[Frontiers in Bioscience, Landmark, 26, 327-345, Jan 1, 2021]

Health risk of heavy metals in street dust

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1. ABSTRACT

Heavy metals in street dust represent a risk to the human health due to their toxicity, persistence and bioaccumulation. Using the US Environmental Protection Agency (USEPA) assessment, here, we review the human health risks of such dust world-wide. The street dust in such cities is contaminated by *As*, *Cd*, *Cr*, *Cu*, *Hg*, *Mn Ni*, *Pb* and *Zn* beyond the median levels of the world soil background values. Among these elements, the median values of the hazard risk indices (non-carcinogenic risk) are highest for As, Cr and Pb and the median values of the risk indices (carcinogenic risk) for As are in the tolerable risk range for children and adults and in the case of Pb, the median value of the carcinogenic risk indices are also in the tolerable range for children. We emphasize that the level of heavy metals in street dust pose a considerable risk to the human health and require monitoring and approaches to reduce such toxic levels.

2. INTRODUCTION

By 2030, 60% of the world population are housed in the urban areas (1). The combined impact of the urban and the industrial development, use of vehicles and human activities, undoubtedly leaves a footprint on the quality of the environment, adversely impacts the quality of air and leads to increasing levels of heavy metals in the street dust (2-3).

Street dust is formed by solid particles deposited on impervious materials that originate from

the interaction of solid, liquid and gaseous constituents in the urban environment (4). It originates from natural and anthropogenic sources. Special attention is paid to the latter because of the pollutants they may contain; anthropogenic sources include traffic-related emissions, industrial discharges, domestic activities, weathering of buildings and other atmospheric depositions (5,6). Therefore, street dust is a sink of pollutants, but it is also a reaction bed and a source of those pollutants which can be released back to the atmosphere, soils and water (4,6,7).

Among the complex components of street dust, heavy metals (arsenic (As), barium (Ba), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), vanadium (V) and zinc (Zn) contamination have drawn public attention because of the high toxicity, concealment, persistence and biological accumulation in the ecosystem and humans (8). They can enter the human body via inhalation, ingestion and dermal exposure, and can have both a non-carcinogenic and carcinogenic risk (2). They may accumulate in the fatty tissues in the body and affect the central nervous and circulatory systems, disrupt the normal functioning of our internal organs, act as cofactors in other diseases and may cause DNA damage (6). At present, As, Cd, Cr (VI) and Ni have been identified as carcinogenic metals to humans, while Pb is classified as probably carcinogenic to humans (9,10).

The above underlines the importance of studying street dust. As it is a relatively new research field related to the environmental sciences, with the earliest studies dating from the 1980s and 1990s (11,12), its study object needs to be addressed from an interdisciplinary perspective. Now, this field has adopted a wide theoretical background and methods from the soil sciences (6,13,14), nevertheless, it is necessary to verify whether these adopted methods and knowledge work well for street dust, and if a specific body of knowledge for study street dust should be developed.

During the past decade, many isolated studies of human health risk assessment of heavy metals in street dust have been carried out employing the model developed by the US Environmental Protection Agency (USEPA) for soils. However, there is not a general view of the topic, and many structural and methodological differences have been found among studies; therefore, it is necessary to review the state of the art on this subject matter, and to establish guidelines for future studies. We reviewed the evolution, state of the art and future lines of research on the concentrations of heavy metals, sources and human health assessments of street dust, during the past decade.

3. PROGRESS IN THE STUDY OF HEAVY METAL CONTAMINATION IN STREET DUST

3.1. Sampling process established for street dust

Along the last ten years, different statistical samplings have been used. A very common one is systematic sampling because it is representative and very useful for spatial interpolations. However, in many studies the type of sampling is neither justified nor well explained and could lead to bias in samplings. Therefore, it is important to look for the best sampling type and to explain with sufficient detail how the sampling was made and the rationale for the method.

The sample size is also a point that requires attention. Most of the studies used a small sample size, between 13 and 74 sites. Mean sample sizes are around 65, and maximum ones are above 250. A small number of samples could not be representative of the entire city and could result in errors, especially when cities are large. The simplest way to define a sample size could be based on the area to be analyzed, with at least one sample per square meter to be taken. Another alternative is to take 100 samples as a minimum when spatial interpolations are to be undertaken (15).

The best practice of sampling should be based on surface area (m^2) and, if the amount is not sufficient, a bigger area must be sampled. The street dust loading (that is, the quantity of street dust per square meter) provides valuable information about the amount of dust and even the amount of heavy metals that is present in the environment, and

therefore should be reported. At present, most of the sampling of street dust are based on an approximate quantity (300–500 g), however, the quantity of dust per square meter (*i.e.*, the street dust loading) must be reported from now on.

In relation to the equipment used to collect the samples, change in the dust loading is obtained by fraction sizes when different sampling methods are used (brushing and vacuuming). For smaller particle mass fractions (less than 74 micrometers), the vacuuming method is more efficient at collecting the sample. On the contrary, for bigger particle sizes (74–500 micrometers), the brushing method is more effective for collecting larger particles. Equations to transform the measured concentrations between methods have been developed by Yu *et al.*, in 2016 (16). Even when both sampling methods give similar concentrations, they can affect the heavy metal loading, so it is important to take this information into account.

With regards to the particle size, there is no consensus. Some authors sieve the street dust through a sieve of less than 250 micrometers, arguing that those particles are most likely to adhere to hands and therefore be involuntarily ingested (17). Others use sieves of less than 100 micrometers, arguing that particles less than 100 micrometers are easily re-suspended and therefore can be inhaled and capable of remaining airborne for considerable durations (3,6). However, less than 63 micrometers are the most preferable size because these particles can be considered to mainly arise from atmospheric deposition and transported by re-suspension (18). Furthermore, the smaller the particle size, the greater the surface area to volume ratio and thus the concentrations of heavy metals (19).

There are several possible explanations for higher concentrations of heavy metals in dust samples with smaller particles: 1) they can be direct by-products of vehicular and industrial activities; 2) their relatively larger available surface area per unit mass means a higher adsorption rate for heavy metals compared to larger particles (19); and 3) they might contain a greater proportion of organics and clay minerals that facilitate the adsorption of metals (5).

However, this is not consistent in the bibliography: depending on the heavy metals, the highest concentrations are identified in different particle sizes. For example, Chen *et al.* (20) report that the highest concentrations for Co, Zn, As, Sr, Cd and Sb were effectively found in the less than 63 micrometers fraction, but for Ni and Cu the highest concentrations occurred in the median sizes (125–500 micrometers), and the mean Pb level is relatively higher in the coarsest fraction (500–1000 micrometers) (20). In addition to these different results, it is recommended that the smallest particle size is analyzed. A fraction of less than 63 micrometers is easy to obtain in a laboratory with a mesh and better reflects the anthropogenic emissions of street dust (21,22).

Chemical and physical properties commonly measured in soils could be very helpful in street dust analysis; those properties are organic matter, clay percentage, pH and cation exchange capacity. Organic matter is a chelating agent, mineral clay adsorbs heavy metals in the surface, pH can modify the mobility of the heavy metals, and cation exchangeable capacity is the soil (dust) property where the heavy metals can be adsorbed (23). The analysis of these properties in street dust could elucidate the role of organics and clay minerals in the content of heavy metals; *e.g.*, González-Grijalva *et al.* (24) observed that kaolinite content in soils increases Pb bioaccessibility in the intestinal phase. Similar studies should be done for street dust. In relation to particle size fractions, in particular, the mineralogy of particles should be addressed, *e.g.*, rutile crystals commonly used worldwide have been identified in nanometric dust particles (25). In addition to mineralogy, the importance of pH and cation exchange capacity in the mobility of heavy metals in street dust also need to be studied.

3.2. Heavy metal contamination of street dust

3.2.1. Geochemical analysis

The most common analytical techniques used are: atomic absorption spectroscopy (AAS),

Table 1. Comparison of some characteristics for different analytical techniques

Characteristic/ Technique	ICP-OES	ICP-MS	AAS	GFAAS	XRF	PXRF
Cost	High	Very high	High	High	Moderate	Low to moderate
Multi or monoelemental	Multi	Multi	Multi (70)	Multi	Multi	Multi
Sample preparation	Acid digestion	Acid digestion	Acid digestion	Acid digestion	Pellet	Little preparation
Detection limits	ppb	ppb, even ppt	ppb	ppb	ppm	ppm
Precision	High	Very high	High	High	Acceptable	Moderate to low
Sample quantity	1 g	1 g	1 to 5 g	1 g	10 g	10 g

ICP-OES: inductively coupled plasma optical emission spectroscopy; ICP-MS: inductively coupled plasma mass spectroscopy; AAS: atomic absorption spectroscopy; GFAAS: graphite furnace atomic absorption spectrometry; XRF: X-ray fluorescence; PXRF: portable X-ray fluorescence; g: grams.

graphite furnace atomic absorption spectrometry (GFAAS), inductively coupled plasma atomic emission spectroscopy (ICP-AES), inductively coupled plasma mass spectroscopy (ICP-MS), inductively coupled plasma optical emission spectroscopy (ICP-OES), portable X-ray fluorescence (PXRF) and X-ray fluorescence (XRF). A comparison of the characteristics of these techniques is presented in Table 1.

Atomic spectroscopy comprises absorption, emission and fluorescence; all involve the process of excitation of an electron and decay to the ground state. With regards to the atomic absorption, AAS and GFAAS are examples of these techniques. In AAS, the concentrations are measured by passing light emitted by a radiation source, in a specific wavelength, through a cloud of atoms from a sample. The reduction in the amount of light intensity reaching the detector is seen as a measure for the concentration of an element. In GFAAS, samples are mixed with modifiers prior to the atomization processes and then dispensed into an atomizer; the sample is retained in the tube and the light path for a prolonged time, which leads to an improvement in sensitivity. Some disadvantages are a limited working range, slow analysis and high cost (14).

The techniques of ICP-AES consist of high energy emitted by a source that excites atoms, which subsequently emit light when they return to the ground state. ICP-OES is based on the emission of photons from excited atoms and ions in a radiofrequency discharge; the ionic excited state species may return to the ground state via emission of photons. The wavelength of the photons can be used to identify the elements and the number of photons is directly proportional to the concentration. ICP-MS uses an argon plasma source to dissociate the sample into its basic atoms or ions that are isolated according to their atomic mass-to-charge ratio by a quadrupole or magnetic sector analyzer. In this case, metal ions are detected rather than the light they emit (14). The fluorescence of the X-ray technique reported in the selected studies was the most common; it is a physical phenomenon that involves the interaction of X-rays with matter. X-ray radiation strikes an atom, detaching some electrons from the inner orbitals; this makes the atom unstable; the unoccupied spaces are filled by electrons from a higher orbital and the energy released is in the form of fluorescent X-rays (14). PXRF is based on the same physical phenomenon, but it is a portable device, smaller and lighter than the stationary equipment.

For the methods that require digestion of the samples to release the heavy metals, generally, standardized protocols are followed, such as the USEPA method 3051A: Microwave-assisted acid digestion of sediments, sludges, soils, and oils (26). This digestion is not intended to accomplish total decomposition of the samples; therefore, the concentrations do not reflect the total content. In the case of XRF the samples are ground and pressed in pellets. This method does not require acid digestion; thus, the concentrations could be higher than ICP.

Table 2. Descriptive statistics of the concentrations of heavy metals in street dust worldwide

HM	N	Mean (mg/kg)	Median (mg/kg)	Standard deviation	Minimum (mg/kg)	Maximum (mg/kg)	Earth-crust values[1]	World soil background[1]
As	22	27.1	12.7	39.2	2	148	1.8	6.83
Ba	6	156.7	194	95.3	12.2	248.5	400	460
Cd	28	3.7	1.1	5.8	0.3	21.4	0.1	0.41
Co	23	13.5	11.5	7.7	4	34	10	11.3
Cr	36	104.3	84.8	93.7	18.4	587.3	100	59.5
Cu	38	696.7	83.4	2731.3	27.5	16000	55	38.9
Fe	14	25522.2	22103	12775.6	8693.7	58300	NA	NA
Hg	10	56.5	0.2	177.2	0.1	560.9	0.07	0.07
Mn	24	601.8	532.9	619	189.9	3407.3	900	488
Ni	32	50.4	36.3	49.8	21	300	20	29
Pb	37	502.9	97.4	2283.3	0.9	14000	15	27
V	12	54.1	52.9	23.2	4	86	135	129
Zn	35	634.6	280.7	1167.7	56.6	6022	70	70

n: number of articles, NA: not available [1](29). Based on (1-9,13,16-18,20,21,27,28,32,33,36,41-44,50-58)

Regardless of the method, quality control must be carried out. This includes reagent blanks, duplicate samples and spiked samples. The detection and quantification limits must also be reported, as well as the recovery percentages with respect to the reference certified materials.

3.2.2. Overview of worldwide heavy metal concentrations in street dust

During the last decade, there has been an upward trend in the study of heavy metals in street dust around the world. In 2018 there was a boom in publications. This general trend highlights the increasing interest in the topic, because an increasing number of people now live in cities and there are many sources of polluted particles that decrease the environmental quality and can be harmful to human health.

Comparison of mean concentrations of heavy metals in street dust in different urban environments is a common practice, even though there are no universally accepted sampling and analytical procedures for geochemical studies of urban deposited materials. Moreover, concentrations of heavy metals in street dust particles vary considerably among cities depending on the local climate conditions, wind patterns and technologies, as well as the density of traffic and industrial activities (4,17).

The heavy metals that are almost always reported in street dust are Cu, Pb, Cr and Zn; the number of articles (n) that reported the concentrations for each heavy metal can be seen in Table 2. The main reasons why Cu, Pb, Cr and Zn are the most commonly measured heavy metals could be: 1) most interest is given to these elements because of their toxicity or extensive use, and 2) they are easier to measured compared to other metals, such as Hg.

Some studies have been carried out in very contaminated urban areas, for example, a mining area (27) and an e-waste processing area (28). In these places, very high concentrations of some heavy metals are found, that is, higher than the median ones for street dust worldwide. Thus, median values are more representative as a central tendency measure for the heavy metal concentrations around the globe (Table 2).

In relation to the variation of the data, the standard deviation reported for each heavy metal in this paper (Table 2) is higher than those reported in each individual study. However, it is expected that

variation found in the worldwide data is greater than inside each city because each location has its own environmental conditions (climate, wind, traffic density, etc.), and different sampling and analytical procedures were used among studies.

To define a level of contamination, a reference value, known as the background, is needed. It should represent the natural or previous concentrations before anthropogenic activities have emitted the pollutants. The heavy metal concentration divided by the background is named the contamination factor (CF). Using the world soil background (29), the CF for the median concentrations of Zn and Pb (CF between 3 and 6) indicates a considerable contamination, and these are the heavy metals released in greater quantities in cities. Median concentrations of Hg, Cd, Cu, As, Co, Cr, Mn and Ni represent a moderate level of contamination worldwide (CF between 1 and 3). There is practically no contamination for Ba and V (CF less than 1), in urban environments.

Even when the soil background concentrations are commonly used as reference values to define a level of pollution for street dust, soils are not the only natural source of heavy metals in street dust, and it is very difficult to find soils unaffected by anthropogenic activities in cities. Therefore, the background values of heavy metals could be obtained from other materials, for example, from the coarse fraction of street dust, since this fraction is not the product of atmospheric deposition due to its large size. However, a possible problem is the fact that the coarse fraction could also be the result of anthropogenic activities, as the materials for construction transport can contribute to the presence of sands and gravels on the surfaces of streets. Nonetheless, we consider this is an alternative that needs to be tested.

No correlation between heavy metal concentrations and the number of inhabitants was found. This disagrees with previous results found in Spain, where increases in metal concentrations with population density were observed in street dust (30). Even when an increase in metal concentration with the number of inhabitants or population density could be expected, this hypothesis needs to be more deeply tested, as the present review shows a discrepancy.

To provide an overview of the concentrations of heavy metals in each country, variance analysis was undertaken. However, this was difficult because of the different number of samples for each country. China was the country for which more articles were published, with 58 percent of the selected studies carried out in Chinese cities. The next country with highest number of published articles was Iran (13 percent), then India (5 percent), and one article (3 percent) was found for each of the following countries: Algeria, Bangladesh, Chile, Mexico, Mongolia, Saudi-Arabia, Serbia, Turkey and Afghanistan. For the last article, two cities were studied, so the same study examined two places.

Among heavy metals only the concentrations of Cr had statistically significant differences between countries, according to Kruskal-Wallis test. China had the highest concentrations, followed by India, Iran and Afghanistan (Figure 1). For the remaining heavy metals, only the country with the highest mean concentration is mentioned, without significant differences: Chile had the highest mean concentration of As and V, in a mining port; Mexico for Ba; Changchun, China, for Cd and Co; an e-waste processing site in China for Cu and Pb, although those concentrations (16,000 mg/kg for Cu and 14,000 mg/kg for Pb) are excluded from Figure 1 for clarity; the same Chinese e-waste processing site for Ni and Zn; Xuanwei, China, for Fe; and an iron mining area in Mongolia for Mn.

The highest mean concentrations are found in urban areas with specific point sources, for example, mining and e-waste recycling. Thus, special attention must be paid to these sites in order to ensure the population health. Furthermore, this shows again the importance of separate industrial activities from population centers, and in this way, exposure can be diminished. Special security and control measures must be taken in those places where very high concentrations of heavy metals are emitted.

3.3. Sources of heavy metals in street dust

Different types of street dust are heterogeneous at a small-scale, due to their mobility, the rapid environmental alteration, and the variable

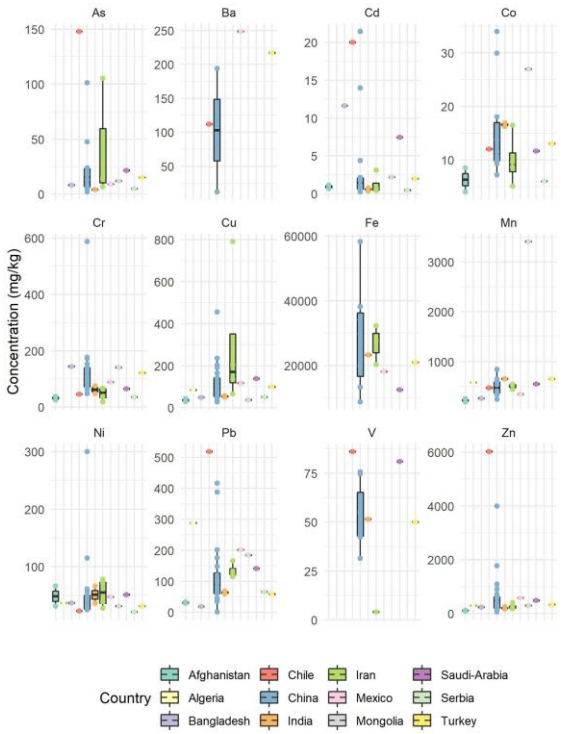

Figure 1. Comparison of the concentrations of heavy metals by country. The maximum concentrations of Cu (16,000 and 6103 mg/kg) and Pb (14,000 mg/kg) were excluded from plots in order to clarify the other concentrations in the figure.

distribution of their urban sources (31). Different approaches have been used to identify the possible sources of heavy metals in street dust. In 2017, studies focused on dividing the cities into different land uses or functional areas, such as industrial, commercial, residential and others (21,32,33). By 2018 and 2019, statistical methods were increasingly implemented, with the most commonly used being principal component analysis, cluster analysis and positive matrix factorization.

Principal component analysis (PCA) uses orthogonal transformation to convert an array of observations of correlated variables into a set of values of linearly uncorrelated variables that are defined as principal components. Therefore, PCA reduces data and extracts a small number of factors (principal components, PCs) for determining the relationships among the observed variables. The eigenvector with the largest eigenvalue is the direction of greatest variation, the one with the second largest eigenvalue is the (orthogonal) direction with the next highest variation, and so on. Each PC contains information on all of the elements combined into a single group, while the loadings of each element indicate their relative contribution to the group (34).

Positive matrix factorization is an efficient multivariate factor analysis tool (31). In the model, the sample concentration data matrices are decomposed into factor contribution matrices and factor profile matrices. Based on the decomposition result, the profile information collected, and the emission inventories investigated, the sources could be determined (7).

Hierarchical cluster analysis also helps in identifying relatively homogeneous groups of elements, using an algorithm that starts with each element in a separate cluster and combines clusters until only one is left (34). Combinations of many source identification methods are often considered as more efficient than one single method to increase the resolution of the dataset (8).

All these methods have been employed in diagnosis studies that determine the concentrations of heavy metals in street dust and their possible sources; however, some specific studies are needed to soundly identify the sources and to update the inventories. These kinds of studies include the analysis of car, industry and house emissions, as well as the weathering of buildings and roads, the releases from crops, etc. In some of these analyses, isotopes are used to track emissions (35). The most commonly cited sources of heavy metals are:

1. Arsenic, easily generated during coal combustion. Coal combustion can cause the emission of fly ash into the atmosphere, with the metals present in the fly ash being deposited on street dust (7).

2. Barium, mainly discharged by the brake systems of motor vehicles (36).

3. Chrome, naturally occurring element in rocks, animals, plants, soil, and volcanic dust and gases. Its most common anthropogenic sources

include the industrial oxidation of mined chromium deposits and possibly combustion of fossil fuels, wood, paper, etc., as well as industrial processes, such as refining (ore), processing (chemical and refractory), production (cement and automobile brake linings and catalytic converters) and tanning (leather) (5). Cr is also emitted through processes like stainless steel wear, auto part wear and tool manufacturing (16). Subsequently, chromium is used in motor parts and the motor's body (6), and it is also produced during coal combustion (7).

4. Cadmium, relatively rare metal that occurs naturally in combination with other elements. The primary sources of airborne Cd are the burning of fossil fuels and the incineration of municipal waste materials (5). Cd is used for the preparation of special alloys and solders, metal plating, pigments in yellow or brown paints (for coloring plastics, glass and polishes), nickel–cadmium rechargeable batteries, and electronic waste (6,16). Cd is an important element contained in lubricating oil and tires, which can release Cd to street dust.

5. Cobalt, mainly produced by the smelting industry (16).

6. Copper, essential trace element, widely distributed in the environment. It occurs naturally in elemental form and as a component of many minerals. Cu possibly originates from exhaust emissions from both gasoline and diesel-fueled road vehicles, wear of the automobile's oil pump, and brake pads of vehicles. Cu is released during industrial activities, such as metal processing and smelting, in addition to being present in building materials.

7. Iron and Manganese, produced by the smelting industry (16), by the wear of the braking system and by the general wear of the cars, are also easily generated during coal combustion (7).

8. Mercury, important element in pesticides and fertilizers, being volatile and easy to migrate. Thus, Hg could migrate into urbanized areas and could be released from pesticides used for creating green spaces in cities. In addition, hospitals and clinics are also typical activities that can cause the release of Hg (7).

9. Nickel, used in the body and parts of cars and is also readily generated during coal combustion (7).

10. Lead, ubiquitous metal in industrialized areas. High Pb concentration in street dust samples is associated with traffic burden, brick kilns and the use of leaded gasoline (5). It is discharged from fuel/oil leakage from automobiles with oil lubricants, and wear and tear of tires, brake linings and other parts. E-waste recycling contributes significant amounts of trace metals such as Pb (16).

11. Zinc, essential trace element widely distributed in the environment. Contamination in dust samples is strongly affected by traffic emissions, including engine emissions, mechanical abrasion of vehicles, and tire and brake wear (5). Zn is added to tire tread rubber mostly as zinc oxide (ZnO), and in lesser quantities as a variety of organo-zinc compounds to facilitate vulcanization of rubber. Zinc is also common in car lubricants and carburetors (6).

12. Vanadium, normally regarded as a marker for fuel oil or petroleum burning. The smelting industry can also produce vanadium (16).

3.4. Human health risk assessment

3.4.1. The human health risk model

Risk assessment implies the evaluation of the degree of exposure, measured as an estimated daily intake (in milligrams of contaminant per unit of body weight and unit of time). The intake received through ingestion, inhalation and dermal absorption of trace elements in street dust depends on four types of variables: contact rate, exposure frequency, exposure duration and the bodyweight of the potentially exposed population. These estimates are each affected by a variable degree of uncertainty (31).

The United States Environmental Agency has developed a model to assess the carcinogenic and non-carcinogenic human health risk to heavy metals present in soils. This model can be adopted for street dust based on the assumptions as follows: (a) intake rates and particle emission for street dust can be approximated by those developed for soil (37); (b) human beings are exposed to street dust through three main pathways: ingestion, inhalation and dermal contact; (c) relevant exposure parameters of children and adults in the study areas are similar to those of reference populations; (d) the overall non-carcinogenic and carcinogenic risk for each heavy metal can be calculated by summing the individual risks from the three exposure pathways (5,16,33).

The following equations are commonly used to calculate the estimated daily intake (EDI) in mg/kg per day by ingestion (EDI_{ing}), inhalation (EDI_{inh}) and dermal contact (EDI_{dermal}), and the lifetime average daily dose (LADD) (Eq. 1, 2, 3 and 4):

Equation 1 $$EDI_{ing} = \frac{C * IngR * EF * ED * CF}{BW * AT}$$

Equation 2 $$EDI_{inh} = \frac{C * InhR * EF * ED}{PEF * BW * AT}$$

Equation 3 $$EDI_{dermal} = \frac{C * SA * AF * ABS * EF * ED * CF}{BW * AT}$$

Equation 4 $$LADD = \frac{C}{PEF x AT_{can}} x \left(\frac{CR_{child} x EF_{child} x ED_{child}}{BW_{child}} + \frac{CR_{adult} x EF_{adult} x ED_{adult}}{BW_{adult}} \right)$$

CR is the contact (or absorption) rate. CR = IngR for ingestion, CR = InhR for inhalation, and CR = SA × AF × ABS for dermal contact.

Generally, C is used as the upper limit of the 95 percent confidence interval for the mean (95 percent UCL), which is considered as a conservative estimate of the "reasonable maximum exposure" but, in some studies, maximum concentrations are used. Instead, other authors consider that the risks are overestimated using 95 percent UCL, therefore, they prefer to use the arithmetic mean (16). The most common exposure factors are presented in Table 3.

In some articles a modified model is used which includes a daily time proportion (0.33 percent) for the ingestion and inhalation rates. In such cases, authors considered that the common rates provide a conservatively more protective assessment because they are based on exposure during a whole day, which is unrealistically long. They also argued that the dust particle size should to be considered (4,38).

Using local exposure factors for each study area is desirable, for example, in Beijing, the Municipal Research Institute of Environmental Protection has estimated the inhalation rate, particle emission factor, exposed skin area, skin adherence factor and dermal absorption factor (16). Using more local parameters improves the reliability of the model for local conditions.

The hazard quotients of ingestion, inhalation and dermal contact ($HQ_{ing/inh/derm}$) are found by dividing the EDI into the reference dose (RfD) as demonstrated in Equation 5:

Equation 5 $$HQ_{ing/inh/derm} = \frac{EDI_{ing/inh/derm}}{RfD}$$

The RfD most commonly used can be seen in Table 4. The inhalation reference dose values are substituted sometimes by oral reference doses because it is assumed that, after inhalation, the absorption of the particle-bound toxicants will result in similar health effects when the particles had been ingested (39).

The hazard index (HI) is presented as the sum of the HQ for the three exposure pathways: ingestion, inhalation and dermal contact. The HI can evaluate the human health risk: if greater than 1, it is possible that non-carcinogenic effects may occur; if the HI value is less than 1 the opposite may be expected (37).

For carcinogens, the incremental lifetime cancer risk ($ILCR$) is commonly calculated with the following equation:

Equation 6 $$ILCR = LADD * CSF$$

The most common cancer slope factors used in the references cited are shown in Table 4.

Table 3. Most commonly reported exposure factors for human health risk assessment

Factor [units]	Value		Reference
	Child	Adult	
Ingestion rate (IngR) [mg/day]	200	100	37
Inhalation rate (InhR) [m^3/day]	7.63	12.8	9
Particle emission factor (PEF)	1.36E+09	1.36E+09	37
Surface of exposed skin area (SA) [cm^2]	2800	5700	37
Dermal absorption factor (ABS)	0.001	0.001	37
Skin adherence factor (AF) [mg/cm^2]	0.2	0.07	37
Duration of exposure (ED) [years]	6	24	37
Frequency of exposure (EF) [days/year]	350	350	28
Average time non-carcinogens (AT) [days]	ED*365	ED*365	9
Average time for carcinogens (Atcan) [days]	70*365	70*365	9
Body weight (BW) [kg]	15	70	18
Heavy metal concentration (C) [mg/kg]	95 percent UCL		Measured in each study
Conversion factor (CF)	1 x 10^{-6}		41
UCL: upper confidence limit, mg: milligrams, m^3: cubic meters, cm^2: ~~squirt~~ square centimeters, kg: kilograms.			

The RfD for Pb has not been established by the USEPA, therefore, the RfD for Pb is 3.561023 mg/kg/day calculated from the provisional tolerable weekly Pb intake limit (25 mg/kg body weight) recommended by the Food and Agriculture Organization and the World Health Organization (FAO/WHO) for adults. The acceptable or tolerable risk is over the range of 1E−06 to 1E−04 (37). These values indicate that one additional case in a population of between 1,000,000 and 10,000 is acceptable (40).

3.4.2. Overview of the health risk assessment worldwide

The heavy metals for which the HI is most commonly calculated are Cu (92 percent for both children and adults), Pb (87 percent for both), Cr (87 percent for children and 92 percent for adults) and Zn (85 percent for both); the number of articles (n) that reported the HI for each heavy metal can be seen in Table 5. The main reason why the number of articles for the HI is out of line with the number of articles that reported concentrations of Cu, Pb, Cr and Zn is because some authors only calculated the HI for children and others only for adults.

Because very high concentrations of some heavy metals are found in some locations, the mean worldwide HI may not be representative of the worldwide situation; therefore, the median concentrations are taken in this review as the central tendency measure. According to the median HI, there is no expected risk of developing adverse effects on human health (HI less than 1), either for children nor for adults (Table 5). Despite this, the median HIs for As, Cr and Pb are the highest of all the heavy metals (E−01) for children, which indicates that special attention should be paid to those heavy metals. Moreover, it has been reported that chronic exposure to an HI greater than 1E−01 may trigger many ailments (17). In the case of the HI for adults, the risk is less (E−02) than for children, but there are many heavy metals at this risk level, *i.e.*, As, Cr, Fe, Mn, Pb and V.

Even when the median HI is at a safe level, in some cities, possible adverse effects on the health of children and adults may occur due to the presence of As, Cu, Ni and Pb in street dust. Cd and Cr can also cause adverse effects for children; see the maximum HI in Table 5. At this point, it is worth mentioning that some extremely high HI values were deleted because they could be mistakes. These extremely high values were identified in boxplots by

Table 4. Reference doses (RfD) and cancer slope factors (CSF)

Heavy metal	Oral RfD	Dermal RfD	Inhalation RFD	Oral CSF	Dermal CSF	Inhal CSF
As	3.00E-04	1.23E-04	3.01E-04	1.50E+00	3.66E+00	1.51E+01
Cd	1.00E-03	1.00E-05	1.00E-03			6.30E+00
Co	2.00E-02	1.60E-02	5.71E-06			9.80E+00
Cr	3.00E-03	6.00E-05	2.86E-05			4.20E+01
Cu	4.00E-02	1.20E-02	4.02E-02			
Fe	8.40E+00	7.00E-02	2.20E-04			
Hg	3.00E-04	2.10E-05	8.57E-05			
Mn	4.60E-02	1.85E-03	1.43E-05			
Ni	2.00E-02	5.40E-03	2.06E-02			8.40E-01
Pb	3.50E-03	5.25E-04	3.52E-03	0.0085		4.20E-02
V	7.00E-03	7.00E-05	7.00E-03			
Zn	3.00E-01	6.00E-02	3.00E-01			

RfD: reference doses, CSF: cancer slope, E: exponential. Based on (6, 19, 35, 40)

country, and linear regressions between the concentrations and the HI; even when high, their corresponding concentrations were close to the median. The HIs deleted for children were: As = 221 (41), Cd = 180 (28), Co = 11.8 (41), Cr= 60 (28), Hg = 103, and Pb = 23,600 (28). The HIs deleted for adults were: Cd = 22 (28), Cr = 7.67 (28), Hg= 22.1, and Pb = 2942.86 (28). In the case of Hg, the concentration was high, but no explanation or discussion was provided.

A probable linear relationship between the HI and the concentrations of heavy metals was expected because the exposure parameters of children and adults in the study areas were close to those of reference populations, and only the concentrations of heavy metals varied. Indeed, for some elements, the correlation coefficients were higher than 0.7, indicating good linear relationships, and only a few points were far away from the central tendency. For other elements, however, no relationship was found, and, for Fe, a negative relationship was observed, *i.e.*, when the Fe concentration increased, the HI for adults decreased. This highlight possible errors in the calculations. Therefore, for future studies, a clear and detailed writing of the methodology is recommended.

Another important point is to always use bioavailable concentrations of heavy metals in street dust for assessing human health risks. The toxicity reference values used in risk assessments for ingestion are expressed in terms of absorbed doses and are often derived from assays that employ soluble salts or other easily available chemical forms of heavy metals. Consequently, human health-risk assessments assume that the concentration of heavy metals used in USEPA equations represents the concentrations of heavy metals that are bioavailable in the gastrointestinal tract (30).

In relation to the carcinogenic risks, where the distributions of frequencies were also skewed to the right, the median was used as a central tendency measure. According to the median RI, As and Pb are in the tolerable risk range (1E–06 to 1E−04) for children, and As was also tolerable for adults. Consequently, once again, special attention must be paid to As and Pb (Table 6). Although the median worldwide RIs were in or below the tolerable range, in some cities, the RI exceeded that range (see maximum RI in Table 6) for As, Cr, Ni and Pb, both for children and adults. Therefore, people could be at risk of developing cancer during a lifetime in those places.

Table 5. Non-carcinogenic indexes (HI) for children and adults

Heavy metal	n	Mean	Median	SD	Minimum	Maximum
Children						
As	18	1.07E+00	2.68E-01	2.32E+00	3.40E-03	9.00E+00[1]
Ba	5	4.29E-02	4.80E-02	4.51E-02	0.00E+00	1.10E-01
Cd	26	1.12E-01	1.07E-02	2.78E-01	1.33E-03	1.02E+00[2]
Co	21	1.03E-01	8.20E-03	1.80E-01	0.00E+00	6.00E-01
Cr	33	4.39E-01	2.79E-01	7.33E-01	0.00E+00	4.06E+00[3]
Cu	36	1.80E+00	1.47E-02	8.38E+00	1.70E-03	4.93E+01[4]
Fe	6	4.86E-02	4.15E-02	3.79E-02	1.21E-04	9.91E-02
Hg	8	1.09E-02	4.73E-02	6.42E-02	2.50E-03	1.72E-01
Mn	23	1.11E-01	7.55E-02	1.42E-01	0.00E+00	6.62E-01
Ni	30	3.33E-01	1.59E-02	1.73E+00	0.00E+00	9.50E+00[5]
Pb	33	2.23E-01	3.93E-01	4.84E-01	3.73E-03	2.19E+00[6]
V	11	6.37E-02	2.17E-02	8.46E-02	0.00E+00	2.70E-01
Zn	33	2.37E-02	7.79E-03	6.23E-02	0.00E+00	3.33E-01
Adults						
As	21	2.20E-01	3.09E-02	4.76E-01	3.33E-03	1.90E+00[1]
Ba	5	6.63E-03	8.23E-03	6.39E-03	0.00E+00	1.50E-02
Cd	28	1.49E-02	1.84E-03	3.55E-02	0.00E+00	1.53E-01
Co	23	1.54E-02	1.55E-03	2.48E-02	0.00E+00	7.50E-02
Cr	35	7.55E-02	3.77E-02	1.07E-01	0.00E+00	5.33E-01
Cu	36	2.05E-01	1.98E-03	1.05E+00	4.94E-04	6.25E+00[4]
Fe	6	1.76E-02	1.53E-02	1.91E-02	8.10E-06	5.30E-02
Hg	9	1.57E-03	1.14E-02	2.08E-02	2.10E-04	6.11E-02
Mn	23	1.90E-02	1.10E-02	2.23E-02	0.00E+00	9.61E-02
Ni	31	4.09E-02	2.30E-03	2.15E-01	0.00E+00	1.20E+00[5]
Pb	33	3.10E-02	4.65E-02	5.87E-02	5.77E-04	3.10E-01
V	12	2.44E-02	1.11E-02	3.30E-02	0.00E+00	1.10E-01
Zn	33	3.18E-03	1.17E-03	7.82E-03	0.00E+00	4.33E-02

n: number of articles, E: exponential, SD: standard deviation, HI: hazard index, When the HI is greater than 1, possible adverse effect on human health may occur. [1]HI greater than 1: (27,9), [2]HI greater than 1: (27, 41), [3]HI greater than 1: (42, 20, 6), [4]HI greater than 1: (28, 27), in addition, HI greater than 1 in reference: (1), [5]HI greater than 1: (28), [6]HI greater than 1: (41), (43), (44)

To reduce exposure to the pollutants, street cleaning is one of the best practices. Therefore, the street cleaning program and planning related to street dust in urban areas is important. Local conditions, climate and specific needs also need to be considered as critical determinants of the ideal street sweeping strategy (technology, frequency, speed, targeted areas, etc.) (4).

4. PERSPECTIVES

We identified the need to standardize the terms used referring the material (matrix) and

Table 6. Carcinogenic risk (RI) for children and adults

Heavy metal	n	Mean	Median	Standard deviation	Minimum	Maximum
Children						
As	14	2.54E-05	3.20E-06	5.84E-05	2.91E-09	2.10E-04[1]
Cd	16	9.54E-06	1.23E-09	2.08E-05	5.66E-11	6.19E-05
Co	14	1.29E-07	5.60E-09	3.22E-07	0.00E+00	1.07E-06
Cr	26	5.06E-05	6.05E-07	1.42E-04	4.61E-10	6.14E-04[2]
Ni	20	3.81E-02	6.06E-09	1.70E-01	4.00E-10	7.60E-01[3]
Pb	9	7.10E-05	2.66E-06	2.06E-04	8.08E-11	6.21E-04[5]
Adults						
As	12	2.34E-05	1.65E-06	7.15E-05	3.90E-10	2.50E-04[1]
Cd	13	1.55E-06	1.30E-09	3.06E-06	1.09E-10	8.69E-06
Co	10	4.39E-07	6.40E-09	1.31E-06	0.00E+00	4.16E-06
Cr	22	1.93E-05	4.90E-07	5.63E-05	1.16E-12	2.11E-04[2]
Ni	15	1.60E-05	4.08E-09	4.25E-05	2.00E-10	1.59E-04[4]
Pb	9	4.19E-05	1.20E-07	1.25E-04	1.08E-11	3.75E-04[5]

The tolerable risk is over the range of 1E-06 to 1E-04 (USEPA, 2001), USEPA= United States Environmental Protection Agency, [1](9), [2]RI is in the tolerable limit on references: (7, 20, 17), [3]RI is in the tolerable limit on: (39, 7, 17), [4]RI is in the tolerable limit on (7), [5] RI is in the tolerable limit on (20)

Figure 2. Some of the main highlights from this review are summarize in the figure: 1) it is necessary to record the sampled area in order to calculate street dust load, and to sieve to 63 µm; 2) there is worldwide contamination of lead and zinc in street dusts; 3) the main sources of heavy metals in street dust are automobiles and fossil fuels; and 4) arsenic, chromium and lead concentrations in street dust worldwide could be a possible risk to human health.

elements of analysis. We encourage readers to use the most common terms found in the literature: "street dust" and "heavy metals". These terms are increasingly recognized by the researchers in the field.

Important guidelines that came from this review (Figure 2) were: 1) Sampling must be clearly defined and preferably should be based on statistical methods. The number of samples must be enough to represent the study population; at least one sample per square kilometer should be taken, or 100 samples taken when spatial interpolations are required to be conducted, according to Oliver and Webster (2015). 2) All studies of heavy metals in street dust should collect samples per square meter, to report street dust loading and even heavy metals loadings. In this way, it is possible to have a general overview of the quantity of dust that is in the urban environment. 3) Particle size should be less than 63 micrometers. The adopted 2 mm size from soil sciences does not work well for street dust, as it is a very coarse fraction which does not represent airborne particles.

Lastly, lead and zinc were identified as the heavy metals most commonly released in cities, since they had the highest contamination category, with reference to the world soil background values. With regards to human health, arsenic, chromium and lead have the highest risk to human health; therefore, they should always be analyzed in studies of heavy metals in street dust.

Some suggestions for future studies are as follows:

A future research topic will be the creation of sorption, mobility and toxicity indices of heavy metals considering the quantity and type of clays, organic matter, aggregation and pH of urban dust (23, 24)

The mobile or bioaccessible fractions should always be used in estimations of the USEPA human health risk model of heavy metals in street dust. The exposition factors for at least each big city should be determined in order to make the health risk assessment more accurate. The case of Beijing (16) is a good example of this effort.

Other proxy methodologies, *e.g.*, color of street dust (45,46,47) and magnetic properties (42,48,49), could be applied to identify the more likely polluted sites, then deeper analysis could be made in those specific sites, saving time and resources. The burning of fossil fuels generates magnetite and maghemite particles that are black minerals and that have high values of magnetic susceptibility, this is the reason for the use of color and the magnetic signal as proxy technologies.

5. ACKNOWLEDGMENTS

This work was supported by CONACYT grant CB-2016-283135.

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Abbreviations: As: arsenic, Ba: barium, Cd: cadmium, Co: cobalt, Cr: chromium, Cu: copper, Fe: iron, Hg: mercury, Mn: manganese, Ni: nickel, Pb: lead, V: vanadium, Zn: zinc, USEPA: United States Environmental Protection Agency, DNA: deoxyribonucleic acid, AAS: atomic absorption spectroscopy, GFAAS: graphite furnace atomic absorption spectrometry, ICP-AES: inductively coupled plasma atomic emission spectroscopy, ICP-MS: inductively coupled plasma mass spectroscopy , ICP-OES: inductively coupled plasma optical emission spectroscopy, PXRF: portable X-ray fluorescence, XRF: X-ray fluorescence, PCA: Principal component analysis, PC: principal components, EDI: estimated daily intake, EDIing: estimated daily intake by ingestion, EDIinh: estimated daily intake by inhalation, EDIdermal: estimated daily intake by dermal contact, LADD: lifetime average daily dose, C: heavy metal concentration, IngR: ingestion rat, EF: exposure frequency, ED: exposure duration, CF: conversion factor, BW: body weight, AT: average time, InhR: inhalation rate, PEF: particle emission factor, SA: surface of exposed skin area, AF: skin adherence factor, ABS: dermal absorption factor, CR: contact or absorption rate, UCL: confidence interval for the mean, HQ: hazard quotient, HQing/inh/dermal: hazard quotient for ingestion/inhalation/dermal contact, RfD: reference dose, ILCR: incremental lifetime cancer risk, CSF: cancer slope factor, FAO: Food and Agriculture Organization , WHO: World Health Organization

Key Words: Heavy Metals, Sampling, Sources, Street Dust, Risk Assessment, Review

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