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Contents and Site-Specific Variations of Potentially Toxic Elements (PTEs) in the Feces of the Laughing Dove *Spilopelia senegalensis* as an Indicator of Environmental Contamination in an Urban Area (a case study of Yerevan, Armenia)

Lusine Aydinyan
researcher.contact.lusine@gmail.com

Scientific Center of Zoology and Hydroecology
Vahram Hayrapetyan
Scientific Center of Zoology and Hydroecology
Astghik Gevorgyan
The Center for Ecological-Noosphere Studies
Gevorg Tepanosyan
The Center for Ecological-Noosphere Studies

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Abstract

This pilot study aimed to characterize the chemical composition of feces from the laughing dove *(Spilopelia senegalensis*), assess site-specific variations in element concentrations within the urban environment of Yerevan, and evaluate their potential as bioindicators of pollution. Sampling was conducted across central and peripheral districts of Yerevan, encompassing areas with varying levels of anthropogenic impact. A total of 16 samples were collected and analyzed using X-ray fluorescence (XRF) spectrometry (Rigaku NEX DE) for 18 elements, including Si, Al, Ca, K, P, S, Fe, Ti, Mn, Zn, Cu, Sr, Rb, Pb, Mo, As, Br, and Zr.

The results revealed pronounced spatial heterogeneity in elemental distribution across the urban landscape. Significantly elevated concentrations were detected in industrial peripheral zones (Norabats, Charbakh), where Pb levels reached 17.8 mg/kg, approximately eight-fold higher than those in the city center. Spearman's rank correlation analysis showed strong positive associations between Pb–As (r = 0.93) and Zn–Mo (r = 0.78), indicating shared anthropogenic sources. In contrast, lithogenic elements (Fe, Ti, Al) demonstrated lower inter-site correlations, reflecting geogenic background influence. Hierarchical cluster analysis confirmed a clear separation between anthropogenic metals (Cu, Pb, Zn, Mo, As) and major elements (K, Ca, P, S), which clustered together, indicating natural dietary origin.

The findings demonstrate that laughing dove feces can serve as an effective, non-invasive biomonitoring tool for tracing urban environmental contamination and support the development of long-term ecological surveillance strategies in urban ecosystems.

1 Introduction

Environmental contamination by potentially toxic elements (PTEs) is one of the most critical ecological issues typical for modern urban ecosystems, driven by rapid urbanization, expanding vehicle fleets, and the intensification of industrial activities. PTEs (e.g., Pb, Cd, Zn, Cu, Ni, etc.) are characterized by their persistence, bioaccumulation capacity, and toxic effects; consequently, they can remain in the environment over several years and enter biological cycles, posing significant threats to both ecosystem stability and human health.

Over the past decade, there has been a growing interest in the application of bioindicators as tools for the integrated assessment of environmental contamination. Birds are widely utilized in ecotoxicological research due to their broad geographic distribution, diverse trophic levels within food webs, and continuous interaction with the different environmental media (Dauwe et al., 2000; Espín et al., 2016).

Avian biological samples, including feathers, eggs, and feces, facilitate the evaluation of the bioavailability and impact of environmental contaminants (Espín et al., 2016; Sadeghi et al., 2019).

Avian feces are considered a non-invasive and highly informative bioindicator substrate that reflects the occurrence of PTEs ingested through both dietary pathways and the respiratory system. Bird feces are frequently employed as a reliable matrix to measure exposure levels to dietary contaminants (Belskii et al., 1995; Berglund et al., 2015; Costa et al., 2014; Janssens et al., 2003).

In urban ecosystems, the primary sources of PTEs include vehicular traffic, fuel combustion, construction dust, and industrial emissions. The cumulative impact of these factors leads to the accumulation of PTEs across various compartments of the urban environment, which can subsequently be incorporated into biological circulation, subsequently posing severe risks to human health (Kampa & Castanas, 2008).

As a densely populated and rapidly developing city, Yerevan is characterized by high traffic intensity and diverse industrial sectors, both of which contribute to the accumulation of PTEs in the environment (Armstat, 2025). Recent studies have demonstrated that the concentrations of PTEs (e.g., Pb, Cu, Zn, As) in the urban soils and dust of Yerevan exceed baseline and safety thresholds. Furthermore, spatial distribution patterns of PTEs exhibit distinct zoning, often corresponding to the specific location of a potential pollution source or an urban functional zone (Tepanosyan et al., 2017). These spatial patterns can also be reflected within biological matrices.

The scientific novelty of this study is further enhanced by the simultaneous investigation of 18 chemical elements, including specific minor and trace elements (Mo, Zr, Rb, and Br). Although non-invasive multi-element biomonitoring methods are well-established and widely implemented in international literature, global data cannot address the specific ecological and geochemical gaps of Armenia. Each geographic region possesses a distinct lithogenic background and unique urban pollution dynamics. Therefore, by focusing on these rarely prioritized elements within the local context, this study bridges a critical regional knowledge gap and establishes the first baseline for urban avian ecotoxicology in the South Caucasus This research establishes baseline data for developing a new biomonitoring strategy to assess and characterize the contamination dynamics in Yerevan.

The objective of this pilot study was to investigate the chemical composition of laughing dove (*Spilopelia senegalensis*) feces, to identify spatial variations across the central and peripheral districts of Yerevan, and to evaluate the potential of using *Spilopelia senegalensis* droppings as a bioindicator of urban PTE contamination. The findings of this study will complement existing environmental monitoring frameworks and contribute to a more comprehensive assessment of potential ecological risks in urban ecosystems.

2 Materials and Methods

2.1. Study Area and Studied Species

The study was conducted in the capital city of Yerevan, incorporating two primary environmental typologies: the central urban zone and the peripheral industrial outskirts (Fig. 1). The central site is Republic Square (coordinates: 40.177973, 44.515451), which is characterized by high population density

(Armstat, 2025), intensive traffic flows, and commercial and administrative activity, all of which contribute to the accumulation of PTEs across various environmental compartments.

The peripheral environment comprises the Norabats–Charbakh area (coordinates: 40.108329, 44.427077 and 40.143605, 44.464522). This zone features a relatively sparse population (Armstat, 2025) but hosts active industrial plants and various anthropogenic infrastructure. Consequently, pronounced and intensive PTEs anomalies are manifested in various environmental components within this area (Tepanosyan et al., 2016). Norabats is physically contiguous with the Charbakh industrial sector, generating additional environmental risks associated with the bioaccumulation of PTEs.

The fecal matter of the laughing dove (*Spilopelia senegalensis*), one of the most common avian species in both central and peripheral urban environments, was selected for investigation. Laughing doves feed primarily on seeds, grains, and opportunistic vegetable matter; due to their residential lifestyle and foraging behavior, which bring them into close contact with urban substrates, they may effectively reflect local environmental levels of PTEs and other contaminants (Coeurdassier et al., 2012; Eeva et al., 2020).

In general, the analysis of avian feces - specifically from laughing doves in this study - constitutes a non-invasive method that enables the assessment of localized PTEs contamination without disrupting the health or natural behavior of the birds. During the breeding season, laughing doves forage within restricted home ranges, feeding predominantly on seeds, grains, and green plant matter (Adamian & Klem, 1999). This localized foraging ensures that the elemental concentrations detected in the feces possess high reliability, reflect a local origin, and serve as direct indicators of localized environmental pollution (Berglund et al., 2015).

2.2. Feces sampling

Throughout the study, a strict non-invasive approach was prioritized to minimize potential stress factors for the local avifauna. Fresh fecal samples were collected exclusively from active nests and their immediate vicinity. Species identity was confirmed through direct visual observation of nesting adults during sampling. This method allowed the retrieval of the necessary biological material without capturing or physically handling the birds, aligning fully with international ethical standards for wildlife research. Each sample was collected using sterile instruments to prevent cross-contamination and was immediately placed into clean 1.5 mL polypropylene tubes. By focusing sampling directly on nesting sites, a "zero-interference" principle was maintained, ensuring that the natural behavior and nesting processes of the birds remained undisturbed throughout the entire sampling period. The number of samples collected from each study site is as follows: Norabats (peripheral) = 5 samples, Charbakh (peripheral) = 7 samples, and Republic Square (central) = 4 samples (total n = 16). The spatial distribution of the sampling sites is illustrated in Fig. 1.

The collected samples were initially preserved at -20°C and subsequently dried under laboratory conditions at 40°C for 72 hours until complete moisture elimination was achieved. The dried samples were then homogenized and ground by an agate mortar and pestle into a fine powder. The mean moisture content (± SD) of the samples was 79.0 ± 6.1%, from which a wet-to-dry weight conversion factor of 0.210 was calculated and applied to adjust the final PTEs concentrations.

This methodological framework provides an indirect but informative approach for assessing the accumulation of PTEs within local urban food webs adjacent to nesting sites. Concurrently, it eliminates any negative sampling impacts on the target population, adhering firmly to the principles of non-invasive monitoring (Berglund et al., 2015; Coeurdassier et al., 2012; Eeva et al., 2020).

2.3. Chemical Analyses

The determination of the chemical elements in avian feces (Si, Al, Ca, K, P, S, Fe, Ti, Mn, Zn, Cu, Sr, Rb, Pb, Mo, As, Br, and Zr) was performed using a Rigaku X-ray fluorescence (XRF NEX DE) analyzer (Rigaku Corporation, Japan). Analytical procedures were conducted at the Department of Environmental Geochemistry of the Center for Ecological-Noosphere Studies. Elemental concentrations were determined on a dry weight basis. The analytical accuracy and reliability of the method were verified using Certified Reference Materials (CRMs: NIST 2710a and NIST 2711a (USA), NCS ZC71021 [China] and duplicate samples demonstrating an accuracy range of 2.0-8.8% and a reproducibility range of 2.7–10.1%.

2.4. Statistics

Statistical analyses were performed using a Python 3.10 environment. Basic descriptive statistics (minimum, maximum, mean values, and standard deviation) were calculated for all 16 investigated elements. For samples displaying element concentrations below the limit of detection (< LOD), specifically in the case of As, Pb, Br, and Mo, the LOD/2 substitution method was applied to ensure the integrity of the multivariate statistical models.

To approximate a normal distribution of the data, a $\log_{10}$ transformation was performed. Inter-element relationships were evaluated using Spearman's rank correlation coefficient and hierarchical cluster analysis, while the urban environment specific PTEs (Cu, Zn, As, Pb, and Mo) and Ca were selected for subsequent detailed analysis. Spatial visualization of the sampling sites was conducted within the ArcGIS 10.8 software environment. This integrated approach enabled an optimal comparison of PTEs concentrations between the Norabats-Charbakh (peripheral) and Republic Square (city center) sites, revealing significant spatial variability patterns of anthropogenic pressure within the urban ecosystem.

3. Results and Discussion

3.1. Concentration of the studied elements

A literature review regarding avian feces as a biomonitoring matrix indicates that this substrate contains a wide spectrum of chemical element concentrations, which directly reflect varying degrees of local environmental contamination (Berglund et al., 2015; Eeva et al., 2020).

The data obtained in this study further verified this established pattern. Specifically, the results demonstrate a pronounced heterogeneity in fecal elemental concentrations, which can be attributed to the varying levels of anthropogenic loading across the studied locations. Laboratory analysis of the dried samples (n = 16) demonstrated that the elemental content, expressed on a dry weight basis (mg/kg), exhibited the variations detailed below.

The statistical analysis results (Table 1) indicate a significant non-homogeneous distribution of chemical elements across the study area. The PTEs, particularly Zn and Pb are characterized by high coefficients of variation (> 100%; 119%, and 161%, respectively) and high positive skewness values (skewness > 1). The notable deviation of maximum values from the mean values (specifically Zn at 481.0 mg/kg and Pb at 17.8 mg/kg) confirms an asymmetric data distribution and points to the existence of localized hotspots of pollution, highlighting potential anthropogenic impacts. Conversely, essential macro-elements (K, Ca, P, and S) exhibit relatively low levels (< 100%), suggesting their natural, lithogenic origin is linked primarily to dietary inputs. Thus, the collected data indicate that the ecological state of the area is shaped by a combination of baseline natural conditions and localized anthropogenic pressures (Table 1).

Table 1
Descriptive statistics of element concentrations (mg/kg) in *Spilopelia senegalensis* fecal samples

Statistics															
	Cu	**Zn**	**As**	**Br**	**Rb**	**Sr**	**Zr**	**Mo**	**Pb**	**K**	**Ca**	**Ti**	**Mn**	**Fe**	**Al**
N	16	16	11	14	16	16	16	12	12	16	16	16	16	16	16
Mean	30.27	98.58	1.19	3.34	2.14	12.93	3.07	1.32	3.04	11658.63	12544.44	377.88	156.11	5968.63	105
Median	22.05	49.75	0.64	1.71	1.21	7.89	1.82	0.82	1.02	11757.00	8257.00	240.00	133.00	2107.00	797
Std. Deviation	21.17	118	1.16	2.90	1.93	13.00	3.14	0.99	4.90	5934.26	12053.22	324.71	104.92	12379.23	503
Skewness	1.04	2.68	1.36	0.73	1.46	1.71	2.17	2.11	2.91	0.23	1.50	1.47	2.33	3.80	1□0
Minimum	9.34	20.40	0.21	0.53	0.20	2.47	0.57	0.68	0.30	2080.00	2251.00	86.00	49.20	419.00	532
Maximum	72.6	481.00	3.64	8.19	7.23	49.20	12.50	3.98	17.80	23450.00	42152.00	1115.00	491.00	51673.00	218 00
CV(%)	70.0	119.3	98.1	86.8	90.1	100.5	102.1	74.8	161.2	50.9	96.1	85.9	67.2	207.4	47□

Note: In the descriptive statistics, mean values (Mean) are calculated based on detected concentrations only (excluding non-detected values: ND). For multivariate statistical analysis, not detected values were replaced using the LOD/2 method.

The highest absolute values for Zn and Cu were recorded at the Norabats site: Zn concentrations ranged from 20.40 to 481.00 mg/kg, while Cu ranged from 10.90 to 72.60 mg/kg. Molybdenum (Mo) content in this zone varied between 0.73 and 3.98 mg/kg (Table 2). In the Charbakh industrial zone, the distribution of elements also exhibited elevated levels: Zn content ranged from 36.10 to 247.00 mg/kg, and Cu ranged between 12.90 and 53.60 mg/kg. The maximum value of Mo here reached 2.23 mg/kg (minimum: 0.68 mg/kg). Comparative analysis indicates that the Zn and Cu concentrations recorded in the Norabats site (and to a lesser extent in the Charbakh industrial zone) significantly exceeded concentration levels reported in similar international studies (Berglund et al., 2015; Coeurdassier et al., 2012).

In contrast to the peripheral zones, values in the central area (Republic Square) were lower: Zn ranged from 23.70 to 75.20 mg/kg, Cu from 9.34 to 48.90 mg/kg, and Mo from 0.78 to 1.13 mg/kg. Nevertheless, lead (Pb) content at Republic Square exhibited a consistently elevated trend (up to 2.13 mg/kg), demonstrating urban pollution driven by intensive traffic flows. This pattern is further amplified by the fact that the city center is located within an intermontane depression; thermal inversions facilitate the atmospheric migration of contaminants from various parts of the city, leading to their precipitation and accumulation in this area. Comparative analysis of the investigated areas demonstrates that the Norabats site stands out with the highest toxic load, where the mean concentrations of Cu (37.40 mg/kg) and Zn (142.2 mg/kg) exceed the levels observed at Charbakh and Republic Square. The content of Pb, whose maximum value in Norabats (17.8 mg/kg) is approximately 8 times higher than the corresponding value in the city center, points to strong industrial and peri-urban anthropogenic influences in this zone (Table 2).

Meanwhile, the content of PTEs at Republic Square is substantially lower and more stable, leading to the conclusion that industrial and peri-urban factors (Norabats and Charbakh) serve as more aggressive sources of environmental contamination than the traffic flows of the center (Table 2; see also Alloway, 2013; Wang et al., 2021).

Table 2
Statistical summary of selected element concentrations in bird droppings by sampling sites (mg/kg)

Sampling Site	Number of samples	Statistic	Cu	Zn	Mo	Pb
Norabats	5	Mean	37.40	142.2	18*	5.28*
		Min	10.90	20.40	0.5	0.30
		Max	72.60	481.00	398	17.8
		±m	14.2	863	079	4.19
Charbakh	7	Mean	294	987	1.14*	2.04*
		Min	129	36.10	0.68	0.45
		Max	536	247.0	223	5.27
		±m	53	28.9	0.29	0.85
Republic Sq.	4	Mean	229	43.8	0.85	1.54
		Min	934	23.7	0.73	0.94
		Max	489	75.2	1.13	2.13
		±m	915	11.9	0.09	0.59

*Note: * values are calculated based on detected concentrations only (excluding ND).**

3.2. Correlation analysis and hierarchical clustering

Statistical analysis confirms a significant positive correlation between Mo and Zn ($r = 0.78$, $p < 0.05$), indicating the presence of potential common anthropogenic sources for these elements within the urban area. This relationship is typical for the soils of the Yerevan city, and is driven by anthropogenic emissions (Tepanosyan et al., 2016).

Macro-elements, such as K, Ca, Mn, and Fe, exhibited wide variations (e.g., Ca: 2251.0–42152.0 mg/kg, Fe: 419.0–51673.0 mg/kg). These values are comparable to international research findings, according to which the macro-element content in avian feces is strictly determined by the chemical composition of local dietary items specific to each avian guild, ranging from vegetation to various invertebrates (Coeurdassier et al., 2012; Eeva et al., 2020). Variations among individual samples can be explained by both spatial contamination and individual dietary preferences (Berglund et al., 2015).

Theoretically, these findings confirm that the feces of the laughing dove represent a reliable non-invasive indicator for local PTEs contamination, especially for resident avian species with high site fidelity, where the concentrations of elements excreted in feces closely correspond to environmental contamination levels (Berglund et al., 2015; Eeva et al., 2020).

Other elements, such as Sr, Rb, and Br, also displayed higher concentrations in the peripheral area, reflecting the potential influence of local industrial emissions. In contrast, key essential elements (K, Ca, Fe, Mn, Al, Si, P, S) showed less variation between the central and peripheral sites, suggesting that these elements primarily reflect nutritional intake rather than localized environmental contamination.

Analysis of the correlation matrix confirms strong and statistically significant relationships ($p < 0.01$ and $p < 0.05$) among the PTEs, indicating potential similarities in their emission sources. Specifically, strong positive correlations were recorded for the pairs Pb-As ($r = 0.93$), Pb-Zn ($r = 0.62$), and Zn-As ($r = 0.71$), which is characteristic of the combined impact of urban transport and industrial emissions. Furthermore, the strong positive correlation of Fe with Pb ($r = 0.82$), Zn ($r = 0.88$), and As ($r = 0.89$), alongside Cu ($r = 0.91$) and Zr ($r = 0.85$), demonstrates that urban dust may acts as the primary medium for the transport and bioaccumulation of these elements. These statistical data support the application of *Spilopelia senegalensis* as a reliable bioindicator for evaluating multi-element environmental contamination (Fig. 2).

The Spearman correlation matrix obtained between the studied elements (Fig. 2) presents the systemic results of the entire sample ($n = 16$), allowing the identification of general patterns of interrelationship and accumulation of the studied chemical elements characteristic of the urban environment. Notably, even when analyzing the whole sample ($n = 16$), the strong positive correlation recorded between Pb and As ($r = 0.93$) serves as the primary indicator of the anthropogenic load within this ecosystem. This close interrelationship is characteristic of both the intensive vehicular traffic hubs in central areas and old industrial zones, where anthropogenic emissions predominate over natural background conditions. The predominantly strong to very strong positive correlations among these contaminants (with r mostly exceeding 0.70, ranging up to 0.94 for Zn–Cu and 0.93 for Pb–As) underscore industrial dust and vehicular emissions as unified, dominant source Hierarchical cluster analysis (Fig. 3) showed that metals associated with industrial pollution (Cu, Zn, Pb, Mo, and As) form a distinct cluster, clearly differentiating from essential elements (K, Ca, Al, Si, and Ti). The strong relationship observed between PTEs and lithogenic indicators (Fe, Ti, Al) suggests that the fecal matrix reflects the mineralogical characteristics of ingested soil. While Fe and Mn oxides typically adsorb PTEs within the soil matrix, the acidic environment of the avian digestive tract facilitates their partial mobilization, followed by complexation with organic ligands, which aligns with processes described in physiologically based extraction studies (Ruby et al., 1996).

The results of this study demonstrate that feces serve as a reliable, non-invasive indicator for assessing localized metal contamination, with peripheral areas in close proximity to industrial activities exhibiting elevated concentrations of PTEs compared to the central zone. These patterns are consistent with

previous studies utilizing avian feces as biomonitoring matrices for environmental metal pollution (Berglund et al., 2015; Coeurdassier et al., 2012; Eeva et al., 2020).

3.3 Discussion

The results of this study demonstrate that laughing dove feces serve as a reliable and spatially sensitive bioindicator of urban environmental contamination by PTEs. The obtained data reveal distinct and statistically substantiated differences between the central and peripheral industrial areas, particularly for metals driven by anthropogenic activities.

In the Charbakh area, which is subject to significant industrial impact, the concentrations of PTEs (Cu, Zn, Pb and Mo) exceeded the minimum recorded values in the sample by 3.8 to 23.6 times. Noteworthy is the wide concentration range observed among the elements; a comparison of maximum values reveals that Zn (481.0 mg/kg) displayed the highest maximum value, exceeding the maximum levels of Cu (72.6 mg/kg) by 6.6 times and Pb (17.8 mg/kg) by 27 times. Analysis of internal elemental variability indicates that the maximum Zn content is 23.6 times higher than its minimum value (20.4 mg/kg), whereas for Cu, this difference is 7.7-fold (72.6 vs. 9.34 mg/kg). These highly pronounced numerical differences can be related to the concentrated contribution of industrial emissions and anthropogenic dust to the processes of Zn and Cu accumulation (Berglund et al., 2015; Eeva et al., 2020).

Within this study, special attention was paid to the distribution of molybdenum (Mo). The maximum concentration of Mo (3.98 mg/kg) exceeds the minimum value of the sample (0.68 mg/kg) by 5.8 times and the median value of the sample (0.82 mg/kg) by 4.8 times. Such a wide range between minimum and maximum values indicates high variability, which may reflect both natural heterogeneity and possible anthropogenic influence (Reimann et al., 2008). Considering that the natural background content of Mo in soils typically ranges between 1.1 and 1.5 mg/kg (Stafford et al., 2016), the recorded maximum values indicate an anthropogenic origin specific to local industrial sources. The relatively high variability of Mo (CV = 74.8%) further supports this hypothesis, aligning with the fact that metal-processing plants are located adjacent to the sampling sites, where Mo acts as a signature component of industrial dust.

These variations observed in PTE concentrations demonstrate a significant contribution of industrial emissions and anthropogenic dust to the bioaccumulation of PTEs, aligning with previous studies that have shown similar patterns in urban and industrial landscapes (Berglund et al., 2015; Coeurdassier et al., 2012; Eeva et al., 2020; Tepanosyan et al., 2021).

The detection frequencies and maximum values of As and Mo were also higher in the Charbakh samples, pointing to the influence of specific industrial sources, as these elements are typically associated with metallurgical waste, fuel combustion, and certain manufacturing processes. The high Spearman correlation coefficients ($r = 0.55–0.93$, $p < 0.001$) among Cu, Zn, Pb, Mo, and As confirm their co-accumulation and the presence of common anthropogenic sources.

In contrast to the studied PTEs, the major macro-elements (K, Ca, Fe, Mn, P, and S) exhibited relatively minor spatial variations. Their concentration ranges correspond with published data on the chemical composition of baseline dietary items in avian diets, indicating that these elements are primarily regulated through dietary intake and physiological mechanisms rather than directly reflecting localized contamination (Eeva et al., 2020).

The results of hierarchical clustering (Fig. 3) showed that the studied chemical elements form two distinct groups. Particularly, the first group includes Cu, Zn, Pb, and Mo - elements identified as being of anthropogenic origin in the study area. This association of elements have also been traced for the soils of Yerevan, displaying anomalous levels in the southern and southwestern parts of the city (Tepanosyan et al., 2016). This demonstrates that the primary factor governing the distribution of these studied metals is the degree of environmental contamination rather than individual dietary or physiological variations.

The results of the present study are consistent with international research evaluating urban ecosystem contamination. Specifically, studies conducted on the rock dove (*Columba livia*) indicate that differences in PTEs concentrations, even across adjacent areas, are determined by the limited mobility of the birds and the influence of localized pollution sources (Frantz et al., 2012). This supports the spatial characteristics recorded across different zones of Yerevan and indicates that *Spilopelia senegalensis* reliably reflects the ecotoxicological state of the target area.

Similar results have been obtained for the great tit (*Parus major*), where metal accumulation is directly linked to the level of pollution (Janssens et al., 2003). The elevated Zn values recorded in our study (up to 481.0 mg/kg) exceed the background levels reported in European populations, such as for the pied flycatcher (*Ficedula hypoleuca*) (Berglund et al., 2011). In this context, our findings are in agreement with international data that consider Mo as a characteristic anthropogenic "fingerprint" of metallurgical and mechanical engineering emissions (Biasioli et al., 2007). Although data regarding Mo in avian feces remain sparse, similar accumulation patterns in industrial zones have been documented in studies of other urban biotas. This confirms the anthropogenic nature of the element within Yerevan's urban ecosystem as well, proving that *Spilopelia senegalensis* reliably reflects the specific profile of local anthropogenic loading. Overall, the high anthropogenic load of the studied areas confirms the applicability of *Spilopelia senegalensis* as a sensitive bioindicator in urban ecosystem monitoring, and it can be successfully utilized for investigating environmental PTEs pollution in urban areas both in Armenia and internationally.

In summary, the evidence-based results of this study confirm that the chemical composition of *Spilopelia senegalensis* feces reliably reflects the spatial distribution of PTEs in the urban environment. The obtained data can serve as a scientific foundation for environmental risk assessments in the industrial areas of Yerevan and for the development of future biomonitoring programs.

This study has several limitations that should be acknowledged. The sample size was relatively limited, and environmental substrates such as soil, dust, or insects were not analyzed simultaneously. Therefore, the identified contamination pathways should be interpreted cautiously. Future studies incorporating larger sample sizes, seasonal replication, and parallel environmental sampling would provide a more comprehensive understanding of PTE transfer within urban ecosystems.

4. Conclusions

This study demonstrates that the feces of the laughing dove *(Spilopelia senegalensis)* represent a sensitive and reliable non-invasive matrix for assessing the spatial patterns of PTE contamination within urban ecosystems. The obtained results revealed clear site-specific variability in element concentrations among the investigated areas of Yerevan, reflecting differences in anthropogenic pressure associated with industrial activity and urban infrastructure.

Elevated concentrations of Cu, Zn, Pb, and Mo recorded in the peripheral industrial zones (Norabats and Charbakh) indicate the substantial influence of anthropogenic emissions on local environmental quality. In contrast, the relatively lower variability observed for major macro-elements such as K, Ca, P, and S suggests a stronger association with dietary and natural geochemical factors rather than localized anthropogenic contamination.

Multivariate statistical analyses further demonstrated distinct grouping patterns between lithogenic (natural) and anthropogenically influenced elements. Particularly strong associations among Pb, As, Zn, Cu, and Mo support the presence of common urban-industrial emission sources and highlight the applicability of *Spilopelia senegalensis* feces as an informative biomonitoring substrate for multi-elemental environmental assessments.

Overall, the findings provide baseline ecotoxicological data for Yerevan and support the broader application of avian fecal analysis in urban biomonitoring programs. The use of laughing dove feces offers a practical and ethically sustainable approach for long-term environmental surveillance and may contribute to the development of localized strategies for assessing urban ecological health and contamination dynamics.

Declarations

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Ethical Responsibilities of Authors All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

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Competing Interests The authors declare that they have no known competing financial interests or personal/non-financial relationships, including business, professional, or family interests, that could have appeared to influence the work reported in this paper.

Ethical Approval The present study used a strictly non-invasive sampling method. Fecal samples were collected from the ground/nesting sites without any physical contact, capture, or handling of the birds. Therefore, no formal ethics approval was required for this study, and it was conducted in full compliance with international ethical standards for wildlife research.

Clinical trial number: Not applicable.

Participate Not applicable.

Consent to Publish Not applicable.

Author Contributions L.G.A. performed the main study conceptualization and design. Material preparation and data collection were performed by L.G.A. and V.T.H. Laboratory processing and a part of the data analyses were conducted by G.H.T. and A.T.G. Statistical analysis and analytical processing were performed by G.H.T. All authors read and approved the final manuscript.

Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

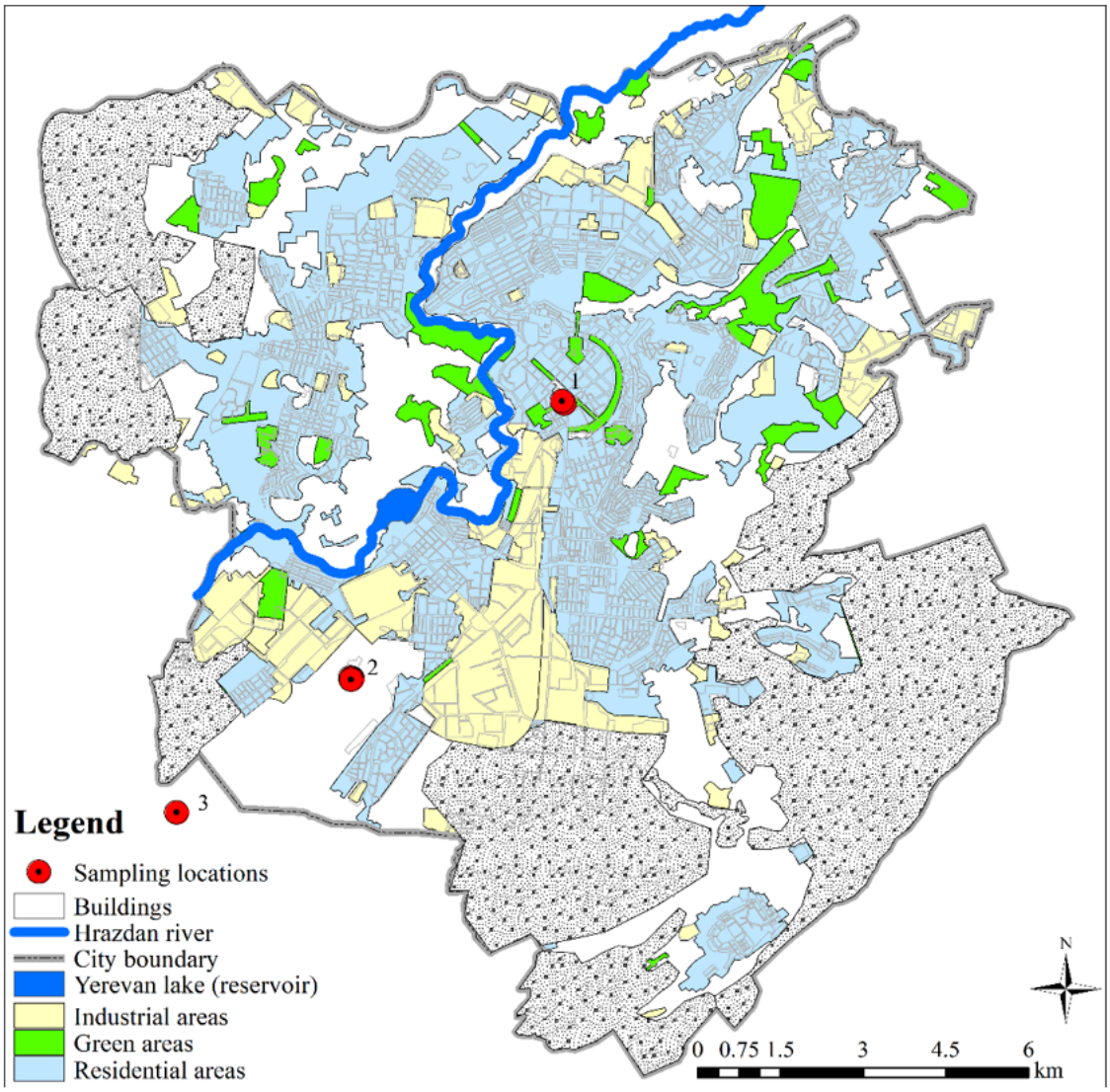


Figure 1

Map of the spatial locations of the study sites in Yerevan (Armenia), showing the central (Republic Square - 1), industrial (2) and peripheral (3) sampling sites.

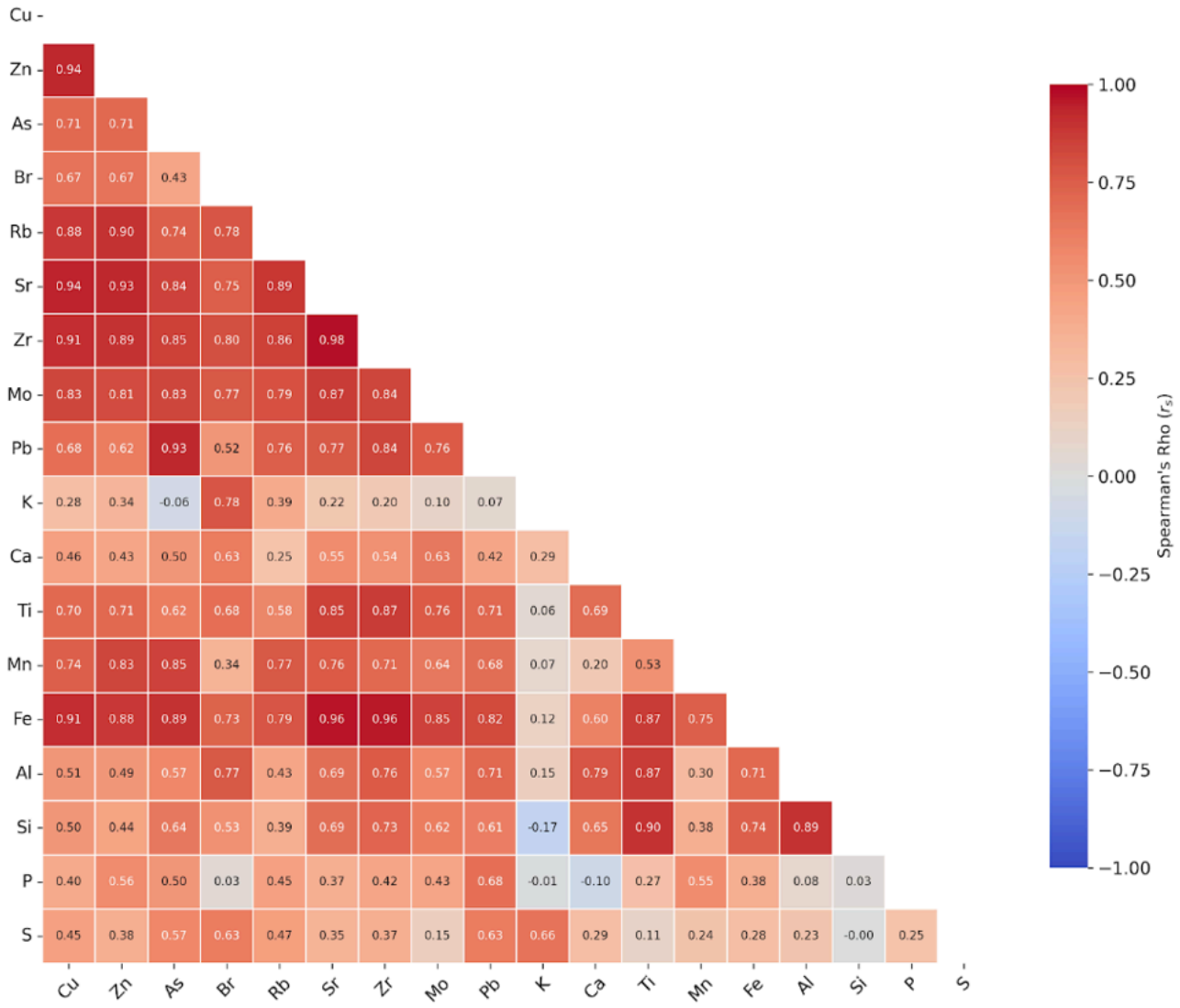


Figure 2

Heatmap of Spearman rank correlation of chemical elements in *Spilopelia senegalensis* fecal samples.

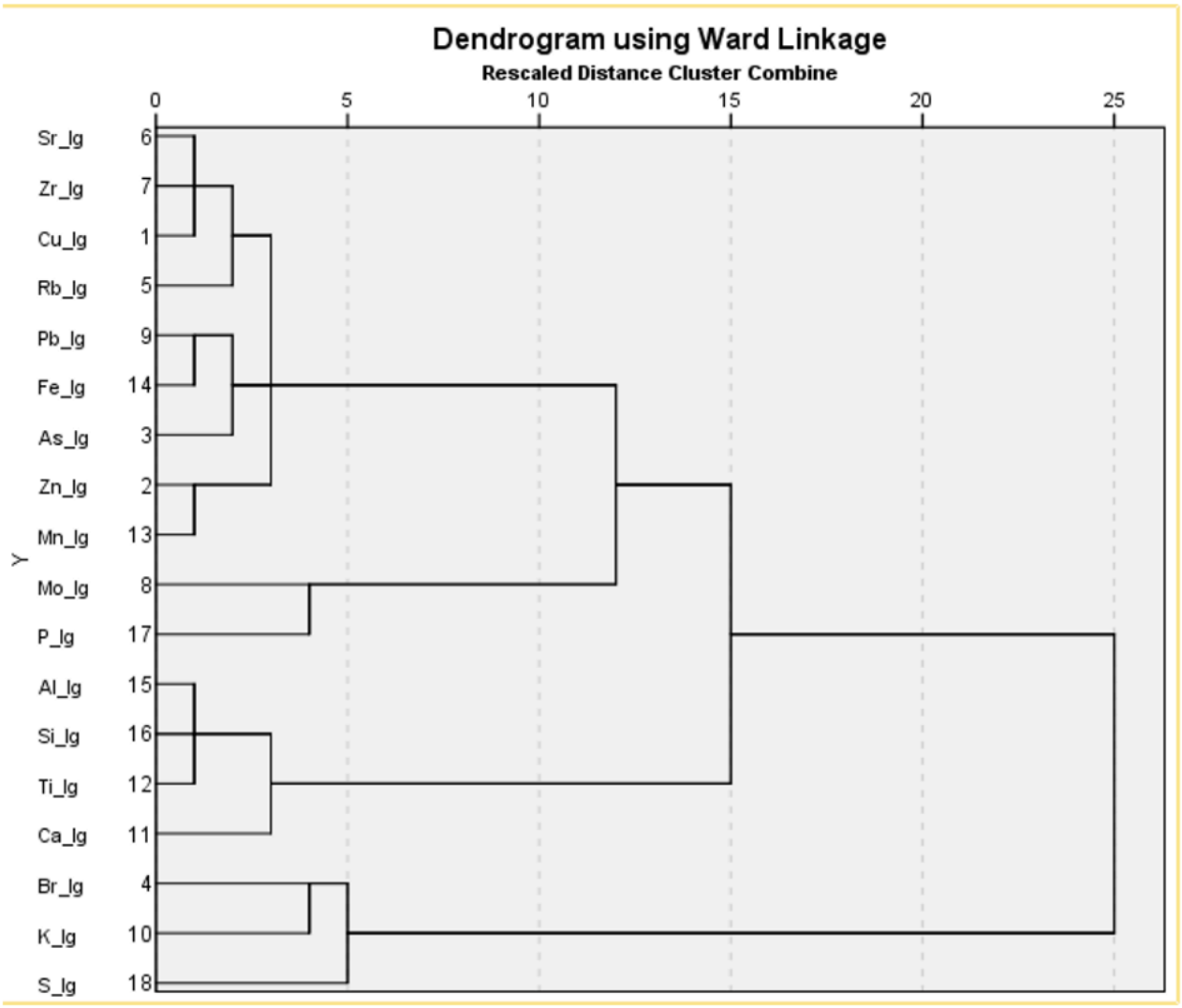


Figure 3

Hierarchical cluster dendrogram of the chemical composition of avian feces