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Risk Assessment of Toxicologically Relevant Metals (TRMs) in Urban Surface Soils and *Columba livia* Feathers

Anahi Aide García-López[1], Juan Carlos Gaytán-Oyarzun[2], Arnold Ibarra-Bautista[3], Griselda Pulido-Flores[4]
[1,2,3,4] Academic Area of Biology, Autonomous University of the State of Hidalgo, Pachuca, Hidalgo, Mexico

ABSTRACT: Metals of toxicological interest (MTI: cadmium [Cd], chromium [Cr], mercury [Hg], and lead [Pb]) are priority contaminants in urban environments due to their persistence, bioavailability, and potential toxicity to ecosystems and human health. In this study, their presence in urban surface soils was determined using quantitative analytical chemistry techniques, and ecological risk (Er), non-carcinogenic risk (HQ), and carcinogenic risk (CRi) were assessed. Additionally, ecotoxicological risk (RQ) was estimated using *Columba livia* feathers as a biomonitor.

The results confirmed the presence of all four MTI in the analyzed soils, with low ecological and non-carcinogenic risk values. However, a relevant individual carcinogenic risk associated with Cd was identified, particularly in the child population. In *Columba livia* feathers, Cd and Hg showed high bioaccumulation, with very high RQ values (>400), indicating cumulative exposure in urban biota.

Overall, these findings suggest that, although soil concentrations do not exceed regulatory thresholds, bioaccumulation processes may increase the risk in living organisms, highlighting the importance of incorporating biomonitors into environmental assessments of urban systems.

KEYWORDS: biotic receptor, bioindicator, domestic pigeon, heavy metals, toxicology.

INTRODUCTION

Toxicologically relevant metals (TRMs) are chemical elements with distinctive properties that differentiate them from other elements in the periodic table, including high density, elevated atomic number (greater than 20), and significant toxicity (Alloway, 2013; Morales, 2013; Londoño-Franco et al., 2016). These elements are considered priority environmental pollutants due to their high persistence, as they cannot be degraded under natural conditions; their bioavailability, which allows them to cross biological membranes; their capacity to bioaccumulate in organs, tissues, and fluids; their biomagnification across food webs; and their potential to cause adverse health effects even at low concentrations (ATSDR, 2005).

TRMs occur naturally in the environment as components of the Earth's crust; however, various anthropogenic and industrial activities significantly increase their release and dispersion (Londoño-Franco et al., 2016). In response to this issue, monitoring strategies have been developed to assess environmental quality and detect changes over time associated with the presence of TRMs (Parra Ochoa, 2014).

Since the 1960s, the use of bioindicators and biomonitors has become a fundamental tool in environmental assessment. These are defined as organisms or biological communities that provide information about environmental quality, either qualitatively (bioindicators) or quantitatively (biomonitors), enabling the evaluation of environmental changes and pollutant presence (Markert et al., 2003). More recent studies confirm that bioindicators respond predictably to environmental variations and allow the detection of contamination and ecological disturbances at different biological levels (Ghannem et al., 2024).

This approach offers significant advantages over analytical chemistry in complex matrices such as water, air, and soil. While chemical methods detect specific contaminants at a given moment, bioindicators integrate cumulative exposure over time, revealing bioaccumulation, actual toxicity in living organisms, and integrated ecosystem responses, such as changes in biodiversity and food webs (Stankovic & Stankovic, 2013; Markert et al., 2003; Van der Oost et al., 2003).

Among the organisms most commonly used as bioindicators of environmental quality are birds, due to their ability to simultaneously reflect contamination in air, soil, and water, as well as their tendency to accumulate toxic substances (Becker, 2003).

The domestic pigeon (*Columba livia* Gmelin, 1789), native to Eurasia, has been widely introduced beyond its natural range and is recognized as an invasive species (GISD, 2008). In Mexico, its distribution is mainly restricted to urban and suburban areas, where it uses cliffs and buildings for roosting and nesting, indicating its close association with human settlements. In recent years, *C. livia* has been recorded in the metropolitan area of Pachuca, Hidalgo, México (Zuria et al., 2019).

The high abundance of this species is closely linked to human populations, as it is frequently fed in public spaces and residential areas. Additionally, it has easy access to water sources such as fountains, basins, and puddles, and feeds on food waste available in the environment (MINAM, 2014), which favors its proliferation in urban areas and reduces its migratory behavior (Zúñiga et al., 2017).

The metropolitan area of Pachuca, Hidalgo, México is located within the Pachuca-Actopan mining region, characterized by the presence of mine tailings, which constitute a significant source of TRMs in the environment. These deposits are the result of more than 500 years of gold and silver extraction, and local climatic conditions favor particle dispersion, increasing their environmental availability (Hernández-Acosta et al., 2009; Servicio Geológico Mexicano, 2018).

Furthermore, the presence of TRMs in urban soils is associated with anthropogenic sources such as agricultural activities (use of fertilizers and pesticides), power generation, industrial processes (particularly iron and steel production), and vehicular traffic (Pérez-Segovia, 2018).

Therefore, the aim of this study is to evaluate the concentration of TRMs in urban surface soils and in *Columba livia* feathers, as well as to estimate ecological risk, non-carcinogenic and carcinogenic risks to human health, and ecotoxicological risk associated with their bioaccumulation in the metropolitan area of Pachuca, Hidalgo, México.

METHODOLOGY

Study area

The study area is located in the Metropolitan Area of Pachuca, Hidalgo, México (ZMP; see **Figure 1**), which comprises the municipalities of Epazoyucan, Mineral de la Reforma, Mineral del Monte, San Agustín Tlaxiaca, Zapotlán de Juárez, and Zempoala, with Pachuca de Soto as the central municipality. According to the 2020 Population and Housing Census, the ZMP covers an area of approximately 1,184.8 km² (INEGI, 2021) and accounts for 21.6% of the total population of the state of Hidalgo, with 665,929 inhabitants (Ramírez-Áviles & Solís-Murcia, 2023).

The high concentration of population and human activities in this region has been associated with various urban pollution problems. The main sources of environmental impact include municipal solid waste, wastewater discharge, land-use changes, and carbon dioxide emissions derived from transportation and other industrial and economic activities (Instituto Municipal de Investigación y Planeación, 2017; SEMARNAT & SSA, 2007).

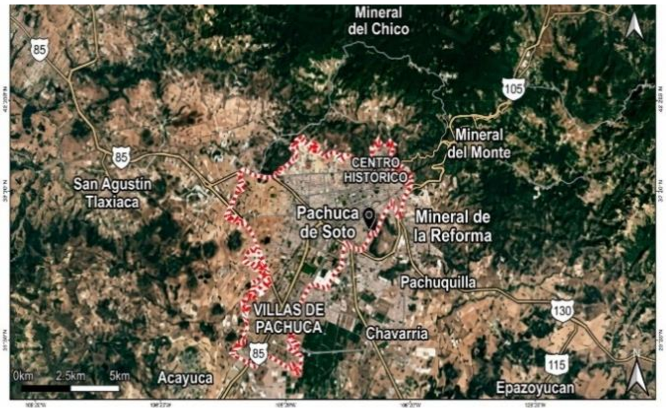

Figure 1. Map of the metropolitan area of Pachuca de Soto, Hidalgo, México.

The study area represents a site of ecotoxicological interest due to the presence of toxicologically relevant metals (TRMs), associated with the accumulation of mine tailings and the operation of at least 39 companies in the automotive, textile, and garment industries (Hipólito, 2022). Additionally, according to the Secretaría de Movilidad y Transporte (SEMOT), approximately 13,688 vehicles circulate in the area (García, 2022), contributing to the emission of potentially hazardous pollutants that affect both environmental and human health.

Sampling points

Using a population aggregation approach, four areas with high natural aggregation of *Columba livia* (Zuria et al., 2019) were identified within the metropolitan area of Pachuca de Soto, Hidalgo, México (>50 individuals). Sampling sites were selected primarily in locations where pigeons exhibit higher abundance and prolonged residence, in order to minimize biases associated with random sampling, following standard practices for population density studies in urban birds (Fruh et al., 2019).

The geographic locations of the sampling sites (GPS coordinates) are presented in **Table 1**.

Table 1. Geographical location of sampling points

Site	Latitude (N)	Longitude (W)
A	20°07’25’’ N	98° 45’22’’ W
B	20°06’60’’ N	98°44’54’’ W
C	20°07’42’’ N	98°44’04’’ W
D	20°06’14’’ N	98°43’10’’ W

Sampling

Urban surface soils

Urban surface soil samples (0–5 cm) were collected at the four previously selected sites. A total of eight individual samples (two per site) were obtained and homogenized into a composite sample (>500 g after sieving to <2 mm), in accordance with the Mexican Standard NMX-AA-132-SCFI-2016 (Secretaría de Economía, 2016).

This sampling design (8 individual samples combined into one composite sample with ≥250 g of fine fraction) is considered representative for sites <0.5 ha in preliminary screening studies of metals in heterogeneous urban soils, as it reduces spatial variability and analytical costs (MINAM, 2014; Pure Earth, 2021). Composite samples represent average contaminant levels in biologically relevant exposure areas, such as pigeon foraging zones, and the use of 6–12 subsamples is recommended to achieve approximately 80% accuracy prior to detailed bioaccumulation analyses in feathers (Mendoza & Espinoza, 2017; MINAM, 2014).

This approach is appropriate for routine analytical chemistry studies in contaminated urban soils, as it allows the detection of horizontal distribution patterns of metals accessible to *Columba livia* as a bioindicator, prior to feather-based assessments (Valladares-Faúndez et al., 2021; MINAM, 2014).

Feathers

At the four sites with the highest aggregation of *Columba livia* in Pachuca de Soto, Hidalgo, México (Table 1), loose feathers were collected (7–8 per site). The feathers were washed with a 1% Tween 20 solution and distilled water, rinsed with 70% ethanol, dried at 40 °C for 24 h, and stored in polyethylene bags at −20 °C until analysis (Burger et al., 2007; Fonseca, 2018).

This protocol removes more than 95% of external contaminants while preserving internally incorporated metals, making it suitable for analytical chemistry studies in urban environments (Scheuhammer & Graham, 2001).

Sample processing

Urban surface soil

The eight individual urban surface soil samples (0–5 cm), previously collected from the four selected sites, were sieved to 0.5 mm to obtain the fine fraction (<500 µm), representative of inhalable particles and those accessible during avian foraging (Secretaría de Economía, 2016). Due to spatial heterogeneity in urban areas with wide species distribution, a homogeneous composite sample was prepared (MINAM, 2014).

From this composite sample, 10 g were weighed and subjected to leaching with 100 mL of distilled water under constant agitation (120 rpm, 24 h, 25 °C) to simulate potential bioavailability. Subsequently, the samples were digested with 10 mL of 65% HNO_3 under acid digestion conditions (90 °C until reduction to 20 mL). The digest was then diluted with distilled water, filtered through a 0.45 µm membrane, and brought to a final volume of 100 mL for analysis by ICP-MS (APHA, 2017).

Feathers

From the 30 collected feathers (7–8 per site), 2 cm segments from the apex (distal portion) and 2 cm from the calamus (base), see **Figure 3,** were selected to capture potential bioaccumulation gradients (Burger et al., 2007).

Each segment (~0.5 g) was weighed using an analytical balance (±0.1 mg), cut and homogenized using a vortex mixer (15 s). Three subsamples per site (~0.2 g) were taken and subjected to closed-vessel acid digestion with 10 mL of 65% HNO_3 (180 °C, 15 min) using a MARSX microwave digestion system (CEM Corporation).

After digestion, the solutions were allowed to cool to room temperature, transferred to volumetric flasks, diluted to 100 mL, and stored at 4 °C until spectroscopic determination by ICP-OES (Fonseca, 2018).

Figure 3. Contrast of the apex and calamus

Analytical procedures

Urban surface soils

Chemical analysis of urban surface soil samples was performed using flame atomic absorption spectroscopy (FAAS), in accordance with the NOM-084-STPS-1994 standard.

Feathers

Chemical analysis of feather samples was performed using inductively coupled plasma optical emission spectrometry (ICP-OES), following the NMX-AA-131/1-SCFI-2021 standard.

Ecological risk assessment

Based on the concentrations of trace metals/metalloids (TMs) determined in the composite urban surface soil sample, a preliminary estimation of the contamination factor (CF) was performed (CEPIS/OPS, 2005; Lu et al., 2015) using the following equation:

$$\mathbf{CF = C_{EXP} / C_{REF}}$$

where C_{EXP} is the measured exposure concentration in urban surface soils (mg/kg), and C_{REF} is the reference concentration based on NOM-147-SEMARNAT/SSA1-2004 and the Canadian Soil Quality Guidelines (CCME, 2007; Lu et al., 2015).

An CF value ≤ 1 indicates low environmental risk, whereas CF ≥ 6 indicates high environmental risk (CEPIS/OPS, 2005; Lu et al., 2015).

Based on the CF values, the potential ecological risk (Er) was calculated. This index is a quantitative indicator used to assess the environmental risk associated with a specific metal by combining its relative concentration with its toxic potential (Hamid et al., 2022), according to the following equation:

$$\mathbf{Er = T_R \times CF}$$

where Er is the potential ecological risk and T_R is the toxic response factor, which quantifies the biological response to exposure to a toxicant by relating the observed effect to its concentration.

The toxic response factor (T_R) is widely used in environmental risk assessment and toxicity studies. According to Hamid and Payandeh (2022), T_R values for As, Cd, Cr, Hg, and Pb are 10, 30, 2, 40, and 5, respectively.

For interpretation, Er values are classified into five categories:

$Er \leq 40$ = low risk;
$40 < Er < 80$ = moderate risk;
$80 \leq Er < 160$ = considerable risk;
$160 \leq Er < 320$ = high risk;

$Er \geq 320$ = very high risk.

Given the presence of multiple MIT in the study area, the cumulative ecological risk index (ErI) was calculated, which applies to metals with similar toxic mechanisms, using the following equation:

$$\mathbf{ErI = \Sigma Er_i}$$

According to Hamid and Payandeh (2022), ErI values are interpreted as follows:
$ErI < 150$ = low risk;
$150 \leq ErI < 300$ = moderate risk;
$300 \leq ErI < 600$ = high risk;
$ErI \geq 600$ = very high risk.Health risk estimation

Human health risk assessment

The presence of metals of toxicological interest (MTI) in soil allows a preliminary estimation of human health risk associated with exposure to urban surface soils through multiple pathways, including oral ingestion, dermal contact, and inhalation.

The daily exposure dose (DDE, mg/kg/day) for each pathway was calculated using the equations proposed by the United States Environmental Protection Agency (US EPA, 1989):

$$\mathbf{DDE_{oral} = (Cs \times IR \times EF \times ED \times CF) / (BW \times AT)}$$
$$\mathbf{DDE_{inh} = (Cs \times IRair \times EF \times ED) / (BW \times AT \times PEF)}$$
$$\mathbf{DDEd_{erm} = (Cs \times SA \times AF \times ABS \times EF \times ED \times CF) / (BW \times AT)}$$

where Cs is the concentration of metals in soil (mg/kg), and the remaining exposure parameters are described in **Table 2** (Department of Environmental Affairs, 2010).

Table 2. Exposure parameters applied in health risk assessment from soil exposure at various exposure routes.

Parameter	Units	Children	Adults
Body weight (BW)	kg	15	70
Exposure factor (EF)	days/year	350	350
Exposure Duration (ED)	year	6	30
Intake rate (IR)	mg/day	200	100
Inhalation rate (IRair)	m^3/ day	10	20
Skin surface area (SA)	cm^2	2100	5800
Soil Adhesion Factor (FA)	mg/cm^2	0.2	0.07
Dermal absorption factor (ABS)	none	0.1	0.1
Dermal exposure ratio (FE)	none	0.61	0.61
Particulate emission factor (PEF)	m^3/kg	$1{,}3 \times 10^9$	$1.3 \text{ x } 10^9$
Conversion factor (CF)	kg/mg	10^{-6}	10^{-6}
Average time (AT) For carcinogens For non-carcinogens	days	365 x 70 365 x ED	365 x 70 365 x ED

Based on these values, the non-carcinogenic risk was assessed using the hazard quotient (HQ), calculated as:

HQ = DDE / Reference value

Reference values included the minimum risk levels (MRLs) established by ATSDR for each inorganic metal. When MRLs were not available, oral reference doses (RfD) and inhalation reference concentrations (RfC) reported by the US EPA (2008) were used.

The cumulative non-carcinogenic risk was estimated using the hazard index (HI), defined as the sum of HQ values for substances affecting the same target organ, organ system, or mechanism of action:

$$\mathbf{HI = \Sigma HQ_i}$$

The HI values were interpreted as follows:
$HI < 1$ = low risk;
$1 \leq HI < 3$ = moderate risk;
$3 \leq HI < 10$ = high risk;
$HI \geq 10$ = very high risk (US EPA, 2005; 2014; Gerba, 2019; AESAN, 2020).

Carcinogenic risk was estimated by calculating the individual cancer risk (CR_i) using the following equation:

$$\mathbf{CR_i = DDE_{total} \times CSF}$$

where DDE_{total} represents the sum of daily exposure doses via oral, dermal, and inhalation pathways, and CSF is the cancer slope factor.

The total carcinogenic risk (TCR) was calculated as the sum of individual risks:

$$\mathbf{TCR = \Sigma CR_i}$$

According to established guidelines, risk values greater than 1E-6 are considered of concern (CalEPA, 2021). Therefore, both individual (CR_i) and cumulative (TCR) risks were classified as follows: values > 1E-6 indicate high cancer risk, whereas values ≤ 1E-6 indicate low cancer risk.

Ecotoxicological assessment
Based on the results of the chemical analysis of C. livia feathers, the bioaccumulation factor (BAF) for the detected TRMs was calculated using the following equation:

$$\mathbf{BAF = C_{OBS} / C_{EXP}}$$

where C_{OBS} is the concentration measured in the organism (feathers), and C_{EXP} is the exposure concentration measured in urban surface soils (mg/kg).
For interpretation, Alderete-Suárez et al. (2019) classify BAF values into three categories:
$BAF < 1$ = excluder species;
$BAF > 1$ = accumulator species;
$BAF > 10$ = hyperaccumulator species.

To evaluate ecotoxicological risk (RQ), the predicted no-effect concentration (PNEC) was first estimated for a non-human ecological receptor (NHER), specifically *C. livia*, following Kaifer et al. (2004).

The PNEC was calculated based on the no observed adverse effect level (NOAEL). As no species-specific data are available for *C. livia*, NOAEL values from other bird species were used, applying an uncertainty factor (FI) ranging from 1 to 10 according to Kaifer et al. (2004), using the following equation:

$$\mathbf{PNEC = NOAEL / FI}$$

where NOAEL corresponds to reference values obtained from other avian species, and FI (uncertainty factor) was set to 5. The selected species included the mallard (*Anas platyrhynchos*), Japanese quail (*Coturnix japonica*), and Muscovy duck (*Cairina moschata*) (US EPA, 1993; Kaifer et al., 2004).
These species are commonly used as non-human ecological receptors in risk assessment studies, particularly when species-specific NOAEL values are unavailable.

Based on the PNEC, the ecotoxicological risk quotient (RQ) was calculated as follows:

RQ = (PEC or MEC) / PNEC

where RQ is the ecotoxicological risk; PEC is the predicted environmental concentration (measured in soil), and MEC is the measured exposure concentration in the evaluated biomarker (feathers).
According to Kaifer et al. (2004), RQ values were interpreted as follows:
RQ ≤ 1 = low ecotoxicological risk;
RQ > 1 = high ecotoxicological risk.

Methodological limitations

This preliminary study used n = 4 sampling points and eight individual subsamples (two per site) to generate a composite sample, an approach considered valid for the initial screening of contaminants in heterogeneous urban environments (MINAM, 2014; Mendoza & Espinoza, 2017).
However, this design reduces spatial variability and limits the application of robust statistical analyses (e.g., ANOVA, spatial variance), thus supporting its preliminary nature. The calculated risk indices are associated with uncertainty (±30–50%) due to the use of composite samples.
Future studies should include at least 12 sampling points and perform individual sample analyses to better characterize spatial gradients and validate regional representativeness.

RESULTS

The analytical chemistry results of urban surface soils in the Metropolitan Area of Pachuca, Hidalgo, México (see **Table 3**) revealed the presence of four Metals of Toxicological Interest (MIT): cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb). Among them, Cr showed the highest concentration (14 mg/kg), whereas Hg presented the lowest value (0.2 mg/kg).

All measured concentrations were below the reference limits established by NOM-147-SEMARNAT/SSA1-2004 and the Canadian Soil Quality Guidelines (CCME, 2007), resulting in contamination factor (CF) values ≤ 1, which indicates a low environmental risk.

The potential ecological risk (Er) values for all metals were below 40 (**Table 3**), indicating low ecological risk according to established criteria. Similarly, the cumulative ecological risk index (ErI) was 6.21, also classified as low risk (<150).

Table 3. Ecological risk of metals in urban surface soils from Pachuca de Soto, Hidalgo, México.

MIT	C_{EXP} (mg/Kg)	C_{REF} * (mg/Kg)	CF	T_R **	Er
As	Nd	12	0	10	0
Cd	1.4	10	0.14	30	4.2
Cr	14	60	0.23	2	0.46
Hg	0.2	6.6	0.03	40	1.2
Pb	11	140	0.07	5	0.35
ErI∑					6.21

Notes: C_{EXP} = exposure concentration; C_{REF} = reference concentration; CF = contamination factor; T_R = toxic response factor; Er = potential ecological risk index; E_RI = cumulative ecological risk index. *Canadian Council of Ministers of the Environment (CCME, 2007). **Hamid et al. (2022).

Regarding human health risk, the estimated daily dose (EDD) values for both children (<3 years) and adults (40–60 years) were low across all exposure pathways (**Table 4**). The highest EDD value in children corresponded to chromium via oral ingestion (1.53E-05), while the lowest was observed for cadmium via inhalation (5.90E-11). In adults, the highest value was also associated with chromium via ingestion (8.22E-06), and the lowest with mercury via inhalation (1.81E-11).
Hazard quotient (HQ) values for all metals were below 1, as was the hazard index (HI), indicating low non-carcinogenic risk.

Table 4. Human Health Risk (HHR) from exposure to metals of toxicological interest (MIT) in urban surface soils from Pachuca de Soto, Hidalgo

Children	**MIT**	**DDEoral (mg/kg/day)**	**DDEinh (mg/kg/day)**	**DDEderm (mg/kg/day)**	**MRLoral (mg/kg/day)***	**MRLinh (mg/m^3/day)***	**HQoral**	**HQinh**	**HQderm**
	Cd	1.53E-06	5.90E-11	1.97E-07	1.00E-04	1.00E-05	1.53E-02	5.90E-06	1.97E-03
	Cr	1.53E-05	5.90E-10	1.97E-06	9.00E-04	5.00E-06	1.70E-02	1.18E-04	2.18E-03
	Hg	1.02E-06	3.93E-11	1.31E-07	1.00E-04	3.00E-04	1.02E-02	1.31E-07	1.31E-03
	Pb	1.21E-05	4.64E-10	1.54E-06	3.60E-03**	1.50E-04**	3.35E-03	3.09E-06	4.29E-04
∑*H*I							4.60E-02	1.27E-04	5.89E-03
Adults	**MIT**	**DDEoral (mg/kg/day)**	**DDEinh (mg/kg/day)**	**DDEderm (mg/kg/day)**	**MRLoral (mg/kg/day)***	**MRLinh (mg/m^3/day)***	**HQoral**	**HQinh**	**HQderm**
	Cd	8.22E-07	1.26E-10	2.04E-07	1.00E-04	1.00E-05	8.22E-03	1.26E-05	2.04E-03
	Cr	8.22E-06	1.26E-09	2.04E-06	9.00E-04	5.00E-06	9.13E-03	2.53E-04	2.26E-03
	Hg	1.17E-07	1.81E-11	2.91E-08	1.00E-04	3.00E-04	1.17E-03	6.02E-08	2.91E-04
	Pb	6.46E-06	9.94E-10	1.60E-06	3.60E-03**	1.50E-04**	1.79E-03	6.62E-06	4.44E-04
∑*H*I							2.03E-02	2.72E-04	5.03E-03

Notes: MIT = metals of toxicological interest. DDE = estimated daily dose (oral, inhalation, and dermal pathways). HQ = hazard quotient (non-carcinogenic risk for each exposure pathway). HI = cumulative non-carcinogenic risk (hazard index). *Values obtained from ToxGuide (ATSDR). **Lead (Pb) does not have an established MRL; therefore, oral reference dose (RfD) and inhalation reference concentration (RfC) values from US EPA (2008) were used.

For carcinogenic risk, the individual cancer risk (CRi) for cadmium via oral exposure in children exceeded acceptable levels, whereas inhalation and dermal pathways remained low. The total cancer risk (TCR) indicated a high carcinogenic risk in children, while both individual and cumulative risks in adults were classified as low (**Table 5**).

Table 5. Carcinogenic risk from exposure to metals of toxicological interest (MIT) in urban surface soils from Pachuca de Soto, Hidalgo

Children	**MIT**	**DDEoral (mg/kg/day)**	**DDEinh (mg/kg/day)**	**DDEderm (mg/kg/day)**	**∑DDEtotal**	**CSF**	**CRi**
	Cd	1.53E-06	5.90E-11	1.97E-07	1.73E-06	6.30E-02	1.09E-05
	Cr	1.53E-05	5.90E-10	1.97E-06	1.73E-05	1.20E-02	2.08E-07
	Pb	1.21E-05	4.64E-10	1.54E-06	1.36E-05	8.50E-03	1.16E-07
TCR = 1.13E-05							
Adults	**MIT**	**DDEoral (mg/kg/day)**	**DDEinh (mg/kg/day)**	**DDEderm (mg/kg/day)**	**∑DDEtotal**	**CSF**	**CRi**
	Cd	8.22E-07	1.26E-10	2.04E-07	1.03E-06	6.30E+00	6.46E-06
	Cr	8.22E-06	1.26E-09	2.04E-06	1.03E-05	1.20E-02	1.23E-07
	Pb	6.46E-06	9.94E-10	1.60E-06	8.06E-06	8.50E-03	6.85E-08
TCR = 6.66E-06							

Notes: MIT = metals of toxicological interest. DDE = estimated daily dose (oral, inhalation, and dermal pathways). ∑DDEtotal = total daily exposure dose (sum of oral, inhalation, and dermal exposure). CSF = cancer slope factor (US EPA, 1986). CRi = individual carcinogenic risk. TCR = total carcinogenic risk.

The chemical analysis of *Columba livia* feathers showed the presence of cadmium and mercury, with concentrations of 674.75 mg/kg and 910.25 mg/kg, respectively (**Table 6**). These values resulted in high bioaccumulation factors (BAF), particularly for Hg and Cd.

Table 6. Bioaccumulation of metals of toxicological interest (MIT) in *C. livia* feathers exposed to urban surface soils in Pachuca de Soto, Hidalgo, México.

MIT	C_{EXP} (mg/Kg)	C_{OBS} mg/kg	BAF = C_{obs}/C_{EXP}
	Soil	*Pigeon*	
Cd	1.4	674.75	481.96
Cr	14	ND	--
Hg	0.2	910.25	4551.25
Pb	11	ND	--

Notes: MIT = metals of toxicological interest. C_{EXP} = exposure concentration (soil). C_{OBS} = observed concentration (feathers). BAF = bioaccumulation factor. ND = not detected (below detection limit). — = not calculated due to non-detectable values.

Ecotoxicological risk assessment based on soil concentrations showed RQ values ranging from 2 (Hg) to 70 (Cr), indicating high risk (RQ > 1) (**Table 7**). Similarly, feather-based RQ values were extremely high, with 2326 for Cd and 10113 for Hg, indicating unacceptable ecotoxicological risk (**Table 8**).

Table 7. Ecotoxicological risk from exposure to urban surface soils in Pachuca de Soto, Hidalgo, México.

MIT	PEC (mg/kg)	NOAEL (mg/kg/day)*			PNEC = (NAOEL/FI) (mg/Kg/day)	RQ
		Anas platyrhynchos	*Cairina moschata*	*Coturnix japonica*		
Cd	1.4	1.45	—	—	0.29	4.83
Cr	14	—	1	—	0.2	70
Hg	0.2	—	—	0.45	0.09	2.22
Pb	11	—	—	1.13	0.22	50

Notes: PEC = predicted environmental concentration (measured in urban surface soils). NOAEL = no observed adverse effect level (reported for non-human ecological receptors). PNEC = predicted no-effect concentration. RQ = ecotoxicological risk quotient. FI = uncertainty factor (FI = 5). — = not available. *Source: Sample et al. (1996).

Table 8. Ecotoxicological risk in *C. livia* from exposure to urban surface soils in Pachuca de Soto, Hidalgo, México

MIT	MEC (mg/kg)	NOAEL (mg/kg/day) *		PNEC = (NAOEL/FI) (mg/Kg/day)	RQ
	Columba livia	*Anas platyrhynchos*	*Coturnix japonica*		
Cd	674.75	1.45	—	0.29	2326.72
Hg	910.25	—	0.45	0.09	10113.89

Notes: MEC = measured exposure concentration (in feathers). NOAEL = no observed adverse effect level. PNEC = predicted no-effect concentration. RQ = ecotoxicological risk quotient. FI = uncertainty factor (FI = 5). — = not available. *Source: Sample et al. (1996).

DISCUSSION

Metals in urban soils

The presence of Cd, Cr, Hg, and Pb in urban surface soils is consistent with previous findings reported for the Metropolitan Area of Pachuca, Hidalgo, México (Pérez-Segovia, 2018), confirming the persistence of these contaminants in the region. However, the differences observed in concentration levels compared to earlier studies can be attributed to the inherent spatial and temporal variability of urban environments. Such variability is commonly influenced by multiple interacting factors, including vehicular emissions, industrial activities, atmospheric deposition, and local climatic conditions such as wind patterns and humidity, which affect the dispersion and resuspension of particulate matter (Cai et al., 2013).

Although all measured concentrations were below the regulatory thresholds established by NOM-147-SEMARNAT/SSA1-2004 and the Canadian Soil Quality Guidelines (CCME, 2007), this does not necessarily imply the absence of environmental concern. The mere presence of MIT in urban soils indicates a continuous input of contaminants and highlights the potential for chronic, low-level exposure. Urban soils act as both sinks and secondary sources of contamination, particularly in areas with high anthropogenic pressure, which may facilitate the transfer of metals to other environmental compartments, including air and biota.

Furthermore, the use of composite samples provides a representative estimate of average contamination levels; however, it may mask localized hotspots of higher concentration. This limitation is particularly relevant in heterogeneous urban systems, where contamination is often patchy and influenced by point sources.

Ecological risk

The low values obtained for Er and ErI indicate that, under the conditions evaluated, the ecological risk associated with the studied metals is limited. These findings are consistent with Adewumi et al. (2022), who reported that ecological risk in urban soils varies widely across global cities, with many sites exhibiting low to moderate risk levels despite the presence of multiple contaminants.

In the present study, Cd and Hg showed comparatively higher Er values within the group of analyzed metals. This pattern aligns with the well-documented toxicological profiles of these elements, as both are known for their high mobility, bioavailability, and toxicity even at relatively low concentrations. Their elevated contribution to ecological risk indices, even when absolute concentrations are low, reflects the importance of considering toxic response factors in environmental assessments.

Although the overall ecological risk is classified as low, it is important to interpret these results with caution. Ecological indices such as Er and ErI are based on reference values and standardized factors, which may not fully capture site-specific ecological dynamics or synergistic effects between contaminants. Therefore, the low-risk classification should not preclude further monitoring, particularly in areas undergoing rapid urbanization.

Human health risk

The human health risk assessment revealed that the oral pathway is the dominant route of exposure, particularly for children, which is consistent with established exposure models (US EPA, 2001). This is primarily due to behavioral factors such as hand-to-mouth activity and incidental soil ingestion, which increase exposure frequency in younger populations.

The estimated daily dose (DDE) values across all exposure pathways were low, and the calculated HQ and HI values indicate that non-carcinogenic risk is within acceptable limits for both children and adults. These findings suggest that, under current exposure scenarios, adverse health effects are unlikely. However, it is important to recognize that these estimates are based on average concentrations derived from composite samples and standardized exposure parameters, which may not reflect individual variability or site-specific conditions.

In contrast, the carcinogenic risk assessment revealed that Cd poses a potential concern for children via oral exposure, with CRi values exceeding commonly accepted thresholds. This result is consistent with findings reported by Adimalla and Wang (2018), who also identified elevated carcinogenic risk associated with Cd ingestion in contaminated urban soils. The higher susceptibility of children to carcinogenic effects is well documented and underscores the need to prioritize vulnerable populations in environmental health assessments.

These results highlight the importance of considering both non-carcinogenic and carcinogenic endpoints when evaluating environmental risk. Even when general exposure levels appear low, specific contaminants such as Cd may pose long-term health risks under chronic exposure conditions.

Ecotoxicological risk

The elevated concentrations of Cd and Hg detected in *Columba livia* feathers, together with the high bioaccumulation factor (BAF) values, provide strong evidence of the species' capacity to accumulate metals from its environment. These findings support previous studies that recognize *C. livia* as an effective bioindicator of urban pollution due to its close association with human settlements and its ability to integrate exposure over time (Burger et al., 2007; Valladares-Faúndez et al., 2021).

The high RQ values obtained for both soil and feather matrices indicate a significant ecotoxicological risk (RQ > 1), particularly when assessed through biomonitoring data. Notably, the extremely high RQ values derived from feather concentrations reflect cumulative exposure and suggest that organisms may experience higher internal burdens of contaminants than those inferred from environmental concentrations alone.

This apparent discrepancy between low soil-based risk indices and high biomarker-based risk highlights the limitations of relying solely on environmental concentrations for risk assessment. Bioaccumulation processes can amplify contaminant levels within organisms, leading to potential toxic effects even when external concentrations are relatively low.

Therefore, the integration of chemical analysis with biomonitoring approaches provides a more comprehensive evaluation of environmental risk. The results of this study emphasize the need to incorporate biological indicators in urban ecotoxicological assessments, as they offer valuable insight into real exposure scenarios and ecological impacts.

CONCLUSION

This study confirms the presence of metals of toxicological interest (MTIs: Cd, Cr, Hg, and Pb) in urban soils of the Metropolitan Area of Pachuca de Soto, Hidalgo, México, through chemical-analytical assessment and the application of ecological, ecotoxicological, and human health risk indicators. The results obtained for surface soils indicate concentrations below regulatory thresholds and non-carcinogenic risk values (HQ and HI < 1), suggesting a low risk to human health under the evaluated conditions, regardless of the exposure pathway.

However, the analysis of urban biota revealed a contrasting pattern. *Columba livia*, used as a bioindicator, showed elevated concentrations of Cd and Hg in feathers, along with high bioaccumulation factors and ecotoxicological risk values (RQ > 1), indicating significant cumulative exposure. This discrepancy highlights an important limitation of assessments based solely on abiotic matrices, as soil samples reflect average environmental conditions, whereas biomonitors integrate bioaccumulation processes and chronic exposure over time.

Overall, these findings underscore the importance of incorporating biomonitors into environmental assessments of urban systems, as they enable the detection of risks that may be underestimated by conventional approaches. In particular, *C. livia* emerges as a sensitive and effective bioindicator for monitoring metal contamination in urban environments.

Finally, future research should include a greater number of sampling sites, detailed spatial analyses, and integrated multi-pathway exposure approaches to improve the representativeness of the results and support more robust decision-making in environmental management and public health.

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