soil systems

Article

Heavy Metal Concentrations in Debrecen’s Urban Soils: Implications for Upcoming Industrial Projects

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Abstract

Monitoring the concentration of heavy metals in urban soils is of a paramount importance for several reasons. These inorganic pollutants can pose a significant health risk to living organisms, as they are toxic even at low concentrations and can be present in the soil for a long period of time. This study assesses the spatial distribution, concentration levels, and potential anthropogenic and natural sources of eight typical heavy metals (As, Cd, Co, Cr, Cu, Ni, Pb and Zn) occurring in urban surface soils across Debrecen, Hungary. A total of 295 topsoil samples were collected; heavy metal concentrations were determined by energy-dispersive X-ray fluorescence (EDXRF) spectrometry. The results were interpreted using descriptive statistics, correlation analysis, hierarchical clustering, factor analysis, ordinary kriging interpolation, and spatial-discriminant analysis. The dual origin of the metal contaminants was revealed: As, Co, Pb, and Zn showed strong anthropogenic signatures associated with traffic, urban waste, and construction materials, whereas Cr and Ni were associated with natural geogenic sources. Cd reflected both lithogenic and point-source urban pollution. The current evaluation incorporated Hungarian and Dutch regulatory benchmarks to identify exceedances of environmental quality thresholds. It was found that only Cd and Cr exceeded the Hungarian target values, on average. Linear discriminant analysis based on pollution maps highlighted contamination hotspots around traffic corridors and newly industrialized zones. The importance of high-resolution soil monitoring in the rapidly urbanizing city is highlighted. Given its anticipated industrial and transportation developments, accumulations of heavy metals are probably going to be further exacerbated; therefore, the results provide a critical baseline for future environmental assessments and long-term monitoring.

Keywords: urban soil; heavy metal; pollution; spatial distribution; monitoring

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1. Introduction

Soil plays a significant role in the provision of ecosystem services to humans and the environment. The exploitation of soil resources for economic gain, such as urbanization, industrialization, and intensive agricultural practices, poses enormous environmental challenges because of the significant pollutant emissions associated with these activities [1–4].

Urban soils serve as critical environmental interfaces that affect ecological stability, public health, and sustainable urban development. These soils act as both a sink and a source of various contaminants, particularly heavy metals (e.g., Cd, Cr, Cu, Pb, Zn, and so on), which accumulate owing to anthropogenic activities such as industrial processes, vehicular emissions, and waste disposal [1,5]. Currently, cities experiencing fast growth in both population and industry place considerable pressure on soils, making them particularly susceptible to contamination by pollutants such as heavy metals [2,4,6,7]. The mobility of these pollutants depends on environmental, chemical, geological, hydrological and biological factors, as well as their composition and characteristics [8,9]; therefore, understanding the extent and nature of soil pollution is critical for effective environmental management and restoration [7,10].

Heavy metals are inorganic pollutants that persist in the environment, posing long-term ecological and health risks through bioaccumulation and potential toxicity [11–13]. Human exposure to these contaminants occurs through multiple pathways, including direct ingestion, dermal contact, and the inhalation of resuspended particulates, which may lead to chronic health issues [5].

Numerous studies across Europe have investigated urban soil contamination using geostatistical methods, multivariate statistical analyses, and geographic information system (GIS) mapping to assess spatial patterns and pollution sources [14–19]. In Hungary, research confirms that urban soil heavy metal concentrations are primarily driven by industrial activity, vehicular emissions, and agricultural runoff [20–24]. However, most studies have focused on Budapest [20] and its industrial surroundings, whereas other major cities, such as Debrecen [21,22], Szeged [5,12,23,24], and industrial cities [25–28], remain underrepresented.

This lack of geographic balance is particularly concerning in the case of Debrecen, which has recently experienced rapid industrial expansion, including various sectors that could be a potential source of emissions of heavy metals. These developments, along with increasing urban traffic and intensive land use, have raised critical concerns regarding potential soil contamination and environmental risks [29]. Although advanced analytical tools, such as GIS-based modeling, remote sensing, and multivariate statistics, are increasingly being applied to detect contamination hotspots [18,19,30], localized geochemical studies in Debrecen remain scarce. As a result, baseline data are insufficient and long-term contamination trends are difficult to assess.

Despite Hungary's progress in environmental policies and soil quality evaluation, systematic long-term monitoring of heavy metal pollution in urban soils remains inadequate. Ensuring compliance with European soil quality directives [31] demands the implementation of targeted monitoring, especially in cities undergoing accelerated industrialization such as Debrecen. To address these challenges, the city has recently implemented a state-of-the-art environmental monitoring system to detect potential risks and to ensure public access to reliable environmental data [32]. This study aims to address this knowledge gap by assessing the concentration, spatial distribution, and potential sources of heavy metals in the urban soils of Debrecen.

The specific objectives are as follows:

1. Identification of typical heavy metals and their concentrations in the urban topsoil of Debrecen;
2. Determination of pollution sources using multivariate statistical analysis to differentiate industrial, traffic, and natural contributions;
3. Development of spatial distribution maps using geostatistical interpolation methods to locate contamination hotspots and assess environmental risks;
4. Comparison of the results with Hungarian and European (EI) soil quality standards to evaluate contamination severity and compliance with regulations.

By addressing these objectives, this study aims to fill the existing research gap in Debrecen's urban soil contamination analysis and provide scientific data to support environmental policy making and urban planning initiatives.

2. Materials and Methods

2.1. Study Area

Debrecen (47.531 N, 21.625 E) is located in Hajdú-Bihar County, eastern Hungary, at the boundary between the Hajdúság and Nyírség microregions of the Great Hungarian Plain. The city lies in a transitional zone, where loess-based soils in the west gradually shift to sandy deposits in the east [21,33,34] (Figure 1).

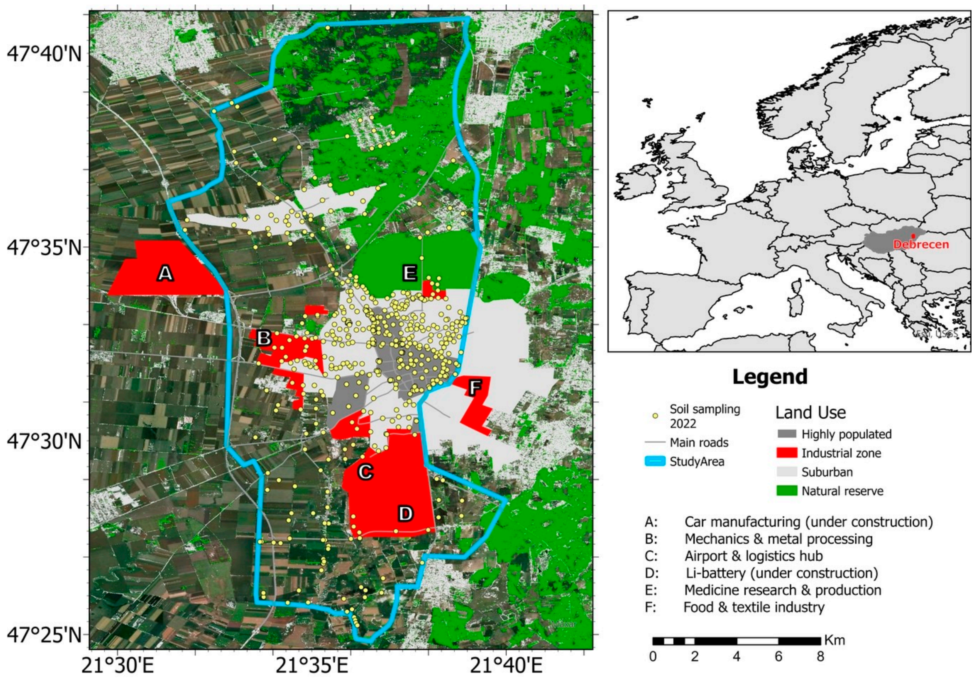

Figure 1. Sampling sites denoted on the map of the city of Debrecen.

The city experiences a continental climate, with hot summers, cold winters, and continuously decreasing annual precipitation of approximately 550 mm. The study was conducted from August to September 2022 during an extremely dry year, which minimized the effects of soil moisture and enhanced the detection of dry atmospheric deposition from industrial and traffic-related emissions. Dry deposition, resulting from airborne dust and pollution settling onto soil surfaces, plays a crucial role in heavy metal accumulation in urban soils, making this period particularly suitable for contamination.

Typically, in the Debrecen region, the depth of the topsoil ranges between 2 m and 3 m, with previous studies indicating that the distribution of heavy metal contamination originated from transportation, urban settlements, and activities [21,22,33,34]. Table 1 summarizes the baseline heavy metal loadings in Debrecen, compared with the corresponding Hungarian geochemical region values (range and expected) and global background values [35,36].

Currently, Debrecen's urban pollution sources include pharmaceutical production facilities, airports with increasing passenger traffic, and several smaller industrial companies with expanding industrial zones. In recent years, large-scale industrial investments in various sectors have been made that could be potential sources of heavy metal emissions such as Pb, Cu, Zn, Ni, and Cr [29]. These, along with the significant traffic emissions from major roads and highways, represent key sources of urban soil contamination. Agricultural runoff from surrounding farmlands contributes to soil contamination through fertilizer and pesticide applications. These diverse land uses and pollution sources, in combination with the region's variable soil properties, result in heavy metal retention and mobility that differ across the study area [3,5,34]. The main soil and land cover types are shown in Figure 2.

Table 1. Background heavy metal loadings (measured at 60 cm depth) in Debrecen derived from the Geochemical Atlas of Hungary, compared with the corresponding Hungarian geochemical region values (range and expected) and global background values [35,36].

Element	Map Readings	Country-Scale Factor Analysis		World Average
		Range	Expected	
As	5–30	5.4–22	12.00	20.0
Cd	0–3	0.5–10.4	20.0	2.20
Co	6–12	9.4–14	2.20	13.40
Cr	15–51	27–92	13.40	79.00
Cu	0–46	21–103	79.00	18.00
Ni	12–27	25–41	18.00	46.00
Pb	10–30	100–600	46.00	18.00
Zn	30–120	30–120	132.00	79.00

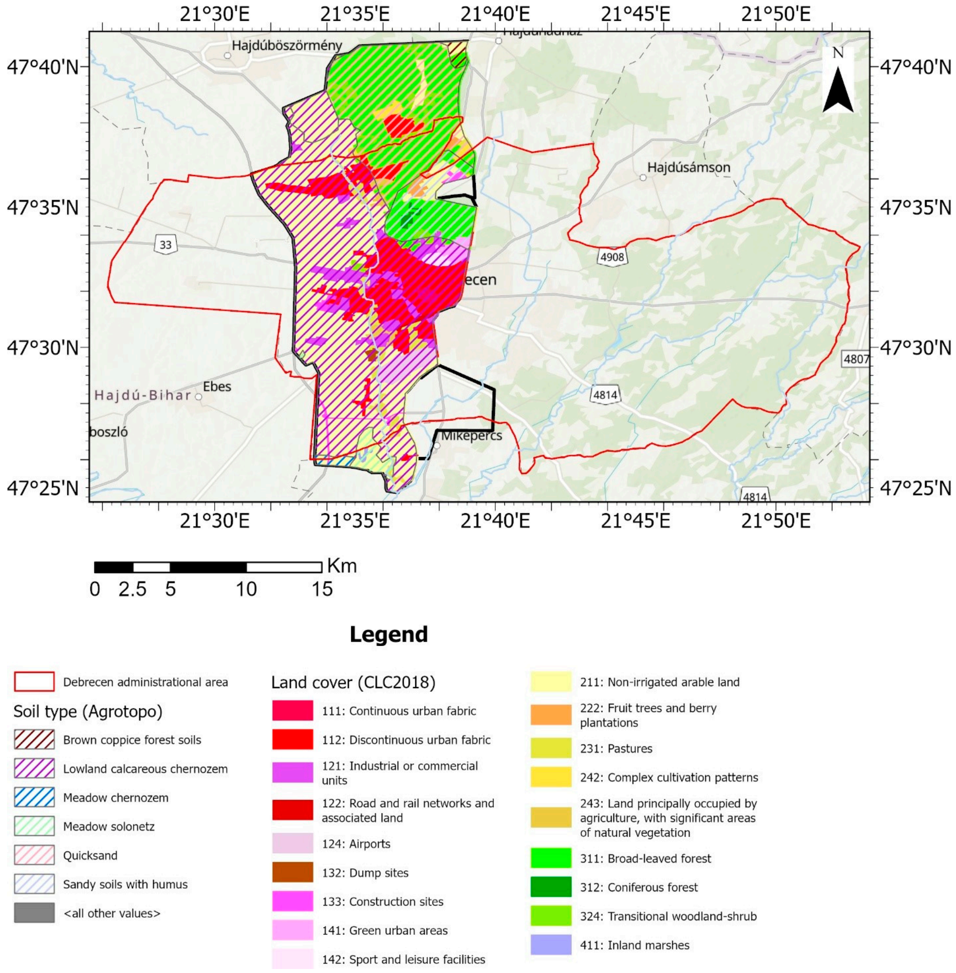

Figure 2. Soil and land cover conditions of the study area.

2.2. Soil Sampling Strategy

Given the diverse pollution sources and their spatial variability, a stratified random sampling approach was employed to ensure a comprehensive and representative coverage of all major environmental influences. The sampling design was based on the methodology recommended by the United States Environmental Protection Agency [37], which enhances the efficiency and reliability of environmental monitoring by accounting for varying pollution levels across land use types. Land-use categories were delineated using municipal zoning maps [29] and verified against CORINE land cover data to ensure consistent classification of sampling strata (Figure 1). Unlike regular grid sampling, which applies to a uniform density, this source-oriented approach allows for greater flexibility in targeting high-risk areas, while maintaining balanced coverage across the urban landscape.

Three primary groups were defined based on pollution intensity and land-use characteristics. The first group focused on background pollution, with sampling points placed in a 500 × 500 m grid in areas presumed to be free from direct industrial or traffic-related influences. These samples served as reference data for evaluating deviations in more affected zones. The second group encompassed agricultural areas, where pollution levels were expected to remain relatively uniform over larger scales; thus, a lower sampling density was used to avoid redundancy while ensuring broad spatial coverage. Agricultural land, expected to be more homogeneous, was sampled at a lower density (0.19 samples/km^2). The third group targeted industrial and high-risk urban zones, such as the vicinity of pharmaceutical production facilities, where a higher sampling density was used to detect localized heavy metal accumulation. Higher densities were also applied in the city center (7.52 samples/km^2) and suburban areas (3.34 samples/km^2), where human activity and potential exposure are greatest. Particular attention was paid to delineating the boundaries between different land-use zones with sufficient detail, while at the same time avoiding oversampling that could introduce bias in the subsequent estimations. Industrial areas and recreational zones were sampled at intermediate densities, reflecting both accessibility constraints and the need to capture potential contamination hotspots. Additional samples were collected from major traffic corridors and urban hotspots to assess contamination from vehicular and industrial emissions. The full distribution of samples across land-use categories is summarized in Table 2.

Table 2. Allocation of soil samples among land-use categories.

Land Use	Area (km^2)	Sample Count	Density (km^{-1})
Urban core	8.77	66	7.52
Industrial	26.35	18	0.68
Suburban	40.13	134	3.34
Recreation	9.65	7	0.73
Agriculture	361.02	70	0.19

2.3. Chemical Analysis and Mechanical Properties

A total of 295 soil samples were collected from the topsoil layer (0–10 cm) to evaluate pollution inputs. Sampling was performed using a stainless-steel hand auger in accordance with EU and Hungarian guidelines [38,39]. The inert materials and plant residues were removed in situ.

Fieldwork was coordinated using ArcGIS Field Maps Early Access release (August 2022) installed on mobile phones; sampling was simultaneously conducted by ten independent field teams. The geographical position of each sampling point was automatically recorded in the cloud, along with the estimated GPS accuracy, which was typically below 3 m and consistently below 10 m. Given the high spatial density of the sampling network, the positioning uncertainty was considered negligible at the scale of the analysis. To improve sample representativeness and reduce the effects of small-scale heterogeneity, each composite sample was prepared from 8 to 12 subsamples collected within a 10 × 10-m area at each sampling location. The cleaned soil samples were placed in labeled polyethylene bags, transported under controlled conditions, and stored at room temperature (20–25 °C) in a well-ventilated room. The samples were dried at 70 °C until a constant mass was reached for further laboratory analysis. The sampling campaign was conducted under dry weather conditions to minimize soil moisture interference and to enhance the detection of dry-deposited pollutants [5,19].

Dried soil samples were sieved through a 2 mm mesh (Retsch system) to remove coarse particles, following the international standard [40]. The particle size distribution was determined using laser diffraction in accordance with international methods [41], which provided clay (<2 μm), silt (2 μm–20 μm), and sand (20 μm–2 mm) proportions for each sample. The particle and bulk densities were measured using a pycnometer and a graduated cylinder, respectively, based on the ISO standard [42]. Porosity was calculated from these values (Equation (1)); the results were used to estimate the saturated hydraulic conductivity and water retention curves using the van Genuchten model (Equation (2)) [43]:

$$P = \left(1 - \frac{\rho_b}{\rho_p}\right) \times 100 \tag{1}$$

where

P is the porosity [%];

ρ_b is the bulk density [kg m^{-3}];

ρ_p is the particle density [kg m^{-3}]:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha\,|\psi|)^n\right]^{1-\frac{1}{n}}} \tag{2}$$

where

$\theta(\psi)$ represents the water retention curve [m^3 m^{-3}];

$|\psi|$ is the suction pressure [m];

θ_s is the saturated water content [m^3 m^{-3}];

θ_r is the residual water content [m^3 m^{-3}];

α is associated to the air entry suction, $\alpha > 0$ [m^{-1}];

n is a measure of the pore-size distribution, $n > 1$ [-].

2.4. Soil Composition and Elemental Content

To characterize the chemical properties of the soil, multiple laboratory analyses were conducted, including pH, organic and inorganic components, and elemental concentration analyses. Soil pH was measured using a 1:5 (*v*/*v*) suspension with 1 M KCl solution for 2 h, following the ISO standard [44], which is a widely accepted method for determining soil pH. The calcium carbonate ($CaCO_3$) content was determined using the volumetric method [45], since it significantly influences heavy metal solubility and retention. Organic matter (OM) content was measured using the sulfochromic oxidation method [46], which serves as an indicator of soil fertility and microbial activity, both of which affect the metal-binding capacity.

2.5. Heavy Metal Element Analysis

To assess soil heavy metal contamination, elemental analysis was conducted using a handheld X-ray fluorescence (XRF) spectrometer (Explorer 9000, Jiangsu Skyray Instrument Co., Ltd., Kunshan, Jiangsu Province, China), which provides rapid, non-destructive, and multi-elemental detection. The measurement time per sample was 60 s with 10 replicates. The instrument was calibrated by using standard soil sample so-called certified reference materials (Blank 180–428, RCRA 180–436 and NCS 73308). Daily correction was used to correct instrument drift. Results were accepted when the RSD values of the measured elements were less than 5.0%. Before the analysis, the detection limits for the analyzed elements were established at the used instrument. The obtained values were as follows: As (1.5 mg kg^{-1}), Cd (2 mg kg^{-1}), Co (2.5 mg kg^{-1}), Cr (5 mg kg^{-1}), Cu (5 mg kg^{-1}), Ni (1 mg kg^{-1}), Pb (5 mg kg^{-1}), and Zn (5 mg kg^{-1}). To ensure measurement reliability, periodic blank sample analyses were conducted to monitor potential contamination; drift corrections were applied to compensate for instrumental variation over time. Precision and accuracy were further supported by repeated measurements; relative standard deviation (RSD) calculations were used to assess instrument stability.

The measured concentrations were compared with natural background levels typical of uncontaminated Hungarian soils and with the average values reported in international datasets. Hungarian soil quality regulations [47] and Dutch soil quality standards [48], which include target and intervention values, served as reference points for contamination thresholds. These benchmarks allowed for the distinction between geogenic and anthropogenic contributions.

2.6. Statistical Analysis

A combination of descriptive statistics, correlation analysis, multivariate statistical methods, and geostatistical techniques was applied to evaluate the distribution patterns, relationships, and potential sources of heavy metals and other analyzed elements. These analyses provided insights into elemental variability, associations between pollutants, and spatial trends in soil contamination across Debrecen.

Descriptive statistical parameters, including mean, median, minimum, maximum, standard deviation, and interquartile range (IQR), were calculated for each analyzed element to assess variability and distribution. To determine whether the dataset followed a normal distribution, the Kolmogorov–Smirnov (K–S) test was conducted, which is suitable for large sample sizes and allows for the assessment of deviations from normality. If the data did not meet normality assumptions, logarithmic transformation was applied to stabilize the variance and improve the suitability for parametric analyses.

Spearman's rank correlation coefficient was calculated to explore the relationships between the elements and detect potential common contamination sources. This non-parametric measure of association is particularly useful for non-normally distributed datasets and helps to identify whether specific elements exhibit similar geochemical behavior. Strong correlations indicated possible shared contamination sources, whereas weak or negative correlations suggested independent variations in the element distribution.

Multivariate statistical methods were employed to further classify elements based on their compositional similarities and pollution origins. Hierarchical clustering using Ward's method with Euclidean distance was applied to group elements with similar spatial distribution patterns and distinguish natural from anthropogenic contamination sources. Factor analysis (FA) was conducted to reduce data dimensionality and identify latent variables representing pollution sources. The analysis was performed using varimax rotation; factors with eigenvalues greater than one were retained for interpretation. Factor loadings above 0.6 were considered significant, helping to distinguish between natural and anthropogenic influences on soil contamination.

Linear discriminant analysis (LDA) was conducted to assess whether heavy metal concentrations could effectively distinguish between different land use categories. This method tested the assumption that land use influences contamination patterns by varying surface practices, anthropogenic pressures, and exposure pathways. LDA also highlighted the elements most responsible for group separation, thereby supporting the interpretation of pollution sources and informing the targeted environmental risk assessments.

2.7. Spatial Estimation with Ordinary Kriging

Geostatistical techniques were applied to investigate the spatial distribution of heavy metals in the soil and detect areas of heightened contamination. By leveraging geographic information system (GIS) tools, discrete soil sampling data were transformed into continuous distribution models, facilitating a clearer interpretation of pollution patterns and enabling a more comprehensive environmental assessment.

The interpolation of heavy metal concentrations was performed in ArcGIS Pro using ordinary kriging, a geostatistical method that accounts for spatial autocorrelation to enhance predictive accuracy. Unlike deterministic techniques, such as inverse distance weighting (IDW) or spline interpolation, which rely on direct distance-weighted averaging, ordinary kriging optimizes predictions by minimizing the variance in estimation errors. This advantage makes it particularly suitable for modeling contaminants that exhibit spatial dependency.

To refine the interpolation accuracy, semi-variogram modeling was employed to characterize the degree of spatial continuity among the sampling points. The model functions (exponential, spherical, or Gaussian) were fitted to the experimental variograms, with the final choice guided both by geostatistical plausibility and by cross-validation statistics. Root mean square error values from leave-one-out cross-validation were used as an empirical measure of predictive accuracy.

Because several heavy metal concentrations exhibited highly skewed distributions, log transformation was applied prior to interpolation to stabilize the variance and approximate normality, which is an assumption underlying ordinary kriging.

Although the sampling points were irregularly distributed, ordinary kriging was inherently compensated for by implementing a Lagrange multiplier in its system of equations. This mechanism ensures that the weights are optimally balanced and sum to one, thereby preventing bias even in areas with locally dense observations. In contrast to other kriging variants, such as universal kriging and simple kriging, which may require manual cluster decomposition to address such density-related distortions, ordinary kriging handles spatial imbalance more effectively and automatically, making it well suited to the present dataset.

Furthermore, ordinary kriging inherently behaves as a low-pass spatial filter (LPSF). Although it effectively captures regional trends and smooths local fluctuations, it attenuates extreme values simultaneously. Consequently, the range of interpolated concentrations becomes consistently narrower than that of the original dataset as both the lower and upper extremes are shifted toward the mean. This smoothing behavior can lead to apparent inconsistencies between the original tabular data and interpolated maps. Because both high and low extremes are attenuated, kriged surfaces may show elevated minima and reduced maxima compared to the measured values. As a result, mapped concentrations may appear less extreme than those observed in the field, potentially obscuring localized environmental risks or exaggerating background levels. The final contamination distribution maps provided insights into the extent and intensity of heavy metal accumulation across various land-use categories, including industrial zones, residential areas, and agricultural fields.

3. Results

3.1. General Physical and Chemical Properties of the Soils

The most important analytical parameters of soil samples from each sampling point were determined (Table 3). Due to the large number of soil samples, only the statistically summarized data are displayed.

Particle size analysis confirmed a predominantly sandy texture with an average sand content of 94.9% (range: 62.9–99.9%). The silt and clay contents were significantly lower, with averages of 3.3% and 1.9%, respectively. The high variability in the silt (RSD = 26.1%)

and clay (RSD = 25.6%) fractions suggests localized inputs of finer particles, possibly from atmospheric deposition, construction materials, or varying parent materials. The studied area is characterized by loess formation.

Table 3. Descriptive statistics of soil physical and chemical properties (*N* = 295).

	pH-KCl	$CaCO_3$ (%)	OM (%)	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g cm^{-3})	Porosity (%)
Mean	6.7	0.3	1.6	94.9	3.3	1.9	1.5	36.9
Median	6.7	0.2	1.3	95.7	2.7	1.5	1.4	36.9
Min	6.0	0.1	0.4	62.9	0.1	0.0	1.3	36.0
Max	7.5	1.2	1.9	99.9	8.3	11.0	1.6	38.4
SD	0.3	0.0	0.5	3.8	2.5	1.6	0.2	0.2
RSD (%)	4.5	6.7	13.4	4.0	26.1	25.6	11.4	0.5

According to the USDA classification, soils predominantly fall into sand and loamy sand categories (Figure 3), which is consistent with the observed dominance of coarse particles. Such textures are typical of disturbed or artificially reworked urban soils, often characterized by low water and nutrient retention capacity.

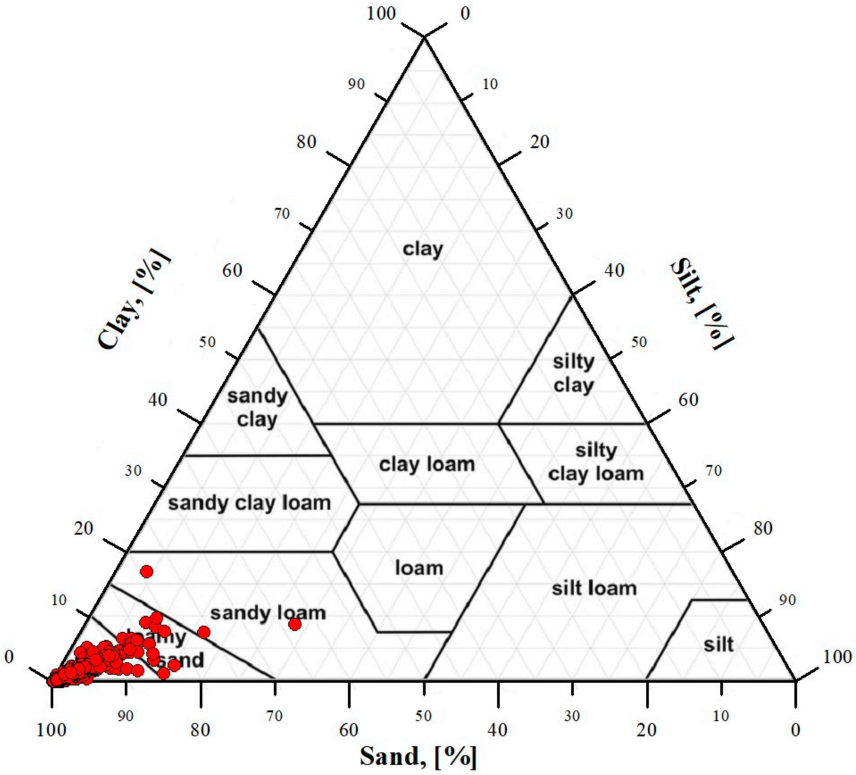

Figure 3. USDA soil texture triangle of the collected soil samples.

Bulk density values ranged from 1.3 to 1.6 g cm^{-3}, with an average of 1.5 g cm^{-3}, which is typical for soil types in this region [21]. This range reflects varying compaction levels, from very loose zones (e.g., in areas with high organic content or landscaping) to more compacted zones (e.g., walkways or traffic-affected sites). The RSD of 11.4% supports this interpretation of mechanical variability in urban topsoil compaction.

The porosity estimates ranged from 36% to 38.4%, with an average of 36.9% and very low RSD of 0.5%. This consistency suggests a relatively uniform pore space distribution, possibly due to the dominance of sandy particles and shallow sampling depth, which limits natural stratification. Consequently, the vertical mobility of the topsoil layer was pronounced; the sorption ability was expected to be weak due to the lack of clay minerals in the investigated soils that otherwise would be able to adsorb positively charged ions such as heavy metals. Therefore, this area is highly sensitive to the vertical movement of different heavy metals, which affects the migration of pollutants [33].

The pH values of the KCl solution ranged from 6.03 to 7.52, with a mean of 6.70, and a relatively low standard deviation (SD = 0.30; RSD = 4.48%), indicating that the soils were mildly acidic to neutral. Such near-neutral values are typical of the soil types found in this region.

The calcium carbonate ($CaCO_3$) content was uniformly low, ranging from 0.1% to 1.2%, with an average of 0.3%. Such minimal carbonate levels indicate decalcified surface horizons, which are typical of urban soils that have undergone leaching or mechanical disturbances. The low variability (RSD = 6.7%) reflects the consistent depletion of carbonates across the sampled sites.

The organic matter (OM) content showed a wider variability, with values ranging from 0.4% to 1.9% and a mean of 1.6%. The relative standard deviation (RSD = 13.4%) indicates heterogeneous organic enrichment, potentially influenced by varying land cover types, vegetation, waste deposition, or localized management practices typical of urban zones [34].

3.2. Exploratory Analysis of Heavy Metal Contaimnation

The concentrations of eight heavy metals commonly found in urban soils were analyzed using a dataset of 295 surface soil samples. The results, summarized in Table 4, include descriptive statistics such as medians, trimmed means, standard deviations, and coefficients of variation.

Table 4. Measured heavy metal contents in urban soils of Debrecen (mg kg^{-1}) (N = 295).

	Median	Trimmed Mean (5%)	Standard Deviation	Coeff. of Variation	Min	Max	Stnd. Skew	Stnd. Kurt
As	9.75	10.6	3.98	0.359	6.03	35.7	**16.71**	**26.8**
Cd	1.64	1.74	0.96	0.533	0.11	5.4	**7.85**	**6.74**
Co	8.47	8.47	2.26	0.266	1.16	23.9	**6.99**	**24.7**
Cr	77.7	77.9	29.6	0.379	4.99	162.0	0.87	−0.4
Cu	29.9	66.8	154	1.711	4.51	1030	**20.33**	**31.8**
Ni	19.5	19.9	10.2	0.509	0.03	47.3	1.03	−1.9
Pb	23.5	30.2	37.5	1.08	0.05	181.1	**9.34**	**7.9**
Zn	78.1	93.2	89.7	0.85	12.62	769.4	**22.12**	**52.9**

Bold indicates significant deviation from a normal distribution.

Additional comparisons were made with data from other European urban environments [18,19,49] to place the results from Debrecen in a broader geographical context.

In descending order of median concentrations, the elements were: Zn (78.1 mg kg^{-1}) > Cr (77.7 mg kg^{-1}) > Cu (29.9 mg kg^{-1}) > Pb (23.5 > Ni (19.5 mg kg^{-1}) > As (9.75 mg kg^{-1}) > Co (8.47 mg kg^{-1}) > Cd (1.64 mg kg^{-1}). Histograms of heavy metal concentrations (Figure 4) showed non-normal distributions for most elements with pronounced right skewness, except for Cr, and possibly Co, which were closer to normality. The log-normal pattern observed for Cu, Pb, Zn, and Cd is typical in environmental geochemistry, where a few samples exhibit unusually high values, whereas most remain near the background levels.

Notably, zinc exhibited the highest median concentration among the analyzed elements. Although it remains below the Dutch intervention threshold, elevated levels are concentrated in the western–central part of the city, likely associated with long-standing and ongoing industrial operations, indicating a persistent localized source of contamination.

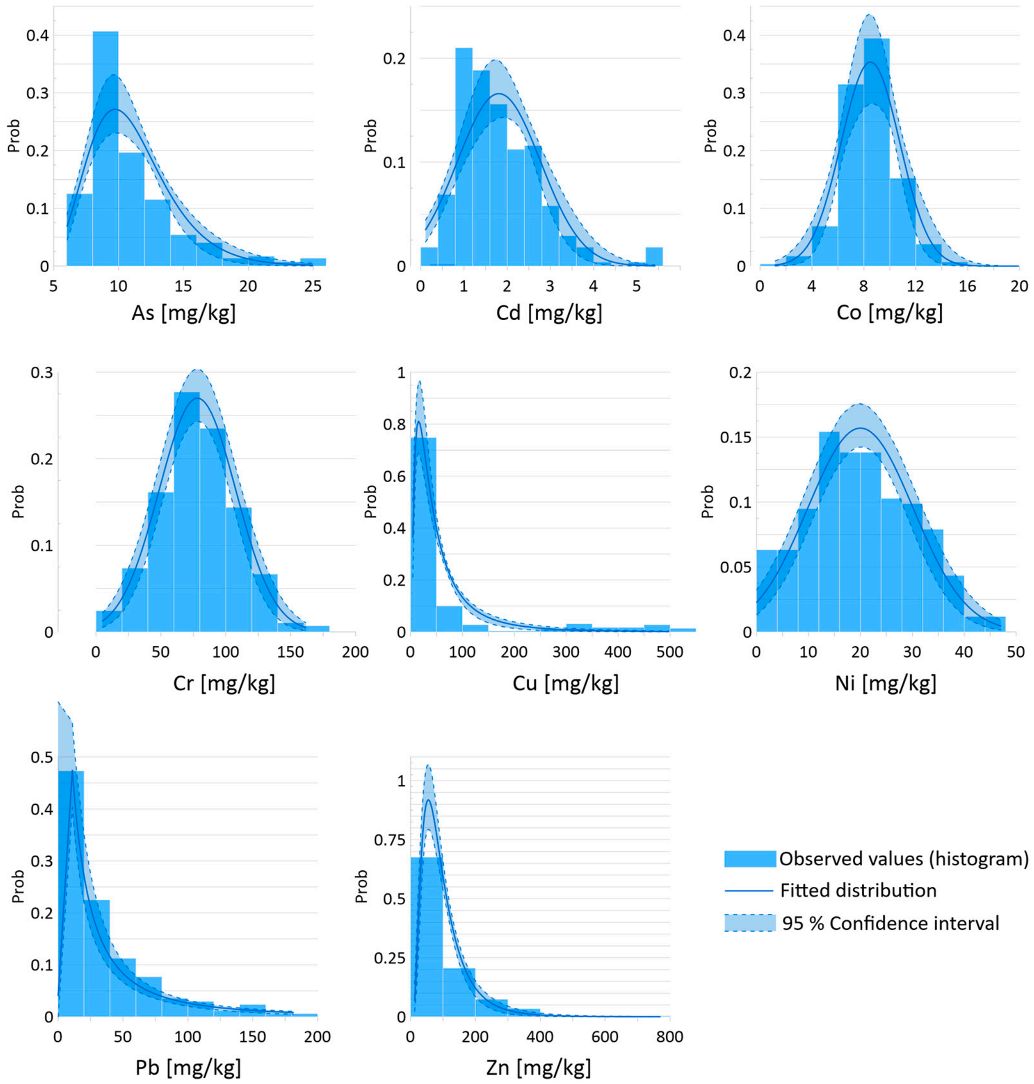

Figure 4. Statistical distribution of measured heavy metal concentrations.

Cu and Zn displayed significant variation, with extreme values observed at certain locations. Cu concentrations ranged from 4.51 to 1030 mg kg^{-1}, with a very high standard deviation of 154 mg kg^{-1} and an RSD of 171.1%. Zn levels ranged from 12.62 to 769.4 mg kg^{-1}, also showing substantial variability (RSD = 85%). Extremely skewed distributions (standardized skewness: Cu = 20.33; Zn = 22.12) and high kurtosis values confirmed the presence of extreme outliers. These patterns indicate localized anthropogenic enrichment, which is most plausibly associated with traffic hubs, industrial emissions, and construction-related surface deposition. The pronounced variations in copper and zinc concentrations are clearly attributable to localized point sources (see industrial zone marked as B in Figure 1). This area, formerly used as a landfill and currently occupied by metal-processing facilities, exhibited exceptionally high levels of both elements. In contrast, within the remaining parts of the study area, the concentrations of both elements remained below the regulatory limit values.

Lead (Pb) showed a median of 23.5 mg kg^{-1}, which is considerably lower than values reported for other central European cities (e.g., Novi Sad: 82.3 mg kg^{-1}; Belgrade: 298.6 mg kg^{-1}) [19,30]. Although the maximum Pb concentration of 181.1 mg kg^{-1} remained below the Dutch intervention threshold (530 mg kg^{-1}), the strong positive skewness (9.34) and high kurtosis (7.9) suggest localized contamination. Lead showed a spatial distribution similar to that of zinc, with the highest concentrations in industrial zone B and the densely populated city center. These hotspots likely reflect traffic emissions, metal-processing activities, and the legacy of former landfilling. In urban soils, Pb levels are thus shaped by the combined effects of historical contamination (leaded fuel, paints, industry) and present-day diffuse sources (traffic dust, demolition activities, waste).

The highest cadmium loads were also detected in the densely populated city center and in the nearby industrial zones (Figure 1). Cadmium (Cd) concentrations had a median of 1.64 mg kg^{-1}, exceeding both Hungarian (1 mg kg^{-1}) and Dutch (0.8 mg kg^{-1}) target values in many samples. Although the maximum concentrations remained below the intervention thresholds, the combination of elevated means and a sharp right-skew (skewness = 7.85) suggests anthropogenic input, possibly from waste or atmospheric deposition and traffic (Figure 4).

The arsenic (As), nickel (Ni), cobalt (Co), and chromium (Cr) concentrations generally remained within acceptable limits. The highest arsenic levels were measured in the northern part of the city, near the pharmaceutical factory. Arsenic showed a median concentration of 9.75 mg kg^{-1}, well below the threshold range of 15–20 mg kg^{-1}. Cobalt (8.47 mg kg^{-1}) and nickel (19.5 mg kg^{-1}) exhibited moderate variability, with relative standard deviations of 26.6% and 50.9%, respectively, and no evidence of significant anthropogenic enrichment.

A summary of relevant values in the literature for metal concentrations in urban soils across Europe is presented in Table 5.

Table 5. Average metal concentration (mg kg^{-1}) in urban soils from European cities.

Study Area	As	Cd	Co	Cr	Cu	Ni	Pb	Zn	Reference
Budapest (HUN)	14.73	*	9.54	138.19	56.24	28.2	302.94	47.11	[20]
Novi Sad (SRB)	6.5	*	7.3	28	38.8	28.7	82.3	100.3	[19]
Beograd (SRB)	*	1.8	16.5	*	46.3	*	298.6	174.2	[50]
Zagreb (CRO)	*	0.4	10.9	54.6	56.1	35.2	23.2	77.9	[18]
Ljubljana (SVN)	*	*	*	34	39	26	87	148	[15]
Sevilla (ESP)	*	*	*	34	55	28	123	105	[15]
Murcia (ESP)	*	0.13	*	19.2	11.8	11.7	67.9	21.57	[10]
Torino (ITA)	*	*	*	171	90	185	169	182	[15]
Berlin (GER)	5.1	0.73	*	35	79.5	10.7	119	243	[16]
major metropolises	13	0.29	6.4	59	46	22	102	130	[4]
Dutch Target	29	0.8	9	100	36	35	85	140	[48]
Hungarian regulation	15	1	30	75	75	40	100	200	[47]
Debrecen	9.75	1.64	8.47	77.7	29.9	19.5	23.5	78.1	This study

* not measured.

Compared to these reference cities, the results from Debrecen show that Cu, Pb, and Zn concentrations are generally lower than the averages reported for major urban centers, including Budapest, Torino, and Belgrade. In Serbia, leaded fuels were produced and sold for general use until 2010, while in Hungary the fuels were sold until 2004.

In contrast, cobalt and nickel levels in Debrecen were somewhat higher than the average values documented across major cities in a study by [4]. This may reflect regional differences in the parent material or historical land use.

Among the western Balkan capitals, the values measured in Debrecen most closely resemble those reported for Ljubljana [15,49]. Notably, in cities with historically intense traffic, such as Belgrade, significantly elevated Pb concentrations were observed [50]. This was largely attributed to traffic emissions, particularly the historic use of leaded petrol, which remained in use in Serbia at the time of soil sampling.

A comparison of regional background values and global soil averages (Table 5) indicates that urban soils in Debrecen are affected by moderate enrichment of typical “urban” metals such as Cu, Pb, Zn, and Cd. While the contamination levels are not as extreme as in some other European metropolises, the presence of outliers and high variability in certain elements underscores the influence of localized anthropogenic inputs. These findings are consistent with observations across many European cities, where historical and ongoing urban activities have led to spatially heterogeneous metal accumulation in the surface soils [17].

3.3. Multivariate Assessment of Heavy Metal Contamination

Factor analysis (FA) and linear discriminant analysis (LDA) require approximately symmetric data distributions for meaningful interpretation. Copper (Cu), zinc (Zn), lead (Pb), and cadmium (Cd) were log-transformed to stabilize variance and align the data structure (Figure 5).

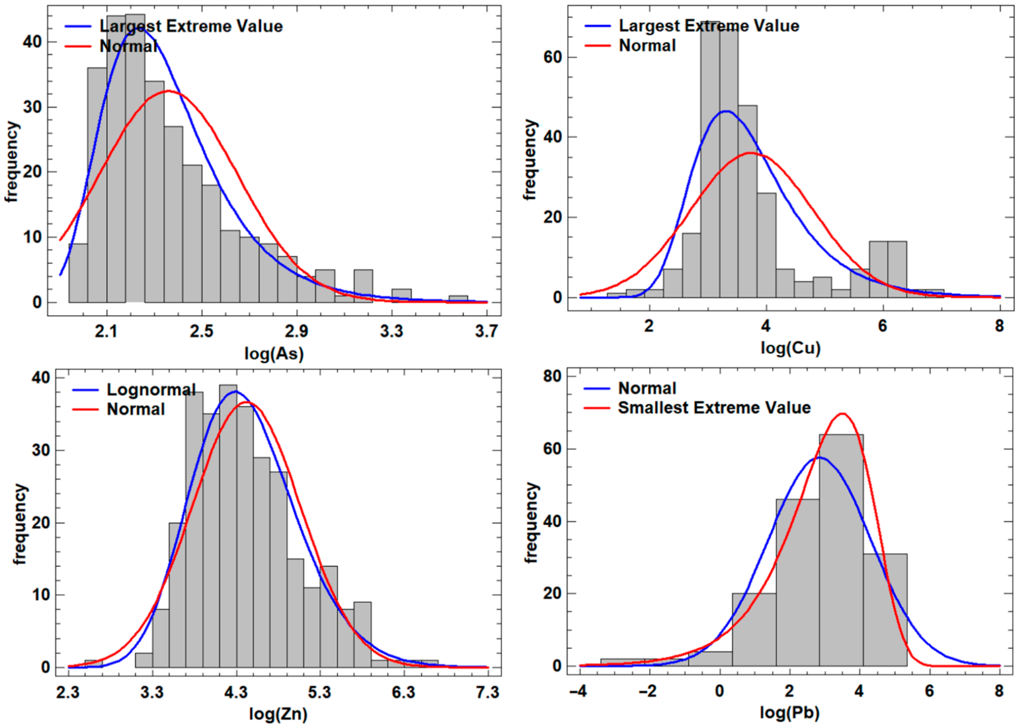

Figure 5. Log transformation of statistical distributions for As, Cu, Zn, Pb.

Spearman's correlation analysis was then used to explore potential co-behavior and common sources among heavy metals (Table 6). Although robust to non-normality, applying consistent data transformations facilitates interpretability across statistical approaches. This analysis revealed two dominant clusters of elements with distinct geochemical signatures, thereby suggesting different sources of contamination.

Table 6. Correlation matrix (Spearman's ρ) for heavy metal concentrations.

	Cd	Co	Cr	log(Cu)	Ni	log(Pb)	log(Zn)
log(As)	0.3125	**0.566**	0.1051	0.1947	−0.0868	**0.719**	**0.7156**
Cd		−0.0641	**−0.4682**	0.149	**−0.5809**	0.0749	0.1117
Co			**0.5018**	0.288	0.2673	0.3802	**0.4641**
Cr				0.0118	**0.7062**	0.1046	0.1142
log(Cu)					−0.1437	0.095	0.2779
Ni						−0.1053	−0.1149
log(Pb)							**0.474**

Bold indicates considerable relationships.

To further support the grouping patterns, hierarchical clustering was performed using Ward's method with Euclidean distance, revealing similar associations among the elements (Figure 6).

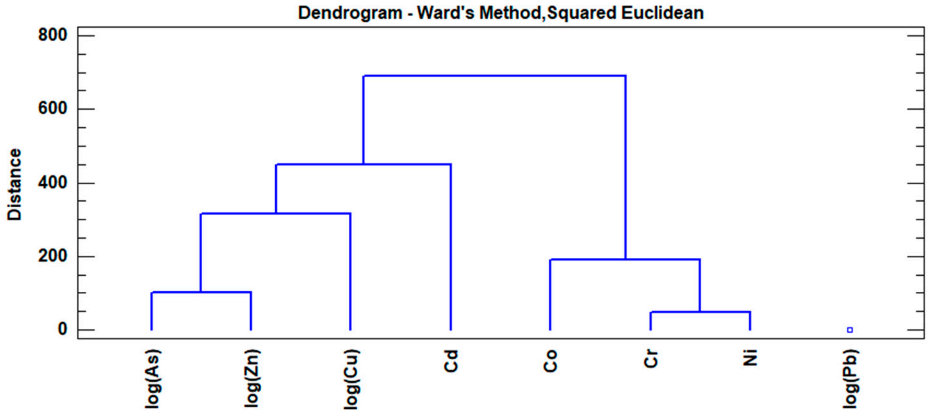

Figure 6. Hierarchical clustering of metal concentrations via Ward's linkage.

The first group includes arsenic (As), cobalt (Co), lead (Pb), and zinc (Zn). These elements were intercorrelated with coefficients, such as As–Pb (r = 0.72), As–Zn (r = 0.72), Pb–Zn (r = 0.47), and As–Co (r = 0.57), indicating a high degree of co-occurrence. This cluster is most likely linked to anthropogenic sources, particularly those associated with urban environments, including the historical use of leaded petrol, vehicular emissions, building materials, and the atmospheric deposition of metal-rich dust. The simultaneous enrichment of Pb and Zn in urban surface soils is well-documented in European cities, whereas As and Co are often associated with long-term diffuse pollution from traffic, fuel combustion, and possibly agrochemical residues [15,49]. The second cluster consisted of nickel (Ni), cadmium (Cd), and chromium (Cr). These elements showed moderate to strong correlations, including Cr–Ni (r = 0.70) and Cd–Ni (r = −0.58). Although the Cd–Ni relationship was negative, it still suggested a shared but inversely varying pattern, potentially reflecting competition for uptake or contrasting local sources. The Cr–Ni linkage is geochemically plausible, because both elements are commonly associated with ultramafic and alluvial parent materials. Thus, this second cluster is interpreted as being more strongly controlled by natural geogenic factors such as soil mineralogy and the composition of the underlying sediment.

Interestingly, Cu did not show strong correlations with either cluster, which could be attributed to its highly skewed distribution (Figures 5 and 6) and the presence of extreme outliers. This may indicate multiple overlapping sources of Cu such as mechanical wear, industrial inputs, and localized hotspots unrelated to the broader geochemical background.

In summary, the correlation structure supports the distinction between anthropogenic clusters (As, Co, Pb, and Zn) and natural or mixed-origin clusters (Ni, Cd, and Cr).

3.4. Factor Analysis

Factor analysis (FA) was applied to the standardized dataset to identify common patterns and underlying factors in the urban soils of Debrecen. The analysis aimed to group variables with similar spatial behavior and potentially common sources, reducing dimensionality while preserving most of the variance in the dataset.

The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was 0.618, indicating that the data structure was appropriate for factor analysis. Bartlett's test of sphericity confirmed the suitability of the data for factor analysis (chi-square = 416.463, $p < 0.001$), suggesting significant correlations among the variables.

Three factors with eigenvalues greater than one were extracted, jointly explaining 73.40% of the total variance in the dataset (Table 7). The first factor accounted for 34.99% of the variance, while the second explained 25.85% and the third contributed 12.55%. The factor loadings after standardization are shown in Figure 7.

Table 7. Explained variance of heavy metal concentrations based on factor analysis.

Factor	Initial Eigenvalues			Extraction of Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**
1	2.80	35.00	35.00	2.80	35.00	35.00	2.90	36.30	36.30
2	2.07	25.85	60.85	2.07	25.85	60.85	2.21	27.68	63.97
3	1.00	12.55	73.40	1.00	12.55	73.40	0.75	9.43	73.40
4	0.82	10.26	83.66						
5	0.55	6.81	90.47						
6	0.32	3.96	94.43						
7	0.28	3.51	97.94						
8	0.16	2.06	100.00						

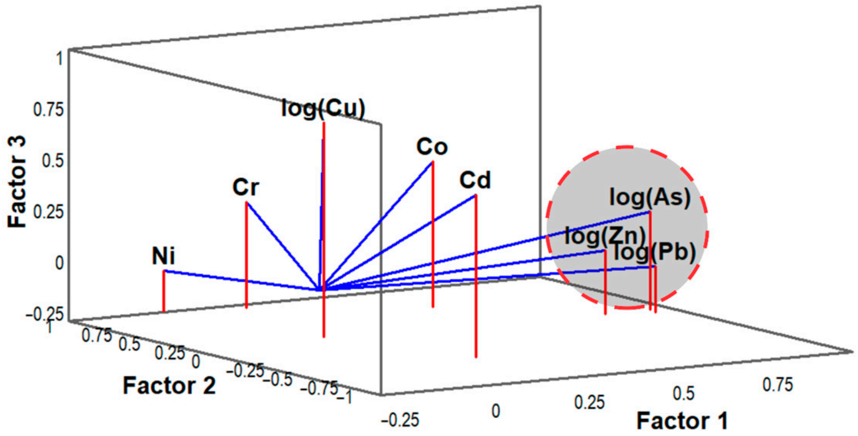

Figure 7. Urban soil contamination patterns revealed by varimax-rotated factors.

Factor 1 was characterized by high positive loadings for log(As) (0.885), log(Pb) (0.876), log(Zn) (0.770), and Co (0.492), clearly indicating a group of elements associated with anthropogenic activities, especially urban pollution. These elements are commonly found in areas with high traffic density, historical industrial use, and intense infrastructure development. The presence of Co in this component may reflect mixed inputs in urban environments, although sometimes of natural origin (Table 8).

Table 8. Exploratory factor loadings after orthogonal varimax rotation.

Element	Factor 1	Factor 2	Factor 3
log(As)	0.885	0.018	0.229
Cd	0.175	−0.613	0.543
Co	0.492	0.490	0.462
Cr	0.129	0.825	0.270
log(Cu)	0.0483	0.090	0.798
Ni	−0.054	0.918	−0.050
log(Pb)	0.875	−0.038	−0.025
log(Zn)	0.769	0.024	0.058

Factor 2 showed strong loadings for Ni (0.919) and Cr (0.826), which are typically regarded as indicators of natural geogenic sources, likely reflecting the mineralogical composition of the alluvial parent material in Debrecen's soils. This grouping aligns well with the second cluster, identified earlier in the correlation analysis. Cd loaded negatively on Factor 2 (−0.614); its moderate contribution suggests a more complex source or behavior that may be partially influenced by both lithogenic and anthropogenic factors.

In contrast, log(Cu) was not strongly associated with any of the two main components. Instead, it loaded most heavily on Factor 3 (0.799), suggesting a distinct behavior that may reflect localized or point-source pollution such as construction debris, vehicular wear, or occasional industrial input. The weak correlation with the main anthropogenic clusters also supports this interpretation.

4. Discussion

4.1. Mapping and Spatial Analysis

The spatial behavior of trace metal concentrations across the urban landscape of Debrecen was evaluated using interpolated maps. Ordinary kriging was employed for each element for interpolation (Figure 8). The best-fitting functions—exponential, spherical, or Gaussian—were selected by evaluating the model's performance based on the root mean square error (RMSE) (Table 9). These maps facilitated the identification of contamination hotspots and assessment of spatial trends related to land use, pollution sources, and potential ecological risks. The reliability of the interpolation was also evaluated using kriging standard deviation maps (Figure 8), which depict the prediction uncertainty across the study area.

Table 9. Applied variogram models for estimating heavy metal loadings, with leave-one-out cross-validation error (RMSE) and hotspot potential of the analyzed elements.

Element	Variogram Model Equation	RMSE	Hotspot Potential
Arsenic (As)	$\gamma(\mathrm{h}) = 0.26066\mathrm{Nugget} + 0.40420\mathrm{Gaussian}(8320.5, 4770.4, 173.0) + 0.41328 * \mathrm{Spherical}(773.73, 268.17, 168.2)$	3.52	Low—largely smooth gradient, only minor local variation
Cadmium (Cd)	$\gamma(\mathrm{h}) = 0.57930\mathrm{Nugget} + 0.18247\mathrm{Spherical}(1898.1, 633.13, 86.1) + 0.22277 * \mathrm{Gaussian}(7568.8, 2849.5, 140.8)$	0.88	High—patchy distribution, strong micro-scale variability
Cobalt (Co)	$\gamma(\mathrm{h}) = 0.69342\mathrm{Nugget} + 0.16179\mathrm{Spherical}(2611.7, 873.69, 51.7) + 0.19310 * \mathrm{Gaussian}(3000, 1296.9, 16.2)$	2.20	High—likely small-scale hotspots, nugget dominates
Chromium (Cr)	$\gamma(\mathrm{h}) = 0.77685\mathrm{Nugget} + 0\mathrm{Spherical}(4238.0, 1582.0, 45.0) + 0.25159 * \mathrm{Gaussian}(4238.0, 1420.4, 17.9)$	27.50	High—nugget overwhelms structure, hotspots expected
Copper (Cu)	$\gamma(\mathrm{h}) = 0.07945\mathrm{Nugget} + 0.26021\mathrm{Spherical}(377.29, 125.87, 84.9) + 0.77189 * \mathrm{Gaussian}(6967.0, 2554.3, 174.0)$	90.23	Unlikely—very smooth, well-structured spatial field
Nickel (Ni)	$\gamma(\mathrm{h}) = 0.67056\mathrm{Nugget} + 0.14385\mathrm{Spherical}(1180.6, 393.68, 88.6) + 0.17102 * \mathrm{Gaussian}(4125.0, 1375.5, 89.5)$	9.44	High—patchy, short-range heterogeneity expected
Lead (Pb)	$\gamma(\mathrm{h}) = 0.45454\mathrm{Nugget} + 0.28753\mathrm{Spherical}(1636.7, 548.18, 102.0) + 0.27885 * \mathrm{Gaussian}(4999.9, 3410.9, 11.6)$	35.69	Low—balanced, hotspots not dominant
Zinc (Zn)	$\gamma(\mathrm{h}) = 0.53349\mathrm{Nugget} + 0.45808\mathrm{Spherical}(6925.9, 4552.1, 9.1)$	82.12	Low—strong regional structure, limited hotspot risk

The spatial patterns of Cr, Ni, and Co were relatively uniform, with only moderate variation and no clear clustering. This homogeneous distribution supports the conclusion, based on FA and correlation analysis, that these elements are mainly derived from natural geological sources and are likely associated with the mineral composition of local sandy alluvial deposits.

In contrast, Cu, Pb, Zn, As, and Cd exhibited strong spatial heterogeneity. Elevated concentrations were particularly prominent in densely built-up zones, city centers, and areas adjacent to major traffic routes. These spatial patterns suggest anthropogenic enrichment and are consistent with typical urban metal inputs, either from traffic emissions, particularly the legacy effects of leaded gasoline and mechanical wear, or from construction and demolition waste, which are often associated with elevated levels of arsenic and lead. Electronic waste, municipal refuse, and sewage sludge contributed to the variability in the Cd, Cu, and Zn concentrations.

Several localized hotspots were observed (Figure 8). Notably, Pb and Zn exhibited high concentrations in central urban locations, whereas Cd showed isolated peaks near the industrial sites. Cu displayed exceptional variability, with some exceptionally high values potentially linked to either past agricultural use of copper-based fungicides or localized waste disposal.

These patterns are in good agreement with previously identified anthropogenic clusters (As, Pb, Zn, and Co) and geogenic clusters (Cr and Ni). Cd exhibited intermediate behavior, reinforcing its identification as a metal with both point-source enrichment and background variation.

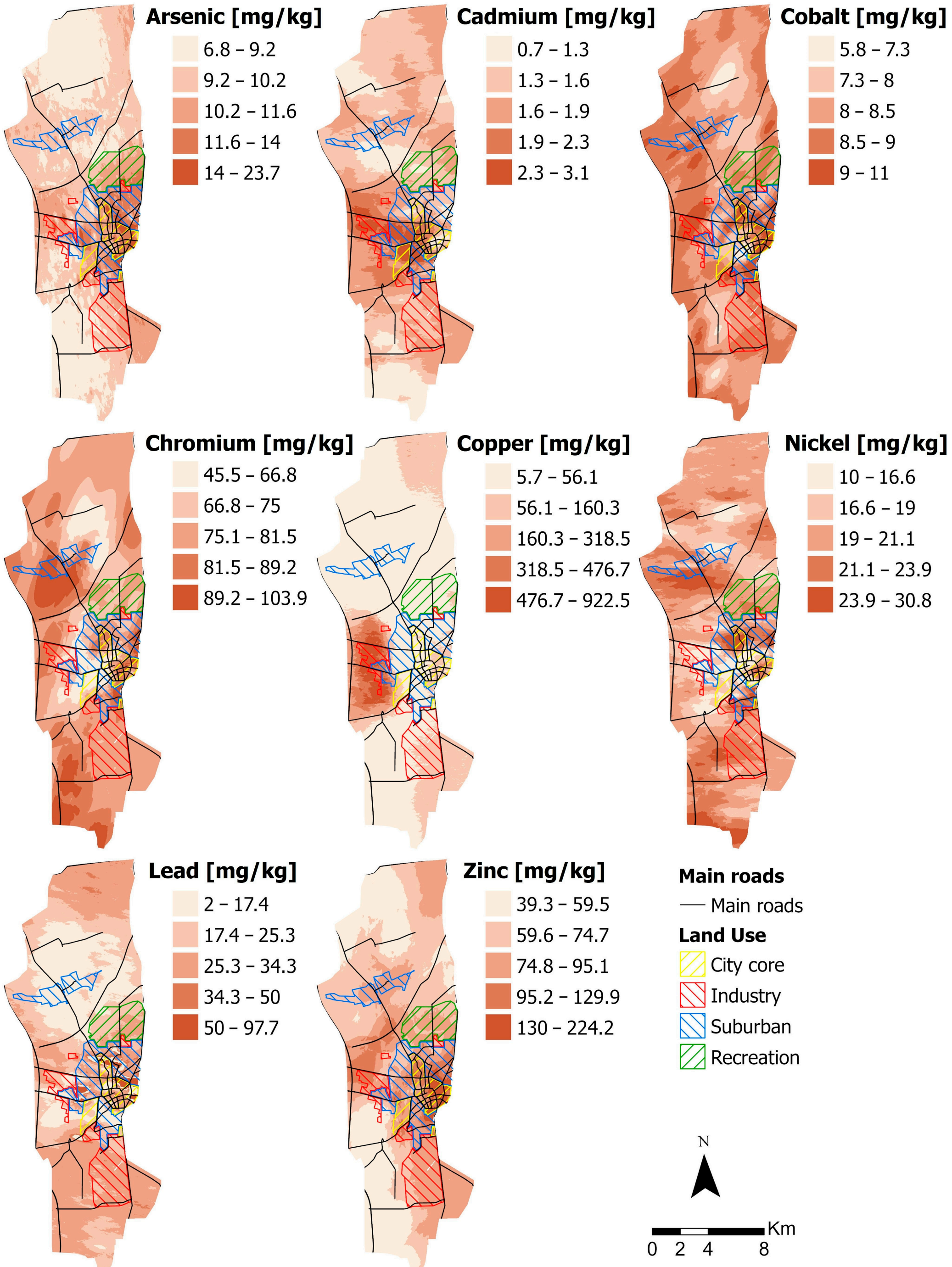

Figure 8. Element-wise spatial distribution of potentially toxic metals in Debrecen soils.

4.2. *Evaluation of Relationship Between Land Use and Heavy Metal Contamination*

Discriminant analysis was applied to evaluate whether the concentrations of the investigated heavy metals could distinguish between the five distinct land-use types (Figure 1). The first three canonical discriminant functions were statistically significant (Wilks' $\lambda = 0.321$, $p < 0.001$), jointly explaining 97.9% of the total variance in the dataset with individual contributions of 64.6%, 27.1%, and 6.2%. The eigenvalues associated with the three functions were 0.97, 0.41, and 0.09, respectively, indicating that the majority of discriminating power resided in the first function. The most influential predictors based on the standardized canonical coefficients were Zn (–1.55), Cr (+0.57), Cu (+0.56), As (+0.50), and Co (+0.32). These findings were corroborated by the structural matrix, where Zn ($r = -0.77$) and As ($r = +0.75$) showed the highest correlations with the first discriminant axis.

The overall classification accuracy was 66.1%, which was significantly higher than that of random chance ($\chi^2 = 410.57$, df = 32, $p < 0.001$). The cross-validated (leave-one-out) classification confirmed the robustness of the model, with a slightly lower accuracy of 63.9%. Agricultural land and urban green spaces were classified best, with accuracy rates of 85.7% and 100%. Suburban gardens, parks, and villa areas had more classification errors, with an accuracy rate of around 54.2%. Zinc levels in these areas showed high variation ($\sigma = 47.1$). Urban residential zones (apartment blocks, old town, shopping areas) also overlapped with other types, with an accuracy rate of 85.5%; however, several misclassifications still occurred due to mixed land use. The canonical centroids reflected this. Agriculture scored −2.15 and green spaces scored +2.42, while mixed residential zones were near zero on the first canonical function. Mahalanobis distances between the groups ranged from 2.1 to 6.8, with the largest gap between agriculture and industrial or commercial areas.

Box's M test revealed significant differences in the variance–covariance matrices across groups (Box's M = 219.3; F = 1.42; $p = 0.016$), suggesting mild violations of the homogeneity assumption. Additionally, high intervariable correlations, such as Zn–As ($r = 0.80$) and Zn–Co ($r = 0.77$), indicated the presence of multicollinearity, which may have affected the stability of the model parameters.

5. Conclusions

In this study, the concentrations and spatial patterns of eight heavy metals (As, Cd, Co, Cr, Cu, Ni, Pb, and Zn) in the urban topsoil of Debrecen, Hungary were investigated. Overall, the results indicated moderate contamination levels, with localized hotspots of Cu, Pb, Cd, and Zn, particularly in high-traffic and industrial areas, suggesting clear anthropogenic enrichment. In contrast, Cr, Ni, and Co exhibit more uniform distributions, indicating a geogenic origin.

Multivariate analyses (correlation, hierarchical clustering, and FA) consistently identified two distinct metal groupings: one dominated by traffic- and waste-related pollutants (As, Pb, Zn, and Co), and another reflecting natural lithological contribution (Ni, Cr, and Cd). Cu remained ungrouped and displayed strong local variability linked to mixed inputs.

Both spatial interpolation and discriminant analysis confirmed these patterns, revealing urban centers as focal points of contamination. Compared to other European cities, Debrecen's heavy metal levels are moderate, although specific elements, such as Cd and Cu, occasionally exceed regulatory thresholds, necessitating site-specific monitoring.

Given its anticipated industrial and transportation developments, the accumulation of heavy metals is probably going to be further exacerbated; therefore, the results provide a critical baseline for future environmental assessments and long-term monitoring.

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