of CO, NO_x, and hydrocarbons, while Pb relevance is more context-dependent and may be associated with legacy contamination or specific local sources (Sun et al. 2022). Among conventional powertrains, gasoline-powered vehicles can be important contributors to urban emissions, particularly under dense traffic conditions. Emission intensity is further modulated by fuel quality, vehicle age, maintenance status, and congestion patterns. Battery electric vehicles generally represent the lowest-emission option at the point of use because they produce zero tailpipe emissions, although total life-cycle emissions depend on the electricity-generation mix (Boretti 2024).

In addition to instrumental air-quality measurements, researchers use living organisms with indicator and biomonitoring capacity. Whereas analyzers provide instantaneous snapshots of ambient conditions, biomonitor species provide time-integrated information on pollutant exposure over extended periods. (Giordano et al. 2021). This time-integrated biomonitoring performance has been consistently documented in previous studies (Caldana et al. 2023; Hasheminejad et al. 2024; Isinkaralar et al. 2024). Tree bark is particularly suitable for assessing long-term air pollution because it is continuously exposed to atmospheric deposition, whereas roots, branches, and leaves can additionally capture shorter-term deposition dynamics, since emitted pollutants accumulate in upper soil horizons and on plant surfaces (Yalcin et al. 2020; Ozyigit et al. 2023). Driven by rapid population growth, Istanbul has undergone dense and, in many districts, unplanned urban expansion, which has increased pressure on infrastructure and environmental quality. Rising traffic intensity, accelerated construction activity, unfavorable meteorological conditions, and legacy urban-planning deficiencies collectively contribute to severe and persistent air pollution across the city (Dogan Guzel and Alp, 2024).

Situated between Asia and Europe, Istanbul functions as a transcontinental megacity where high population density and mobility demand intensify urban emission pressure. As Türkiye's largest metropolitan area, Istanbul sustains a highly dynamic population and intense mobility demand. The city's large motor-vehicle fleet constitutes a major source of urban pollutant emissions, enhances atmospheric transport and

redistribution processes, and contributes to persistent air-quality deterioration across the metropolitan area (Capraz and Deniz 2021a; Edelman 2021). According to December 2025 data from the Turkish Statistical Institute, the national motor-vehicle stock reached 33,612,650, while Istanbul accounted for approximately 6,246,012 vehicles (18.58% of the national total), indicating a substantial concentration of emission pressure in the metropolitan system (TUIK 2026).

Several studies in Türkiye have investigated pollution detection using *Robinia pseudoacacia* as a biomonitor. One of the earliest studies was conducted in Denizli, where leaves of *R. pseudoacacia* were analyzed to assess urban heavy-metal deposition. The findings showed that Pb and Cu accumulated predominantly in samples from high-traffic areas, whereas Cd, Fe, Mn, and Zn were more intensively deposited in samples collected from industrial zones (Celik et al., 2005). A study in Sanliurfa (Central District) evaluated traffic-related Pb, Zn, Cu, Ni, and Cd accumulation in leaves of *R. pseudoacacia*, and Cd accumulation did not differ significantly among stations or seasons (Karakeci et al. 2021). In a comparative biomonitoring study conducted in urban İzmit, Türkiye, *R. pseudoacacia*, *Cupressus arizonica*, and *Platanus orientalis* were evaluated as landscape trees to trace atmospheric Al, Cr, and Mn pollution over the last 30 years. Deposition intensity at different sites was assessed by comparing metal concentrations in bark and wood tissues. The observed concentration patterns indicated progressive metal accumulation in parallel with year-by-year industrialization in the region. Overall, the study identified *R. pseudoacacia* as the most suitable species for local-scale assessment of both historical and recent atmospheric metal pollution (Isinkaralar 2022). In a recent study on *R. pseudoacacia*, an artificial neural network (ANN) was developed to predict heavy-metal concentrations in both plant and soil matrices, with Fe, Mn, and Ni modeled primarily from Cu and Zn measured across five locations (Sari et al. 2023).

Although *R. pseudoacacia* has been used in several biomonitoring studies in Türkiye, the available evidence remains limited for *R. pseudoacacia* and/or its varieties under megacity conditions. Most previous reports focused on species-level assessments or narrower local designs, leaving insufficient information on tissue-specific metal partitioning and integrated soil–plant relationships for this cultivar in Istanbul. This study addresses that gap by jointly analyzing plant tissues and corresponding soil samples across urban gradients. Specifically, the research sought to characterize the extent and nature of contamination and to determine the distribution of Al, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn across selected urban regions of Istanbul.



Compared with many commonly planted urban species, this cultivar offers three operational advantages for routine bio-monitoring: wide spatial availability in city plantings, tolerance to roadside stress, and multi-compartment sampling potential (leaves, bark, branches, and corresponding soils). These characteristics support its use as a reliable indicator for local-scale assessment of both current and cumulative atmospheric metal pollution in Istanbul.

Materials and methods

Description of species

R. pseudoacacia var. *umbraculifera*, commonly known as “Umbrella Black Locust”, is a small deciduous tree belonging to the Fabaceae family and is one of the botanical cultivars of *R. pseudoacacia*. It typically reaches a height of 15 to 20 feet and a spread of 20 to 25 feet. The tree is characterized by a dense, symmetrical, and rounded or slightly weeping crown, with individuals exhibiting remarkably uniform canopy shapes. It is primarily used as an ornamental tree and is often grafted onto *R. pseudoacacia* rootstocks. The foliage consists of odd-pinnately compound leaves, arranged alternately, with 6 to 14-inch-long dark green leaf blades comprising multiple smooth-edged leaflets. Leaflet shapes vary from elliptic and oblong to obovate, with each leaflet being less than 2 inches long and exhibiting pinnate venation. Leaf emergence occurs late in spring, and leaves tend to fall early in autumn. The tree rarely produces flowers, with only occasional blooms scattered within the crown. Despite this, persistent, dark red to black, leathery seed pods, measuring 2 to 4 inches, may occasionally develop and remain on the tree through winter. The bark, trunk, and branches tend to droop with age, necessitating regular pruning to maintain clearance in urban environments. This cultivar grows best in full sun to partial shade and tolerates a wide range of soil types, including clay, loam, sand, acidic, alkaline, and well-drained soils. It demonstrates high tolerance to drought and aerosol salt and moderate tolerance to soil salinity (Gilman and Watson, 1994).

Study area

This study was conducted in Istanbul, the largest metropolitan area in Türkiye. Covering approximately 5,343 km² and inhabited by more than 16 million people, Istanbul represents the country’s most concentrated demographic and

economic system. In addition to its contemporary role as Türkiye’s principal economic center, the city has long served as a historical and cultural nexus. Owing to its strategic location between Europe and Asia, Istanbul has historically supported maritime trade, commercial activity, and cross-cultural exchange. Geographically, the city extends across both shores of the Bosphorus Strait, a roughly 20-mile (32-km) waterway that connects the Black Sea to the Sea of Marmara and, through the Turkish Straits system, to the Mediterranean basin (Ozturk et al. 2020; Capraz and Deniz 2021a).

The city lies at approximately 40 m above mean sea level in northwestern Türkiye, at 41°0.01' N and 28°0.95' E. Istanbul has a transitional climate influenced by both Mediterranean and Black Sea systems. Its complex topography, characterized by numerous hills and valleys, contributes to notable spatial and seasonal variability in temperature and precipitation. Winters are generally cool and humid, whereas summers are warm and humid. The annual mean temperature is about 13.8 °C, with a mean monthly minimum of 5.3 °C in February and a mean monthly maximum of 22.8 °C in August. The mean wind speed is approximately 3.2 m s⁻¹. Annual precipitation ranges from 660 to 848 mm, and about 60% of this total occurs between November and March. The prevailing wind directions are northeasterly and southwesterly (Sahin et al. 2024; Yilmaz et al. 2025).

Istanbul is among Türkiye’s most economically developed metropolitan regions and remains a major center of production and services, despite the relocation of part of its industrial base to surrounding provinces. The city’s natural assets and deep cultural heritage also sustain a strong tourism economy. However, in recent years, rapid migration-driven population growth and expansion of the vehicle fleet have intensified pressures on urban air quality (Yalcin et al. 2020). Istanbul hosts 38 Air Quality Monitoring Stations (AQMS), of which 12 are operated by the Ministry of Environment and Urban Planning (MoEUP) and 26 by the Istanbul Metropolitan Municipality (IMM) (Sahin et al. 2020).

Sampling design and site selection

Soil and plant samples were collected from ten locations across Istanbul, encompassing both the Asian and European sides of the city. Nine locations were roadside sites adjacent to major roads and highways in Bakirkoy, Besiktas, Kazasker, Kucukyali, Levent, Maltepe, Okmeydani, Sile, and Uskudar (Table 1), while Buyukada, where motor-vehicle traffic is absent, was included as a control site to represent background pollution conditions. Sampling focused on *R. pseudoacacia* var. *umbraculifera* because of its widespread



Table 1 Location coordinates information of the study area

Localities	Coordinates
Buyukada Loc-1	40°51'50.53"N 29°07'34.87"E
Sile Loc-2	41°10'27.04"N 29°36'42.81"E
Okmeydani Loc-3	41°03'18.49"N 28°57'37.58"E
Kucukyali Loc-4	40°56'46.50"N 29°06'43.25"E
Besiktas Loc-5	41°02'52.76"N 29°00'29.94"E
Bakirkoy Loc-6	40°57'47.89"N 28°48'37.30"E
Kazasker Loc-7	40°58'30.34"N 29°05'16.34"E
Levent Loc-8	41°04'58.51"N 29°01'07.30"E
Maltepe Loc-9	40°56'50.12"N 29°08'19.86"E
Uskudar Loc-10	41°01'04.27"N 29°03'49.23"E

distribution along traffic corridors and in urban green spaces. At each site, eight replicate trees were sampled to capture biological variability. Leaf and branch materials were collected consistently from the mid-canopy zone at 2.0–2.5 m above ground, corresponding to the layer most directly exposed to traffic-related emissions and particulate deposition. Bark samples were collected from the main stem at approximately 1.0 m above ground level. At each soil point, approximately 500 g of soil was collected from a depth of 10–20 cm, transferred to sterile bags, and transported to the

laboratory. Sampling locations were selected to represent a pollution-intensity gradient, from high-traffic urban hotspots to relatively low-traffic or residential areas. This stratified design improved inter-site comparability and enabled robust assessment of spatial variation in heavy-metal accumulation.

Calculating element concentrations and verifying data accuracy

All samples, including those from the control site, were transported to the laboratory in sterile bags. Leaf samples were divided into two subsamples to differentiate atmospheric deposition from soil-derived uptake: one subsample was rinsed with sterile distilled water prior to analysis, whereas the other was analyzed without washing. This design, together with the detailed plant-sample preparation procedure, followed our previously published protocol (Ozyigit et al. 2023). After sample preparation, elemental concentrations were quantified in soil and plant tissues using inductively coupled plasma optical emission spectrometry (ICP-OES; PerkinElmer Optima 7000DV). Specifically, Al, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn were measured. Therefore, in addition to heavy metals, selected mineral elements were also included in the analytical framework. (Karahan et al. 2020; Ozyigit et al. 2023).

Using previously prepared external standards, elemental concentrations were quantified by ICP-OES with high analytical precision, expressed as relative standard deviation (RSD, %) in the range reported in Table 2. Plant samples were subjected to microwave-assisted acid digestion using the EPA 3051A protocol (or its adapted form for plant matrices) prior to instrumental analysis. Elemental composition was then determined by ICP-OES (Sharma et al., 2020).

Table 2 Parameters used in the ICP-OES analytical technique

Element	Spectral line (nm)	LoD (mg kg ⁻¹)	LoQ (mg kg ⁻¹)	RSD (%)	R ²
Al	396.153	0.845	2.817	0.81	.999922
Ca	317.933	1.115	3.717	0.68	.999812
Cd	228.802	0.011	0.037	1.36	.999905
Co	228.616	0.016	0.053	0.75	.999934
Cr	267.716	0.012	0.040	1.05	.999872
Cu	327.393	0.082	0.273	0.88	.999921
Fe	238.204	0.765	2.550	0.77	.999891
K	766.490	0.915	3.050	1.15	.999877
Mg	285.213	0.645	2.150	0.98	.999936
Mn	257.610	0.106	0.353	0.83	.999901
Na	589.592	0.735	2.450	1.21	.999865
Ni	231.604	0.019	0.063	1.25	.999814
Pb	220.353	0.016	0.053	0.92	.999899
Zn	213.857	0.091	0.303	0.83	.999928

LoD: limit of detection; LoQ: limit of quantification; RSD: relative standard deviation; R²: determination coefficient



For each analyte, eight-point calibration curves were constructed, yielding linearity with $R^2 > 0.999$. Limits of detection (LOD) and limits of quantification (LOQ) were calculated from reagent blank measurements (e.g., $3\sigma/\text{slope}$ for LOD and $10\sigma/\text{slope}$ for LOQ) (Cao et al., 2016; Goncalves et al., 2019). Analytical wavelengths were selected according to the literature and instrument recommendations, as listed in Table 2 (Barin et al., 2012; Lee et al., 2017; Goncalves et al., 2019).

To quantify elemental uptake and environmental contamination in the soil–plant system, three established indices were calculated: Transfer Factor (TF), Bioaccumulation Factor (BAF), and Pollution Index (PI). All indices were computed using literature-based equations provided in the Methods section. Together, these metrics enabled integrated evaluation of element transfer from soil to plant tissues, accumulation behavior, and site-specific contamination status (Rastmanesh et al. 2024; Zhang et al. 2022).

The Transfer Factor (TF), expressed as $TF = C_p / C_s$, is the ratio of the element concentration in the plant (C_p) to that in the corresponding soil (C_s). In this study, C_p was defined as a composite plant concentration, calculated as the arithmetic mean of concentrations measured in washed leaf, branch, and bark tissues at each site. The Bioaccumulation Factor (BAF), expressed as $BAF = C_{lp} / C_{cp}$, is the ratio of the element concentration in plants from contaminated sites (C_{lp}) to that in plants from the control site (C_{cp}). As in the TF calculation, both C_{lp} and C_{cp} were derived from the same tissue set using the same averaging procedure. Soil contamination was evaluated using the Pollution Index (PI), calculated as $PI = C_s / C_b$, where C_s is the element concentration in sampled soil and C_b is the corresponding concentration in reference (uncontaminated) soil. Together, TF, BAF, and PI provide an integrated framework for interpreting soil-to-plant transfer, relative accumulation, and contamination status for heavy metals and selected mineral elements in the study area.

Statistical evaluation of metal concentrations

All element concentration calculations were performed considering the dry weight of soil, bark, stems, and leaves. Pearson Correlation was performed by using IBM SPSS Statistics v25 (IBM Corp., Armonk, NY, USA). Levels of statistical significance were denoted as * $p < 0.01$ and ** $p < 0.05$, with a two-tailed test employed for all analyses (Karahan et al. 2023).

Results and discussion

This study quantified Al, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn in washed and unwashed leaves, branches, and bark of *R. pseudoacacia* var. *umbraculifera*, together with paired soil samples collected from ten localities across Istanbul. The resulting dataset was used to evaluate the species' biomonitoring capacity and to characterize tissue-specific distributions of mineral nutrients and trace metals along urban pollution gradients.

Based on the results, the control site (Buyukada) generally exhibited the lowest elemental burdens across the study area. Specifically, the lowest values for Ca, Cd, Cr, Cu, Fe, Mg, Na, Ni, Pb, and Zn were recorded in branch samples, with mean concentrations (mg kg^{-1} dry weight, dw) of 1975.483, 0.137, 0.052, 1.656, 107.453, 147.840, 144.953, 0.123, 1.839, and 1.549, respectively (Table 3). In contrast, the minimum concentrations of Al and K were observed in bark samples, at 28.300 and 341.567 mg kg^{-1} dw, respectively (Table 3). For Mn, the lowest concentration was measured in washed leaf samples (3.126 mg kg^{-1} dw; Table 3).

Across the investigated matrices, the highest concentrations were largely associated with Besiktas, consistent with its characterization as a major traffic hotspot where intense vehicular activity, non-exhaust emissions (brake/tire wear and road-dust resuspension), and limited dispersion in a dense urban setting collectively elevate local pollutant loads. The highest Al concentrations were recorded in branch tissue from Besiktas (304.631 mg kg^{-1} dw) and in the paired soil at the same site (5001.500 mg kg^{-1} dw). Cd also reached its maximum at Besiktas, with 0.873 mg kg^{-1} dw in unwashed leaves and 1.796 mg kg^{-1} dw in soil. For Ca, the highest value in plant tissues was detected in bark from Besiktas (6195.120 mg kg^{-1}), whereas the maximum soil Ca concentration occurred at Bakirkoy (13,045.150 mg kg^{-1}). Fe exhibited the same spatial pattern as Al and Cd, with the highest Fe measured in Besiktas bark (598.100 mg kg^{-1}) and in Besiktas soil (13,492.560 mg kg^{-1}). Similarly, the highest Cr concentrations were observed at Besiktas, reaching 4.561 mg kg^{-1} dw in unwashed leaves and 33.445 mg kg^{-1} dw in soil, while Cu peaked at the same location with 14.054 mg kg^{-1} in unwashed leaves and 35.822 mg kg^{-1} in soil. In contrast, K and Mg showed their highest plant-tissue concentrations at Buyukada, where bark K reached 5007.358 mg kg^{-1} and unwashed-leaf Mg reached 836.364 mg kg^{-1} ; however, the corresponding maximum soil concentrations for these elements were again recorded at Besiktas (K: 4145.667 mg kg^{-1} ; Mg: 2523.849 mg kg^{-1}). Na and Mn followed the dominant Besiktas signal: the highest Na occurred in Besiktas unwashed leaves (1083.246 mg kg^{-1}) and soil (3932.176 mg kg^{-1}), and the highest Mn occurred in Besiktas bark (13.104 mg kg^{-1}) and



Table 3 Accumulation of elements (mg kg⁻¹) in plant parts and paired soil samples in ten different locations of Istanbul

	Locations	Washed leaves	Unwashed leaves	Branch	Bark	Soil
Al	Buyukada Loc-1	40.962 ± 0.125	63.304 ± 0.193	125.149 ± 0.383	28.300 ± 0.273	3445.867 ± 23.944
	Sile Loc-2	43.268 ± 0.132	68.387 ± 0.209	147.551 ± 0.451	33.083 ± 0.301	3611.150 ± 25.221
	Okmeydani Loc-3	47.045 ± 0.144	72.082 ± 0.220	231.433 ± 0.707	49.900 ± 0.371	4250.317 ± 29.571
	Kucukyali Loc-4	45.724 ± 0.140	69.124 ± 0.211	201.981 ± 0.617	39.750 ± 0.329	3988.233 ± 27.924
	Besiktas Loc-5	50.889 ± 0.156	74.759 ± 0.228	304.631 ± 0.931	63.067 ± 0.701	5001.500 ± 35.015
	Bakirkoy Loc-6	49.588 ± 0.275	71.791 ± 0.421	284.929 ± 1.682	61.350 ± 0.443	4805.117 ± 33.506
	Kazasker Loc-7	46.151 ± 0.301	68.694 ± 0.395	208.643 ± 1.235	42.600 ± 0.407	4120.333 ± 28.721
	Levent Loc-8	47.239 ± 0.274	70.183 ± 0.394	242.536 ± 1.398	52.950 ± 0.440	4534.017 ± 31.450
	Maltepe Loc-9	44.697 ± 0.251	64.375 ± 0.410	184.393 ± 1.140	37.383 ± 0.328	3814.417 ± 26.610
	Uskudar Loc-10	48.391 ± 0.318	70.525 ± 0.452	254.857 ± 1.555	58.383 ± 0.445	4642.817 ± 32.522
Ca	Buyukada Loc-1	2005.946 ± 6.131	2910.167 ± 8.895	1975.483 ± 6.038	3183.360 ± 22.323	7595.880 ± 80.502
	Sile Loc-2	1906.328 ± 5.827	2863.245 ± 8.752	2026.014 ± 6.193	3707.200 ± 38.969	8811.380 ± 91.605
	Okmeydani Loc-3	1848.144 ± 5.649	2680.033 ± 8.192	2888.222 ± 8.828	5242.740 ± 51.140	12,268.400 ± 105.860
	Kucukyali Loc-4	1886.404 ± 5.766	2762.327 ± 8.443	2603.803 ± 7.959	4285.560 ± 30.890	9844.400 ± 105.127
	Besiktas Loc-5	1805.265 ± 5.518	2507.649 ± 7.665	3588.152 ± 10.968	6195.120 ± 60.069	12,867.560 ± 140.146
	Bakirkoy Loc-6	1802.500 ± 11.411	2581.071 ± 15.381	3303.286 ± 20.869	6009.900 ± 52.023	13,045.150 ± 106.775
	Kazasker Loc-7	1845.446 ± 11.642	2728.107 ± 17.148	2859.929 ± 17.710	4390.333 ± 39.045	9503.950 ± 84.097
	Levent Loc-8	1829.393 ± 11.884	2711.946 ± 16.780	3028.857 ± 17.569	5297.600 ± 42.848	12,711.083 ± 103.085
	Maltepe Loc-9	1887.625 ± 12.794	2783.661 ± 17.149	2492.839 ± 16.447	3687.283 ± 28.069	8600.633 ± 60.034
	Uskudar Loc-10	1809.036 ± 9.124	2644.696 ± 13.936	3190.089 ± 17.739	5726.067 ± 47.239	12,717.900 ± 86.566
Cd	Buyukada Loc-1	0.472 ± 0.001	0.556 ± 0.002	0.137 ± 0.001	0.193 ± 0.009	0.599 ± 0.013
	Sile Loc-2	0.486 ± 0.001	0.684 ± 0.002	0.165 ± 0.001	0.349 ± 0.014	1.070 ± 0.014
	Okmeydani Loc-3	0.550 ± 0.002	0.686 ± 0.002	0.401 ± 0.001	0.666 ± 0.008	1.516 ± 0.026
	Kucukyali Loc-4	0.523 ± 0.002	0.648 ± 0.002	0.280 ± 0.001	0.518 ± 0.017	1.196 ± 0.029
	Besiktas Loc-5	0.707 ± 0.002	0.873 ± 0.003	0.639 ± 0.002	0.947 ± 0.035	1.796 ± 0.067
	Bakirkoy Loc-6	0.633 ± 0.010	0.883 ± 0.004	0.539 ± 0.004	0.893 ± 0.007	0.599 ± 0.013
	Kazasker Loc-7	0.544 ± 0.004	0.663 ± 0.005	0.360 ± 0.002	0.573 ± 0.005	1.070 ± 0.014
	Levent Loc-8	0.557 ± 0.004	0.718 ± 0.005	0.452 ± 0.002	0.658 ± 0.005	1.516 ± 0.026
	Maltepe Loc-9	0.503 ± 0.003	0.595 ± 0.003	0.197 ± 0.001	0.400 ± 0.003	1.196 ± 0.029
	Uskudar Loc-10	0.593 ± 0.002	0.758 ± 0.004	0.515 ± 0.003	0.703 ± 0.006	1.796 ± 0.067
Cr	Buyukada Loc-1	1.628 ± 0.005	2.144 ± 0.007	0.052 ± 0.000	0.097 ± 0.001	6.238 ± 0.068
	Sile Loc-2	2.061 ± 0.006	2.809 ± 0.009	0.139 ± 0.000	0.159 ± 0.002	10.790 ± 0.119
	Okmeydani Loc-3	2.316 ± 0.007	3.650 ± 0.011	0.724 ± 0.002	1.265 ± 0.014	25.419 ± 0.269
	Kucukyali Loc-4	2.228 ± 0.007	3.274 ± 0.010	0.357 ± 0.001	0.458 ± 0.005	15.243 ± 0.161
	Besiktas Loc-5	2.583 ± 0.008	4.561 ± 0.014	1.130 ± 0.003	1.678 ± 0.019	33.445 ± 0.401
	Bakirkoy Loc-6	2.440 ± 0.015	2.144 ± 0.007	1.010 ± 0.005	1.612 ± 0.012	31.048 ± 0.246
	Kazasker Loc-7	2.273 ± 0.012	2.809 ± 0.009	0.551 ± 0.003	0.526 ± 0.004	17.842 ± 0.135
	Levent Loc-8	2.327 ± 0.015	3.650 ± 0.011	0.897 ± 0.006	1.351 ± 0.010	26.867 ± 0.210
	Maltepe Loc-9	2.172 ± 0.013	3.274 ± 0.010	0.248 ± 0.001	0.384 ± 0.003	12.994 ± 0.093
	Uskudar Loc-10	2.398 ± 0.014	4.561 ± 0.014	0.978 ± 0.006	1.549 ± 0.012	29.594 ± 0.225
Cu	Buyukada Loc-1	5.526 ± 0.017	6.203 ± 0.019	1.656 ± 0.005	3.113 ± 0.056	12.636 ± 0.134
	Sile Loc-2	6.392 ± 0.020	7.431 ± 0.023	2.144 ± 0.007	6.370 ± 0.095	15.659 ± 0.132
	Okmeydani Loc-3	9.448 ± 0.029	10.754 ± 0.033	5.693 ± 0.017	9.441 ± 0.139	27.128 ± 0.152
	Kucukyali Loc-4	8.284 ± 0.025	9.728 ± 0.030	4.254 ± 0.013	7.505 ± 0.112	19.444 ± 0.130
	Besiktas Loc-5	11.618 ± 0.036	14.054 ± 0.043	9.074 ± 0.028	11.429 ± 0.106	35.822 ± 0.272
	Bakirkoy Loc-6	11.097 ± 0.066	12.940 ± 0.082	8.038 ± 0.050	10.725 ± 0.073	34.813 ± 0.245
	Kazasker Loc-7	8.802 ± 0.059	10.379 ± 0.056	4.856 ± 0.027	7.396 ± 0.056	19.405 ± 0.140
	Levent Loc-8	10.072 ± 0.060	11.378 ± 0.061	6.384 ± 0.037	9.436 ± 0.070	30.919 ± 0.231
	Maltepe Loc-9	7.485 ± 0.044	8.954 ± 0.052	3.138 ± 0.020	6.589 ± 0.051	17.740 ± 0.126
	Uskudar Loc-10	10.572 ± 0.055	12.121 ± 0.075	7.400 ± 0.047	10.040 ± 0.073	33.187 ± 0.260



Table 3 (continued)

	Locations	Washed leaves	Unwashed leaves	Branch	Bark	Soil
Fe	Buyukada Loc-1	150.006±0.459	184.656±0.564	107.453±0.328	162.900±1.959	5942.820±77.430
	Sile Loc-2	158.091±0.483	195.628±0.598	115.711±0.354	212.788±2.197	8118.520±100.347
	Okmeydani Loc-3	192.308±0.588	244.571±0.748	165.598±0.506	511.860±4.675	11,918.700±111.028
	Kucukyali Loc-4	187.110±0.572	220.172±0.673	130.477±0.399	264.020±3.218	9929.020±97.466
	Besiktas Loc-5	206.168±0.630	286.296±0.875	245.871±0.752	598.100±7.846	13,492.560±133.404
	Bakirkoy Loc-6	202.964±1.205	270.911±1.556	238.518±1.386	528.917±3.918	12,783.367±109.724
	Kazasker Loc-7	188.054±0.964	234.054±1.386	141.144±0.790	246.783±2.258	9131.967±63.463
	Levent Loc-8	198.429±1.154	250.089±1.301	197.429±1.209	449.900±4.137	11,719.717±97.667
	Maltepe Loc-9	176.732±1.011	213.196±1.262	121.186±0.683	217.083±1.585	8240.450±64.145
	Uskudar Loc-10	201.571±1.189	258.089±1.510	227.661±1.193	478.217±3.869	12,616.750±107.783
K	Buyukada Loc-1	1038.634±3.175	1094.507±3.345	5007.358±15.306	341.567±2.390	2933.683±20.491
	Sile Loc-2	1064.621±3.254	1146.626±3.505	4721.496±14.432	359.033±2.493	3080.267±21.494
	Okmeydani Loc-3	1161.064±3.549	1320.309±4.036	3609.808±11.034	389.400±2.699	3523.967±31.069
	Kucukyali Loc-4	1110.677±3.395	1237.727±3.783	3967.714±12.128	377.433±2.574	3293.067±23.003
	Besiktas Loc-5	1279.018±3.909	1444.328±4.415	3200.361±9.782	437.000±2.984	4145.667±28.966
	Bakirkoy Loc-6	1241.679±7.594	1398.321±7.755	3295.250±20.949	427.717±2.968	3995.167±27.917
	Kazasker Loc-7	1121.411±5.378	1265.036±7.185	3773.714±22.358	387.100±2.708	3460.067±24.182
	Levent Loc-8	1180.536±6.972	1318.125±7.481	3442.196±17.693	392.533±2.721	3652.283±25.468
	Maltepe Loc-9	1085.589±7.819	1187.500±7.106	4309.375±22.893	366.867±2.562	3201.267±22.436
	Uskudar Loc-10	1218.411±7.872	1346.446±8.419	3318.750±18.789	412.617±2.901	3801.283±26.655
Mg	Buyukada Loc-1	739.778±2.261	836.364±2.556	147.840±0.452	215.000±2.255	1311.960±14.240
	Sile Loc-2	724.185±2.214	813.842±2.488	170.940±0.522	309.220±2.963	1450.780±16.544
	Okmeydani Loc-3	693.289±2.119	781.358±2.388	200.537±0.613	406.960±4.556	2224.500±22.227
	Kucukyali Loc-4	707.582±2.163	799.404±2.443	188.409±0.576	382.600±4.503	1634.460±17.127
	Besiktas Loc-5	676.253±2.067	763.888±2.335	232.733±0.711	442.320±3.725	2523.849±28.976
	Bakirkoy Loc-6	670.339±4.979	771.696±5.301	223.018±1.192	426.683±2.929	238.333±1.172
	Kazasker Loc-7	696.893±2.925	792.375±5.070	194.411±1.206	396.233±2.529	1664.333±13.244
	Levent Loc-8	683.857±3.188	784.589±4.662	211.929±1.867	422.867±3.768	2241.533±16.484
	Maltepe Loc-9	698.411±12.434	798.161±5.094	181.536±1.169	360.317±2.550	1408.600±12.124
	Uskudar Loc-10	679.018±3.775	774.036±4.312	215.446±1.348	423.583±3.051	2274.317±18.286
Mn	Buyukada Loc-1	3.126±0.010	4.558±0.014	3.136±0.010	5.402±0.063	129.520±1.390
	Sile Loc-2	3.617±0.011	5.557±0.017	3.788±0.012	10.689±0.131	151.858±1.859
	Okmeydani Loc-3	4.839±0.015	7.126±0.022	7.139±0.022	7.266±0.086	244.140±2.334
	Kucukyali Loc-4	4.346±0.013	6.347±0.019	5.396±0.016	13.104±0.136	171.344±2.107
	Besiktas Loc-5	7.526±0.023	10.299±0.031	9.858±0.030	12.642±0.099	310.794±3.510
	Bakirkoy Loc-6	6.893±0.044	9.785±0.055	8.955±0.056	7.195±0.054	281.083±1.727
	Kazasker Loc-7	4.515±0.024	6.651±0.051	6.436±0.039	10.867±0.079	160.767±1.258
	Levent Loc-8	5.673±0.033	8.107±0.053	7.417±0.041	6.018±0.043	261.617±2.187
	Maltepe Loc-9	3.994±0.021	5.681±0.030	4.564±0.027	12.073±0.085	146.583±2.111
	Uskudar Loc-10	6.336±0.037	8.941±0.052	4.978±0.062	5.402±0.063	268.700±1.965



Table 3 (continued)

	Locations	Washed leaves	Unwashed leaves	Branch	Bark	Soil
Na	Buyukada Loc-1	856.721 ± 2.619	884.153 ± 2.703	144.953 ± 0.443	266.880 ± 2.856	1896.380 ± 21.731
	Sile Loc-2	883.719 ± 2.701	924.722 ± 2.827	157.946 ± 0.483	321.280 ± 3.760	2408.317 ± 22.617
	Okmeydani Loc-3	900.178 ± 2.751	1017.266 ± 3.109	229.123 ± 0.700	453.863 ± 3.818	3455.700 ± 36.497
	Kucukyali Loc-4	894.259 ± 2.733	986.948 ± 3.017	194.618 ± 0.595	382.400 ± 3.821	3033.862 ± 26.251
	Besiktas Loc-5	906.675 ± 2.771	1083.246 ± 3.311	258.576 ± 0.790	498.867 ± 5.650	3932.176 ± 40.510
	Bakirkoy Loc-6	896.607 ± 5.804	1056.125 ± 7.638	250.054 ± 1.524	482.133 ± 3.986	3745.417 ± 26.825
	Kazasker Loc-7	889.929 ± 4.963	992.732 ± 5.326	217.161 ± 1.714	399.633 ± 2.577	2957.050 ± 20.886
	Levent Loc-8	895.536 ± 4.962	1007.750 ± 5.870	234.143 ± 1.373	462.333 ± 3.627	3606.767 ± 26.849
	Maltepe Loc-9	883.214 ± 5.979	965.357 ± 6.242	180.054 ± 1.138	302.200 ± 2.284	2510.633 ± 21.867
	Uskudar Loc-10	895.696 ± 5.845	1023.357 ± 6.355	242.446 ± 1.531	479.783 ± 3.468	3620.067 ± 27.069
Ni	Buyukada Loc-1	0.895 ± 0.003	1.526 ± 0.005	0.123 ± 0.000	0.048 ± 0.001	2.806 ± 0.029
	Sile Loc-2	1.224 ± 0.004	2.302 ± 0.007	0.205 ± 0.001	1.280 ± 0.013	4.675 ± 0.042
	Okmeydani Loc-3	1.396 ± 0.004	3.115 ± 0.010	0.715 ± 0.002	4.363 ± 0.057	12.327 ± 0.135
	Kucukyali Loc-4	1.353 ± 0.004	3.709 ± 0.011	0.458 ± 0.001	1.965 ± 0.022	7.946 ± 0.067
	Besiktas Loc-5	1.580 ± 0.005	4.834 ± 0.015	1.223 ± 0.004	5.953 ± 0.062	16.322 ± 0.158
	Bakirkoy Loc-6	1.455 ± 0.009	4.536 ± 0.029	1.073 ± 0.006	4.209 ± 0.029	18.502 ± 0.144
	Kazasker Loc-7	1.355 ± 0.007	3.845 ± 0.022	0.670 ± 0.004	2.207 ± 0.016	9.049 ± 0.069
	Levent Loc-8	1.394 ± 0.009	3.979 ± 0.024	0.838 ± 0.005	3.162 ± 0.024	13.180 ± 0.100
	Maltepe Loc-9	1.291 ± 0.007	3.274 ± 0.019	0.388 ± 0.002	1.592 ± 0.008	6.813 ± 0.053
	Uskudar Loc-10	1.395 ± 0.007	4.089 ± 0.026	0.944 ± 0.005	3.821 ± 0.030	13.834 ± 0.106
Pb	Buyukada Loc-1	4.669 ± 0.033	5.113 ± 0.036	1.839 ± 0.006	2.851 ± 0.070	42.470 ± 0.328
	Sile Loc-2	7.124 ± 0.050	8.224 ± 0.055	2.489 ± 0.008	5.632 ± 0.160	54.966 ± 0.689
	Okmeydani Loc-3	10.147 ± 0.071	12.144 ± 0.085	5.541 ± 0.017	11.080 ± 0.151	84.496 ± 0.263
	Kucukyali Loc-4	7.835 ± 0.055	10.362 ± 0.073	4.258 ± 0.013	7.310 ± 0.151	70.707 ± 0.412
	Besiktas Loc-5	15.690 ± 0.110	18.845 ± 0.132	8.424 ± 0.026	15.561 ± 0.251	101.983 ± 0.453
	Bakirkoy Loc-6	13.658 ± 0.097	17.355 ± 0.121	7.223 ± 0.042	13.353 ± 0.093	94.858 ± 0.709
	Kazasker Loc-7	8.883 ± 0.062	11.163 ± 0.078	4.852 ± 0.029	10.590 ± 0.079	79.693 ± 0.619
	Levent Loc-8	10.719 ± 0.075	12.958 ± 0.091	5.970 ± 0.035	11.910 ± 0.086	86.738 ± 0.678
	Maltepe Loc-9	7.416 ± 0.052	9.534 ± 0.067	3.559 ± 0.018	5.948 ± 0.040	65.869 ± 0.491
	Uskudar Loc-10	12.851 ± 0.090	14.955 ± 0.105	6.717 ± 0.041	13.155 ± 0.101	92.216 ± 0.676
Zn	Buyukada Loc-1	24.418 ± 0.075	31.016 ± 0.095	1.549 ± 0.005	13.832 ± 0.191	37.790 ± 0.398
	Sile Loc-2	29.050 ± 0.089	37.371 ± 0.114	1.854 ± 0.006	19.144 ± 0.309	54.034 ± 0.432
	Okmeydani Loc-3	38.587 ± 0.118	45.887 ± 0.140	4.258 ± 0.013	36.536 ± 0.391	120.609 ± 0.550
	Kucukyali Loc-4	33.107 ± 0.101	38.187 ± 0.117	3.154 ± 0.010	30.285 ± 0.371	82.592 ± 0.508
	Besiktas Loc-5	51.743 ± 0.158	62.999 ± 0.193	5.792 ± 0.018	43.886 ± 0.575	146.318 ± 0.615
	Bakirkoy Loc-6	44.449 ± 0.246	58.711 ± 0.305	5.409 ± 0.032	41.392 ± 0.323	101.998 ± 0.772
	Kazasker Loc-7	34.446 ± 0.172	42.839 ± 0.271	4.004 ± 0.024	33.032 ± 0.238	84.215 ± 0.670
	Levent Loc-8	40.566 ± 0.252	50.953 ± 0.288	4.549 ± 0.031	38.282 ± 0.315	89.976 ± 0.728
	Maltepe Loc-9	31.006 ± 0.183	35.898 ± 0.204	2.585 ± 0.016	26.373 ± 0.192	76.190 ± 0.642
	Uskudar Loc-10	43.259 ± 0.253	54.147 ± 0.327	5.122 ± 0.028	39.389 ± 0.316	95.118 ± 0.719

soil (310.794 mg kg⁻¹). For Ni, the lowest plant concentration was measured in Buyukada bark (0.048 mg kg⁻¹ dw), whereas the highest plant Ni was detected in Bakirkoy bark (5.953 mg kg⁻¹ dw). In soil, Ni similarly ranged from a minimum at Buyukada (2.806 mg kg⁻¹ dw) to a maximum at Bakirkoy (18.502 mg kg⁻¹ dw). Leaf washing markedly

reduced Ni concentrations, with the highest removal rates observed at Besiktas and Bakirkoy (65%) and the lowest at Buyukada (42%). Finally, Pb and Zn reached their highest levels at Besiktas, with Pb attaining 18.845 mg kg⁻¹ in unwashed leaves and 101.983 mg kg⁻¹ in soil, and



Zn attaining 62.999 mg kg⁻¹ in unwashed leaves and 146.318 mg kg⁻¹ in soil.

The observation that the highest concentrations of for many elements co-occurred in plant tissues and paired soils at the same localities indicates a strong correspondence between environmental load and plant accumulation. These results suggest that *R. pseudoacacia* var. *umbraculifera* has potential as a biomonitor of traffic-related pollution, particularly through leaf accumulation of Cd, Cr, and Pb. Environmental variability and plant-part-specific differences may influence pollutant accumulation, thus further studies across seasons, sites, and species are needed to validate the broader applicability of these findings (Table 3).

Washed-leaf concentrations of Cd, Cr, Cu, Fe, and Zn were broadly aligned with commonly accepted background ranges reported for similar contexts, whereas Pb exceeded the corresponding threshold at selected localities; by contrast, Mn and Ni remained below their cited ranges, indicating limited enrichment under the studied conditions and reinforcing Pb as the most diagnostically informative element for localized contamination within this dataset (Severoglu et al. 2015; Yalcin et al. 2020; Ozyigit et al. 2026).

Mean backward air-mass trajectory analyses indicate that particulate matter (PM) in Türkiye is shaped by both local anthropogenic emissions and episodic long-range transport, including inflow from Europe and the Black Sea region as well as dust-laden air masses originating from North Africa (Sahara) and the Middle East (Capraz and Deniz 2021b). Despite regulatory and mitigation measures, including the complete ban on leaded gasoline in motor vehicles by 1 January 2006, restrictions on Pb-containing chemicals, and initiatives to expand urban green spaces in Istanbul, the persistence of elevated pollutant loads suggests that additional control strategies remain necessary, likely reflecting legacy deposits and ongoing resuspension and non-exhaust pathways. While long-range transport can influence the regional PM background, the within-city spatial gradients observed in the present dataset are more consistent with local emission intensity: the control locality (Buyukada) exhibited the lowest elemental burdens, whereas Besiktas showed the most pronounced values across multiple plant compartments and paired soils, consistent with its high traffic intensity. The relatively low anthropogenic pressure on the Princes' Islands, characterized by the absence of major industrial activity, limited seasonal population increases, and extensive natural cover, further supports their suitability as a low-impact reference setting, particularly for airborne particulate-associated contamination (Ozyigit et al. 2015; Tepe and Eti 2024). By contrast, although Besiktas is small in area, its daytime population increases substantially due to bridge-connection routes linking the two continents, major business districts along the Levent–Maslak axis, and dense institutional activity, and it is recognized among the most

socioeconomically developed districts in Türkiye (Ministry of Industry and Technology 2022; Yalcin et al. 2020). Historically, vehicle traffic and fossil-fuel combustion were primary pollution sources in Besiktas; while SO₂ levels have decreased with the widespread use of natural gas for heating, increasing vehicle density continues to sustain high PM loads (Baran 2021; Yalcin et al. 2020).

Unwashed leaves consistently exhibited higher elemental concentrations across all analyzed elements. With the exception of Ca and Mg, the control site showed the smallest discrepancies, corroborating its relative cleanliness with respect to air pollution. A detailed evaluation of the most polluted sites reveals the following ranked percentage differences between washed and unwashed leaves: Al (location 5, 32.43%), Ca (location 1, 31.09%), Cd (location 4, 40.23%), Cr (location 5, 43.42%), Cu (location 5, 17.38%), Fe (location 5, 27.99%), K (location 5, 11.45%), Mg (location 1, 11.55%), Mn (location 5, 26.93%), Na (location 5, 16.29%), Ni (location 5, 67.34%), Pb (location 5, 16.75%), and Zn (location 5, 17.87%). These results clearly demonstrate that leaf washing substantially alters the measured elemental concentrations, highlighting its critical role as a methodological step in the accurate assessment of atmospheric deposition and pollution levels.

In general, TF values below 1 indicate limited transfer from soil to plant tissues (i.e., restricted transfer and/or physiological exclusion), whereas TF values above 1 suggest relative accumulation. TF values approaching 1 indicate comparable concentrations in plant tissues and soil, reflecting neither pronounced exclusion nor pronounced accumulation and potentially a proportional transfer relationship depending on element bioavailability and physiological regulation (Elhady et al., 2023). With the exception of Mg, which exceeded 1 at certain sites and is consistent with its essential metabolic role, *R. pseudoacacia* var. *umbraculifera* exhibited predominantly low accumulation tendency across the analyzed elements. This exclusion pattern was particularly evident for Al, Fe, Mn, Na, and Ni, where elevated soil concentrations did not translate into proportionally higher tissue levels, suggesting limited bioavailability and/or strong physiological regulation restricting internal translocation. Importantly, biomonitoring performance does not necessarily require TF values > 1 for all elements; rather, an effective biomonitor should reliably capture spatial contamination gradients, exhibiting higher tissue burdens at traffic-intensive sites and lower burdens at background sites. In this context, the consistently site-dependent enrichment of several traffic-related metals in plant tissues, together with the pronounced washed-unwashed leaf contrasts, reinforces the suitability of *R. pseudoacacia* var. *umbraculifera* as a biomonitor of urban vehicular pollution and strengthens interpretation by distinguishing elements that are more faithfully



Table 4 Transfer factor and bioaccumulation factor values

	Al		Ca		Cd		Cr		Cu		Fe		K		Mg		Mn		Na		Ni		Pb		Zn	
	TF	BAF	TF	BAF	TF	BAF	TF	BAF	TF	BAF	TF	BAF	TF	BAF	TF	BAF	TF	BAF	TF	BAF	TF	BAF	TF	BAF	TF	BAF
Adalar Loc-1 (Control)	0.02	1.00	0.31	1.00	0.45	1.00	0.09	1.00	0.27	1.00	0.02	1.00	0.73	1.00	0.28	1.00	0.03	1.00	0.22	1.00	0.13	1.00	0.07	1.00	0.35	1.00
Sile Loc-2	0.02	1.15	0.29	1.07	0.31	1.25	0.07	1.33	0.32	1.45	0.02	1.16	0.67	0.96	0.28	1.09	0.03	1.14	0.19	1.07	0.19	2.54	0.09	1.63	0.31	1.26
Okmeydani Loc-3	0.03	1.69	0.27	1.39	0.36	2.01	0.06	2.42	0.30	2.39	0.02	2.07	0.49	0.81	0.19	1.18	0.03	2.02	0.15	1.25	0.18	6.07	0.11	2.86	0.22	1.99
Kucukyali Loc-4	0.02	1.48	0.30	1.22	0.37	1.64	0.07	1.71	0.34	1.95	0.02	1.38	0.55	0.85	0.26	1.16	0.03	1.51	0.16	1.16	0.16	3.54	0.09	2.07	0.27	1.67
Besiktas Loc-5	0.03	2.15	0.30	1.62	0.43	2.85	0.05	3.03	0.30	3.12	0.03	2.50	0.40	0.77	0.18	1.23	0.03	2.71	0.14	1.31	0.18	8.21	0.13	4.24	0.23	2.55
Bakirkoy Loc-6	0.03	2.04	0.28	1.55	0.40	2.57	0.05	2.85	0.29	2.90	0.03	2.31	0.41	0.78	1.85	1.20	0.03	2.53	0.14	1.28	0.12	6.32	0.12	3.66	0.30	2.29
Kazasker Loc-7	0.02	1.53	0.32	1.27	0.37	1.84	0.06	1.89	0.36	2.05	0.02	1.37	0.51	0.83	0.26	1.17	0.04	1.61	0.17	1.19	0.16	3.97	0.10	2.60	0.28	1.80
Levent Loc-8	0.03	1.76	0.27	1.42	0.35	2.07	0.06	2.57	0.28	2.52	0.02	2.01	0.46	0.79	0.20	1.20	0.03	2.13	0.15	1.25	0.14	5.06	0.11	3.06	0.31	2.10
Maltepe Loc-9	0.02	1.37	0.31	1.13	0.39	1.37	0.07	1.58	0.32	1.67	0.02	1.23	0.60	0.90	0.29	1.12	0.03	1.30	0.18	1.08	0.16	3.07	0.09	1.81	0.26	1.51
Uskudar Loc-10	0.03	1.86	0.28	1.50	0.36	2.25	0.06	2.77	0.28	2.72	0.02	2.16	0.43	0.77	0.19	1.20	0.03	2.35	0.15	1.28	0.15	5.78	0.12	3.50	0.31	2.21

TF < 1.0 → indicates restricted transfer or limited accumulation relative to soil concentrations. TF ≈ 1.0 → suggests comparable levels between plant tissues and soil/environment. TF > 1.0 → indicates enrichment of the element in plant tissues relative to soil/environment

Table 5 The Heavy Metal Pollution Index (PI)*

Heavy metal pollution index	Cd	Cr	Ni	Pb
Sile Loc-2	1.79	1.73	1.67	1.29
Okmeydani Loc-3	2.53	4.07	4.39	1.99
Kucukyali Loc-4	2.00	2.44	2.83	1.66
Besiktas Loc-5	3.00	5.36	5.82	2.40
Bakirkoy Loc-6	2.90	4.98	6.59	2.23
Kazasker Loc-7	2.25	2.86	3.23	1.88
Levent Loc-8	2.67	4.31	4.70	2.04
Maltepe Loc-9	1.57	2.08	2.43	1.55
Uskudar Loc-10	2.78	4.74	4.93	2.17

*PI = C_s / C_b (the metal concentration in the sampled soil C_b (the corresponding value in the uncontaminated (reference) soil)

mirrored in plant tissues from those subject to exclusion mechanisms.

The bioaccumulation factors, calculated relative to the control site, are summarized in Table 4. The results indicate that *R. pseudoacacia* var. *umbraculifera* exhibits elevated accumulation for several metals compared with the control, supporting its suitability as a biomonitor for environmental assessment in the study area. The most pronounced enrichment was observed for Ni and Pb, followed by Cu and Cr, patterns that are plausibly linked to traffic intensity and associated urban emission sources. Consistent with this interpretation, enrichment was strongest at the high-traffic districts (e.g., Besiktas and Bakirkoy) and lowest at the background control (Buyukada), indicating a coherent contaminated-to-background gradient across the study area (Tables 3 and 4).

Pollution index (PI) results are presented in Table 5. Ni showed the highest PI values, indicating substantial Ni contamination across most locations, with the exception of Sile; this pattern is consistent with the bioaccumulation factor results. Although healthy trees and representative tissues were selected, phenological stage and tissue age were not strictly standardized. These factors may have contributed to variability in metal accumulation and distribution and should be considered when interpreting the results; future studies would benefit from controlling these variables more rigorously.

In an Istanbul-focused biomonitoring study using conifer needles/leaves of *Cedrus* sp. the mean concentrations of Cd, Pb, and Zn were found to be 0.16 ± 0.07 mg kg⁻¹, 5.75 ± 6.89 mg kg⁻¹, and 44.60 ± 22.00 mg kg⁻¹, respectively, which were relatively lower compared to the results obtained in the current study. On the contrary, average concentrations of Cr, Cu, and Ni were found to be as 16.38 ± 19.57 mg kg⁻¹, 18.35 ± 10.09 mg kg⁻¹, and 10.49 ± 15.92 mg kg⁻¹, respectively, which were 2 to 4 times higher than this current investigation, including all locations, as well (Turan et al. 2020). In another Istanbul



Table 6 Comparison of Cr, Cu, Ni, Pb, and Zn concentrations (mg kg⁻¹) with literature data (Ozkok and Cobanoglu 2023)

	Maltepe current study	Maltepe study per- formed in 2023	Sile current study	Sile study per- formed in 2023
Cr	2.17	53.32	2.06	57.03
Cu	7.48	19.95	6.39	11.68
Ni	1.29	6.88	1.22	6.49
Pb	7.42	7.73	7.12	6.17
Zn	31.01	79.25	29.05	28.02

study employing *Celtis australis* as a biomonitor, roadside unwashed leaves showed relatively high mean values for (in mg kg⁻¹) Cd (0.65 ± 0.13), Cu (19.94 ± 1.17), Pb (14.90 ± 2.96) and Zn (42.53 ± 3.08) were found in unwashed leaf samples taken from the roadside. In our unwashed-leaf samples, Cd and Zn were broadly comparable, whereas Cu and Pb were generally lower, with the most notable Pb elevations occurring at Besiktas and Bakirkoy (Ozturk et al. 2017). Additionally, a lichen-based survey using the cosmopolitan foliose lichen *Xanthoria parietina* across eight districts on the Anatolian side reported higher Cr, Cu, Ni, and Zn levels in Maltepe relative to the present study, while Pb values were comparable; in Sile, Cr, Cu, and Ni were considerably higher, whereas Pb and Zn were slightly lower than our measurements (Table 6) (Ozkok and Cobanoglu 2023).

Furthermore, our statistical analyses determined a positive correlation between coefficients. From the data evaluated, the highest correlation is obtained among Ca and Al (> 0.934), Cd and Ca (> 0.881), Cr and Al (> 0.927), Cu and Cd (> 0.969), Fe and Al (> 0.989), Mn and Cr (> 0.978), Na and Cr (> 0.963), Ni and Cu (> 0.969), Pb and Fe (> 0.990), Zn and Cd (> 0.926) (Table 7). These correlation patterns

suggest that several elements may originate from common emission sources and may share similar environmental pathways. While the observed associations strengthen the biomonitoring relevance of *R. pseudoacacia* var. *umbraculifera*, more detailed source-apportionment and mechanistic investigations would be valuable to disentangle overlapping inputs and confirm causal relationships.

The concurrent elevation of traffic-related elements (Al, Cd, Fe, Cr, Cu, Pb, and Zn) in both tissues of *R. pseudoacacia* var. *umbraculifera* and paired soils at Besiktas, together with similarly high contamination signals at Bakirkoy, suggests that intense vehicular activity along major urban corridors and bridge-connection routes promotes metal enrichment through non-exhaust processes (brake and tire wear, road-surface abrasion) and the resuspension of contaminated road dust, while dense urban morphology can further limit dispersion and enhance local deposition (Fussell et al. 2022; et al., 2025). In our dataset, Besiktas is consistently identified as the most impacted locality for plant and soil burdens (Table 3), and soil-based pollution indices for Cd, Cr, Ni, and Pb are among the highest at both Besiktas and Bakirkoy (Table 5). Conversely, districts characterized by lower contamination pressure show reduced PI values (Table 5), and at Buyukada (the control), where motorized vehicular traffic is historically restricted, the lowest metal loads are likewise mirrored by low concentrations in plant tissues (Table 3). Taken together, the reproduction of a clear contaminated-to-background gradient across independent matrices (soil and multiple plant compartments) supports the interpretation that *R. pseudoacacia* var. *umbraculifera* reliably tracks spatial variability in traffic-driven urban metal inputs and therefore functions as an effective biomonitor under megacity conditions (Fussell et al. 2022; Salva et al. 2025).

Table 7 Correlation matrix (R) data between element concentrations of *Robinia pseudoacacia* var. *umbraculifera* DC. obtained by Pearson correlation method

	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	Pb	Zn
Al	.934**	.835**	.927**	.872**	.989**	.557**	.796**	.977**	.942**	.851**	.976**	.781**
Ca		.881**	.908**	.886**	.952**	.405**	.726**	.951**	.876**	.908**	.943**	.788**
Cd			.926**	.969**	.879**	.251**	.788**	.887**	.915**	.955**	.921**	.926**
Cr				.967**	.964**	.468**	.807**	.978**	.963**	.956**	.973**	.885**
Cu					.914**	.327**	.791**	.933**	.940**	.969**	.947**	.925**
Fe						.518**	.811**	.994**	.960**	.901**	.990**	.830**
K							.248**	.519**	.387**	.327**	.467**	.123*
Mg								.802**	.878**	.717**	.827**	.842**
Mn									.955**	.918**	.984**	.834**
Na										.908**	.974**	.912**
Ni											.929**	.904**
Pb												.882**

**Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed)



Conclusion

Recent air-quality studies in Istanbul frequently report conventional metrics such as PM, SO₂, NO_x, and CO; however, evidence based on multi-matrix elemental profiling using biomonitor organisms remains comparatively limited. Within this framework, the present study evaluated *R. pseudoacacia* var. *umbraculifera* as a biomonitor of urban metal contamination by integrating washed and unwashed leaf data with branch, bark, and paired soil measurements across ten localities. Collectively, the results indicate that tissue burdens captured a clear contaminated-to-background gradient, with traffic-impacted districts showing systematically higher metal loads and the control setting exhibiting consistently lower burdens across compartments. Importantly, the pronounced washed–unwashed contrasts, particularly for traffic-associated elements, demonstrate a substantial contribution from surface-deposited particulates, consistent with current understanding that non-exhaust emissions (brake and tire wear), road-surface abrasion, and resuspension of contaminated road dust are major drivers of urban metal-bearing PM even where exhaust controls have improved.

Overall, the concordant spatial patterns observed across independent matrices, together with strong site-specific enrichment signatures for traffic-related metals, confirm that *R. pseudoacacia* var. *umbraculifera* functions as an effective and spatially sensitive biomonitor under megacity conditions. The close correspondence between elemental burdens in plant compartments and paired soils indicates that local environmental loading is reliably captured by the species, while foliage provides particularly informative signals for elements commonly associated with vehicular influence, including Cd, Cr, and Pb. Beyond its diagnostic performance, *R. pseudoacacia* var. *umbraculifera* offers practical advantages for routine monitoring, including broad availability in urban landscapes, high tolerance to city stressors, and a multi-compartment structure that enables simultaneous assessment of atmospheric deposition and site-associated contamination. Accordingly, the species can be directly integrated into urban biomonitoring frameworks to support hotspot screening, spatial risk mapping, and evidence-based environmental management aimed at reducing traffic-derived metal exposures and improving urban ecosystem and public health protection.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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