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# Reported Lead Levels in Different Environmental Matrices in Colombia\*

Niveles de plomo reportados en diferentes matrices ambientales en Colombia

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## Abstract

*Objective:* The aim of this paper is to present a review of specific cases that reported lead concentrations in blood, objects, food, soil, bioindicators, air, and water in specific places in Colombia and evaluate the reported concentrations against target values. *Materials and Methods:* A systematic qualitative literature review of publications between 1995 and 2019 was done; using Boolean operators 1571 papers were identified, to which 3 inclusion and 4 exclusion criteria were applied. A total of 57 studies met the defined criteria. The reports in these studies were geolocalized and compared with acceptable values. *Results and Discussion:* Results suggest that lead is present in all environmental matrices, widely distributed in the Colombian territory, and that 72 % of the cases exceeded regulation limits. The percentage of noncompliance per environmental matrix was 89 % for blood samples, 71 % in food, 63 %, in soil, 89 % for bioindicators, 60 % for air, and 55 % for water. *Conclusion:* These results show that lead pollution is a large-scale problem in the country, more systematic studies are needed, and control measures, policy-making and regulatory updating should be pursued.

**Keywords:** Lead (II), Colombia, poisoning, environmental pollution, heavy metals, systematic review.

## Resumen

*Objetivo:* este artículo tiene como propósito presentar una revisión de casos concretos que reporten concentraciones de plomo en sangre, objetos, alimentos, suelos, bioindicadores, aire y agua en lugares específicos del territorio colombiano y evaluar las concentraciones reportadas con valores objetivo. *Materiales y Métodos:* se realizó una revisión sistemática cualitativa de literatura entre los años 1995 y 2019, empleando operadores booleanos que permitieron identificar 1571 artículos, sobre los que se aplicaron 3 criterios de inclusión y 4 criterios de exclusión. 57 estudios cumplieron con los criterios definidos. Los reportes fueron ubicados geográficamente y comparados con los valores permisibles. *Resultados y discusión:* los resultados evidencian que el plomo está presente en todas las matrices ambientales, que está ampliamente distribuido en el territorio colombiano y que el 72 % del total de los casos sobrepasan los límites establecidos por la normatividad para cada matriz. Este porcentaje de incumplimiento por matriz ambiental fue de 89 % en el caso de muestras de sangre, 71 % en alimentos, 63 %, en suelos, 89 % en bioindicadores, 60 % en aire y 55 % para el agua. *Conclusiones:* estos resultados evidencian que la contaminación por plomo es un problema a gran escala en el país, que se requieren más estudios sistemáticos y que se deberían extremar las medidas de control, definir políticas y actualizar la normatividad.

**Palabras clave:** Plomo (II), Colombia, intoxicación, contaminación, metales pesados, revisión sistemática.

## **Introduction**

Heavy metals are defined as those that form positive ions in a solution and have a density five times greater than that of water. In addition, they have a particular toxicological importance as in the case of lead, cadmium, and mercury [1]. Lead is widely used for its importance in modern industry [2] due to properties such as a low melting point (327.4 °C), high density, low hardness, resistance to acid and chemical stability in air, water, and soil. For these reasons it is appealing for use in industries related to construction, paint manufacturing, electroplating, mining, metallurgy, manufacturing and recycling of electric accumulators and batteries, among others [3]. It is for this reason that among the main sources of exposure to this metal are lead paints used inside and outside of buildings [4], [5], atmospheric emissions from stationary sources such as paint factories, metal processing facilities, battery factories, power plants, hazardous waste treatment plants, and mobile sources [6]; also, contaminated food and water, ceramics with leaded glazes [7], and occupational sources.

Lead is transported through all environmental matrices. Initially it can be emitted into the air, where, by the action of rain, it precipitates and directs toward bodies of water [8]. On the other hand, the soil appears as a natural deposit of this heavy metal, where part of it remains indefinitely [9] and the rest is transported to bodies of water through runoff, either in rural areas or on the paved streets in urban areas [10]. Additionally, lead is transferred to plant or animal species in contact with contaminated air, soil, or water, accumulating and moving up the food chain until it reaches humans. It can also reach humans through contact of food with welds that contain lead, as in the case of cans [11] or utensils [4], or even through inhalation or dermal contact with projectiles [12].

Once in the human body, this metal has no known biological function, is highly persistent, bioaccumulates in organs and tissues [13], [14], increases the risk of lung, stomach, or bladder cancer [15], [16], and generates damage to the nervous, reproductive, cardiovascular, gastrointestinal, hematopoietic, and immune systems [17], [18].

In Colombia, despite the fact that lead was eliminated from gasoline through the Decree 948 of 1995 [19], resolution 1180 of 2006 establishes a maximum allowed of 0.013 g/L [18]. Therefore, its release into the atmosphere continues being a public health problem [20]. However, in the country no study has been carried out that makes a systematic review of its concentrations in the environment or in clinical studies, underestimating the real magnitude of this problem and generating a large gap in knowledge about the associated toxicological risks in the country. In addition, the lead content is not currently regulated in some of the environmental matrices, such as soil and living beings.

The main purpose of this document is to contribute to the review of specific cases that report lead concentrations in human blood, objects, food, soil, bioindicators, air, and water in clearly defined places as detailed in articles published between 1995 and 2019. The search was carried out in Scopus and SciELO. The concentrations identified were geolocated and compared with national and international regulations. It was found that, in most cases, lead concentrations exceed established limits and are also present in a wide regional diversity across the country and in all defined environmental matrices, which should lead to extreme control measures, definition of policies, and updating of regulations.

## **Materials and Methods**

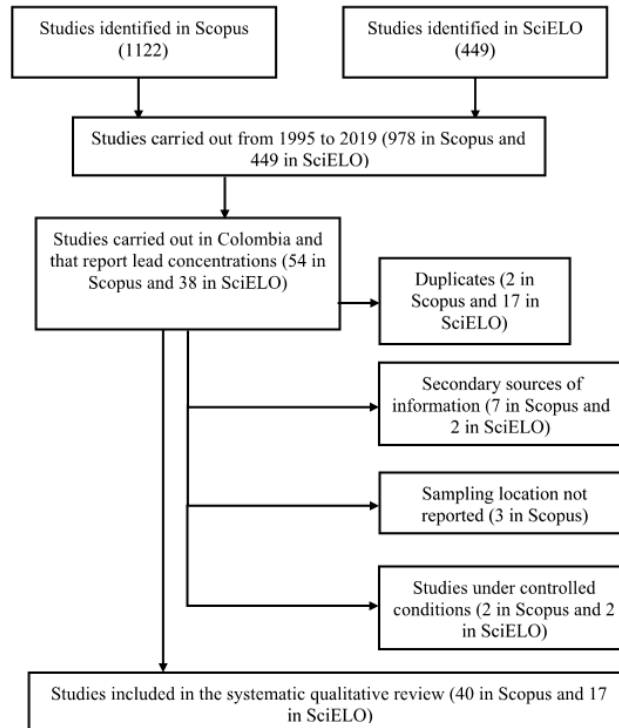
A qualitative systematic review [21] of the scientific articles published in databases on the presence of lead in the different environmental matrices in Colombia was carried out, using Boolean operators such as “AND” and “OR” to obtain more specific results [22]. In the first case, an advanced search was carried out in the Scopus database requesting articles with the expressions (“lead” OR “lead” OR “Pb”) in their title, abstract, or keywords and that in turn contained throughout the document the words “Colombia AND metal.” Additionally, another advanced search was carried out, this time in the regional information source SciELO, with the expression (((Lead) OR (lead) OR (Pb)) AND (Colombia)) [23]. However, the results covered articles that were not relevant to the objective of our research, although they included the words “lead” and “Colombia” in their content, which is why it was required to verify them under inclusion and exclusion criteria [24], [25], as seen in figure 1.

Three inclusion criteria were defined as follows: 1) the studies were carried out in the period between 1995 and 2019 were included, that is, starting from the year in which regulations eliminated lead in gasoline [19]; 2) the samples of the environmental matrix under investigation were located in Colombia, since some authors mentioned the country, but used samples from other places and therefore their results were not of interest for this study; and 3) the results reported quantitatively the lead concentrations determined, in such a way that they could be compared with reference values.

Similarly, 4 exclusion criteria were defined as follows: 1) studies found in both searches (duplicates); 2) studies that reported lead levels which were not determined by the study itself, that is, those that reported secondary information; 3) studies that did not report the specific place where the samples were taken, which ruled out the possibility of geolocating and performing an analysis based on said location; and 4) studies carried out under controlled or laboratory conditions, that is, studies that did not show actual field results, since it is essential that the appearance of lead in the sample occurred involuntarily.

Finally, results were coded according to the environmental matrix in which they were reported: Water (W), air (A), soil (S), bioindicators (V), blood in humans (B), food (F), and objects (O). The concentrations of lead reported were compared with the maximum limits allowed by national and international regulations and the associated sources and effects observed were identified. Additionally, results were georeferenced and located on a map of the country.

**Figure 1. Methodological scheme of the systematic search**

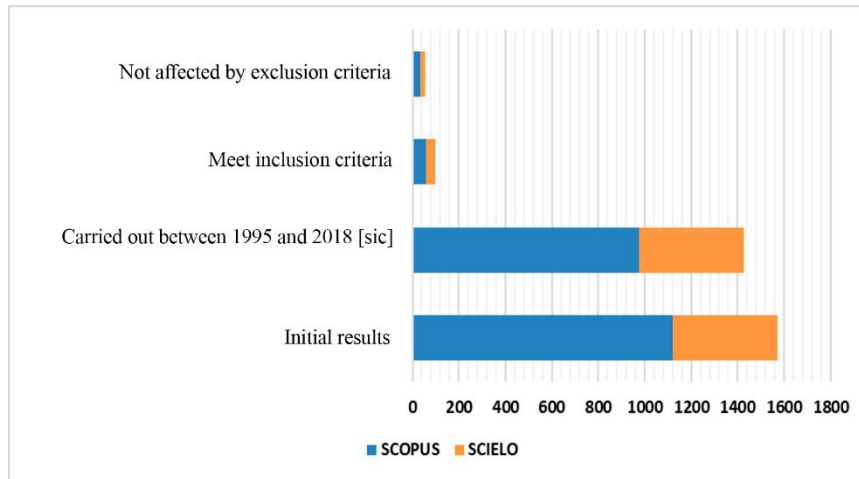


**Source: Adapted from “Preferred Reporting Items for Systematic Reviews and Meta-Analyzes: The PRISMA Statement,” 2009 [26].**

## Results

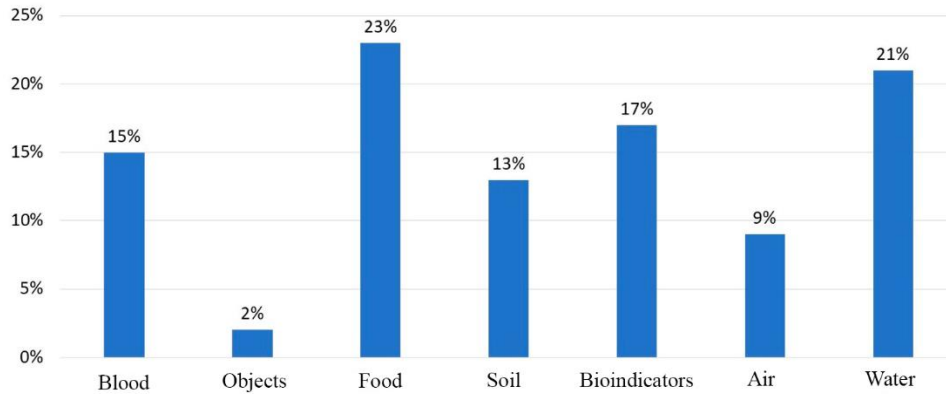
Figures 2 and 3 show the results of the systematic search in the databases used. As indicated in figure 1, 1122 articles were found in Scopus and 449 in SciELO, that is, a total of 1571 articles adding up the results from the two databases. This number reduced to 54 and 38 once the inclusion criteria had been validated and successively to 40 and 17, respectively, after verification of the exclusion criteria, for a total of 57 articles. Of these, 9 determined the lead level in blood in populations of children and adults (15 %), 1 in objects (2 %), 14 in food (23 %), 8 in soil (13 %), 9 in bioindicators (17 %), 5 in air (9 %), and 11 in water (21 %), as presented in figure 3.

**Figure 2. Preliminary results of the database search**



Source: Own source.

**Figure 3. Articles validated by environmental matrix**



Source: Own source.

Table 1 shows the main characteristics of the studies resulting from the systematic review, while figure 5 geolocates the studies that reported lead levels in the different environmental matrices. It can be observed that they are distributed mainly in the Caribbean Coast region and the central area of the country. The city of Bogotá stands out as the one with the highest frequency, followed by Cartagena, Cali and Medellín.

Lead concentrations in blood were compared to maximum acceptable limits determined by the Center for Disease Control and Prevention (CDC), which states that health effects can occur with blood lead levels as low as 5  $\mu\text{g}/\text{dL}$ , while in adults the maximum allowed value is 38  $\mu\text{g}/\text{dL}$  [27].

## **Blood Lead Levels**

Regarding the studies carried out in the country, it was found that the first was an occupational study and was carried out in Bogotá [28]. In the battery production industry, 84 % of the workers had lead levels greater than 38 µg/dL associated with variables such as infrequent change of clothes, washing clothes at home and poor hygiene and industrial safety habits. Similarly, it was reported the presence of symptoms such as abdominal pain, headache, blurred vision, metallic taste in the mouth, cramps, and irritation in the eyes and throat. This is due to the fact that in the battery industry lead is used in the casting of grids, edges, and solder, turning into a source of exposure to lead vapors and particles. This situation worsens in informal establishments where there is no environmental control measures (ventilation) and occupational health (personal protection elements). Other studies carried out in Bogotá also show high levels of lead in other industrial sectors. Blood lead levels of 39 µg/dL were found in a printing press [29] and higher than 77 µg/dL in other battery manufacturing companies, reporting, among others, symptoms such as headaches, abdominal pain, anemia, basophilic stippling, metallic taste, blurred vision, and memory impairment [30].

On the other hand, in 2007, the first clinical study was carried out in children aged 5 to 9 in Cartagena, in which it was found that 7.41 % of the sample presented levels greater than 10 µg/dL. Results were associated with the fact that metal smelting and fishing lead weight manufacturing activities were carried out in the study sites, mostly informally in homes or warehouses, thus workers indirectly exposed their children [31]. Another study, carried out on 32 children under 12 years of age, para-occupationally exposed to the battery recycling process in the municipality of Soacha and in the city of Bogotá, found that they all presented lead levels higher than those allowed, with a maximum value of 90 µg/dL and symptoms such as headaches, abdominal pain, hyporexia, Burton's line, vomiting, and sleep disorder [20].

In recent years, investigations have focused on environmental exposure to lead, beginning with one carried out on 350 children aged 6 to 14 in the north of the city of Cali [32], in which 69 minors exposed to industrial emissions from battery and metal smelting factories, as well as 16 unexposed minors, presented levels greater than 5 µg/d, which are those allowed by regulations [33]. The latter were associated with the handling of batteries at home, the consumption of contaminated fish, and a low socioeconomic level. Similarly, in the city of Cartagena, 118 blood samples were collected from children aged 5 to 16, of which 3.4 % (4 samples) had levels above the acceptable value, with a maximum of 34.05 µg/dL in the El Bosque neighborhood, associated with exposure to emissions from companies engaged in metal smelting [34]. Another study [35] that reviewed data in several Caribbean cities found values within regulations for Cartagena, Valledupar, and La Paz, but in Tasajera values of

8.9 to 34.05 µg/dL were reported. This relationship between exposure to emissions in industrial zones and blood lead levels is also observed in a study carried out in the city of Bogotá, which reported a maximum value of 67.91 µg/dL and averages above 10 µg/dL in the localities (districts) of Puente Aranda, Rafael Uribe Uribe, Kennedy, Antonio Nariño, San Cristóbal, and Usme, most of which have been declared as source areas of air pollution [36], with accounts of clinical manifestations such as memory loss, tremors, and attention problems [37].

Regarding the adult population, in the city of Cali, lead levels associated with a poor diet and low socioeconomic status were reported in 14 women in their first trimester of pregnancy, with values above 5 µg/dL, which persisted until the third trimester in 7 of them [38]. On the other hand, in the municipalities of San Marcos and Sucre in the region of La Mojana (Sucre), lead levels of 0.15 µg/dL to 52.46 µg/dL were identified as a consequence of the use in the area of agrochemicals such as lead arsenate and the use of food and water from the Cauca River, in which substances derived from gold mining and industrial activity are transported along its streambed [39]. On the other hand, J. Gerstner Garcés [12] explored lead poisoning from projectiles or shrapnel lodged in the human body as a consequence of gunshot wounds, presenting two cases in the city of Cali with lead levels of 62 and 90.3 µg/dL in blood, associated with symptoms in the gastrointestinal, nervous, musculoskeletal, and circulatory systems.

### **Lead Levels in Objects**

Currently, Colombia has technical regulations on the health requirements for toys, their components and accessories that are marketed in the national territory, issued by resolution 3388 of 2008 [40]. This regulation establishes a maximum value of 0.7 µg for the daily bioavailability of lead resulting from the use of a toy and 90 mg/kg (ppm) as the maximum migration of this metal to the human body by ingestion. However, a study identified 8 samples of paints used to coat toys with a lead level higher than recommended, with values ranging from 244 to 47,600 ppm, of which 6 toys were manufactured in Colombia and the others in China [41]. In the same way, it was found that 64 % of the analyzed household paints contain a total concentration of lead greater than 600 parts per million (ppm) [42], when the standard establishes that a concentration of 100 ppm should not be exceeded [43]. This presents a significant risk to the health of children since paint particles can be ingested directly or indirectly when they are mix with dust or remain on the hands. At the international level, lead has also been found in different objects associated with children such as toys, stained glass, arts and crafts materials, and faux jewelry and cosmetics [7].

## Contaminated food

Worldwide, the Codex Alimentarius [44] establishes the maximum limits for contaminants in different foods and their provisional tolerable monthly intake, which for lead is 25  $\mu\text{g}/\text{kg}$  of body weight. In Colombia, the maximum levels of lead have been established in food and fishery products for human consumption [45], [46].

The consumption of food contaminated with lead directly affects the health of human beings, even in low amounts, since if the exposure is constant it can increase the risk of poisoning. Such is the case of foods for daily consumption such as potatoes, from Tunja, Boyacá, in which Mariño and others [47] identified lead with values ranging between 0.085 and 0.150  $\text{mg}/\text{kg}$ . Also, chives, lettuce, and cabbage grown in Norte de Santander [48] that exceeded the maximum limit established by the Ministry of Health were identified. Likewise, in the east of the city of Cali, lead levels in drinking water between 0.11-0.36  $\mu\text{g}/\text{L}$  [49] were reported. Although these values are below the limit of 10  $\mu\text{g}/\text{L}$  established in Colombian regulations [50], they constitute a chronic health risk since daily consumption cannot be reduced. The same applies to the consumption of salt that, although it can be reduced, it is a product of daily consumption and thus it is worrying that lead levels of up to 1  $\text{mg}/\text{kg}$  have been reported in table salt distributed by different supermarkets in Bogotá [51].

Regarding bovine meat, those from the valleys of the Sinú and San Jorge rivers, in the department of Córdoba, reported lead concentrations of 0.007-0.095  $\mu\text{g}/\text{g}$  in muscle and 0.020-0.098  $\mu\text{g}/\text{g}$  in liver tissue [52]; although these levels do not exceed the 0.1 ppm limit, the upper end values are very close to it. In the city of Barrancabermeja, levels above the limits established for bovine meat and viscera were reported, with average values of 0.62, 0.54 and 0.24  $\text{mg}/\text{kg}$  in liver, kidney, and muscle tissues, respectively, which were found to be higher than those found in the municipality of Yondó, with values of 0.49, 0.38, and 0.22  $\text{mg}/\text{kg}$ . The source of the metal is associated with the contamination of the pastures consumed by the cattle as a consequence of the industrial activity carried out in neighboring areas [53], which can generate acute health effects in livestock [54]. This is confirmed by a study that made an inventory of the pastures near an oil refinery in Barrancabermeja, Santander, and to extraction wells in Yondó, Antioquia, showing higher concentrations of lead at a distance of 100 m from the oil refinery, both in soil and in plant species, with values of 794.04 and 16.07  $\text{mg}/\text{kg}$ , respectively [55].

Different studies have been carried out in order to determine the Pb content in frequently consumed fish. *Eremophilus mutisii* (“Capitán de la Sabana” or Captain of the Savannah) was analyzed in the municipalities of Chocontá and Suesca, detecting maximum concentrations of 7.7 and 7.3 ppm respectively, which exceeds alarmingly the limit of 0.3 ppm [56]. However, in the Ciénaga de Mallorquín, in the city of Barranquilla, lead levels of 0.66-2.03

$\mu\text{g/g}$  (dry weight) were reported, associated with the Barranquilla industrial area, as well as the accumulation of pollutants in mangrove forests and in the sediment load of the Magdalena River [57]. Similarly, in the upper basin of the Chicamocha River, lead levels were found in the Nile tilapia (*Oreochromis niloticus*), with maximum values of 0.47  $\mu\text{g/g}$ , 0.51  $\mu\text{g/g}$ , and 0.45  $\mu\text{g/g}$  in liver, gill, and muscle tissue respectively [58]. Additionally, in the Gulf of Urabá, amounts of Pb were reported in crevalle jack (*Caranx hippos*) above the allowed limit in a range of 0.667-23.378 mg/kg, with mean values of 1.30 mg/kg in muscle tissue, 0.95 mg/kg in residues, 7.8 mg/kg in viscera, 13.3 mg/kg in head and gills, and 19.4 mg/kg in fins and tail [59]. On the other hand, levels below the reference value were found in fish marketed in the city of Bogotá, with average maximum concentrations of 0.0595 mg/kg for salmon (*Oncorhynchus sp.*), followed by the sierra (*Scomberomorus sp.*) with 0.034 mg/kg, snook (*Centropomus sp.*) with 0.0289 mg/kg, Basa fish (*Pangasius sp.*) with 0.029 mg/kg, red tilapia (*Oreochromis sp.*) with 0.0281 mg/kg, catfish (*Pseudoplatystoma sp.*) with 0.0264 mg/kg, “bocachico” (*Prochilodus sp.*) with 0.0254 mg/kg and long-whiskered catfish (*Pimelodus sp.*) with 0.0199 mg/kg [60].

Also, lead contents greater than that allowed by international regulations (0.1-0.3 mg/L) has been detected in artisanal alcoholic beverages such as “ñeque” or “chirrinchi” [61]. For these cases, in the department of Bolívar they found levels between 0.5 and 0.76 mg/L [62]; however, these values were higher than those found in a second study in the department of Sucre, with a maximum of 0.41 mg/L [63]. In the latter, the San Jorge river was determined as a possible source of contamination since the water with which the drinks were prepared was taken from its waters and its contamination by mining activity has been reported.

Contamination with Pb in fish is attributed to eating habits that include sediments [56], benthic algae, phytoplankton, eggs and larvae of other species, as well as the presence of the metal in the aquatic ecosystem as a result of the discharge of domestic and industrial wastewater [58], [57]. This increases the bioavailable lead for animal and plant species in water systems, which eventually bioaccumulates it in their body. Such is the case of fish species such as *Eremophilus mutisii* (“Capitán de la Sabana” or Captain of the Savannah), striped catfish (*Pseudoplatystoma orinocoense* and *P. metaense*) and capaz (*Pimelodus grosskopfii*) from the Bogotá river (Cundinamarca), Puerto López (Meta) and the Betania dam (Huila, Colombia), respectively [64]. As a result, the presence of lead in blood was identified (in 93 % of captains, 44 % of striped catfish, and 28 % of capaz) with levels between 3.6 and 9.5  $\mu\text{g/dL}$ .

On the other hand, contaminated crops can indicate an exchange of these elements with the soil, deposition of atmospheric emissions, residues of lead ammunition, application of fertilizers, pesticides and soil conditioners [65]. Exposure to this type of pollutants is aggravated for people of low socioeconomic status due to factors such as proximity to or poor handling of hazardous waste, emissions from nearby atmospheric sources, inhalation of

particulate material from unpaved or poorly maintained roads, restricted access to drinking water, and overcrowding [6].

### **Bioindicators of Contamination**

In this case, exposure to lead associated with the ingestion of food contaminated by contact with solid waste with concentrations between 2.86 and 9624 mg/kg is evidenced in the Morro de Moravia open-air landfill in the city of Medellín. Likewise, animal species that inhabit this place such as different arachnids and the house mouse (*Mus musculus*) presented average levels of 5.01 mg/kg and 45.05 mg/kg, respectively, exceeding the values of 0.5-7 mg/kg for species in uncontaminated sites [66]. Regarding plant species, the Pb content ranged from 0.125 to 123.7 mg/kg, of which the maximum value was obtained from *L. virginicum* [67]. In contrast, in the areas where charcoal extraction is carried out in the municipalities of La Loma and La Jagua in the department of Cesar, lead was found in the liver tissue of house mice with values of 0.18 and 0.35 µg/g, respectively. However, meteorological conditions were considered as variables that influenced the low concentrations, since the sampling was carried out after rainy periods [68]. Similarly, in the municipality of Los Córdoba, department of Córdoba, Pb was found in muscle tissue and in the liver of bats with concentrations between 0.051-0.066 µg/g and 0.020-0.038 µg/g, respectively.

Other animal species such as hummingbirds of the Bogotá Savanna were used as bioindicators of Pb, obtaining an average concentration of 3.25 ppm in the Encenillo Reserve, in the municipality of Guasca, 4.05 ppm in the Hacienda San Carlos of the municipality of Zipacón, and 4.69 ppm on the campus of the Universidad de los Andes in the city of Bogotá [69]. These values were associated with the environmental contamination of the areas produced by mining activities and nearby roads. On the other hand, mollusks are considered biomarkers of environmental pollution in coastal areas due to their bioaccumulation capacity. For this reason, Valdelamar-Villegas & Olivero-Verbel [70] reported Pb levels of 0.110, 0.060 and 0.100 µg/g in the Berrugas, Cartagena, and Rioacha beaches respectively, associated with artisanal fishing.

The lead content in the tissues of animal species can come from the application of fertilizers and/or pesticides in the food they consume or in areas surrounding them. It is higher in carnivores because they are in a higher link of the food chain and consequently bioaccumulate the metal. Other variables that influence exposure to this pollutant are meteorological conditions, which affect its bioavailability, for example during the rainy season [71].

On the other hand, studies carried out on plant species have focused on those that remove and accumulate the contaminant in their tissues without phytotoxic effects [72], through analysis of the concentrations of lead in leaves, roots, and stems. In the case of *Rhizophora*

*mangle* located in the Ciénaga Grande of Santa Marta, higher levels of Pb were found in its roots with values of 7.2 to 27.92 µg/g, although different organs were analyzed, which shows a fixation mechanism in the roots that prevents the metal contained in the sediments from being transported to the rest of the plant [73], [74]. Similarly, in the upper basin of the Bogotá River values of 7.63, 7.38, 7.78 and 45.02 mg/Kg of Pb were reported in individuals collected in the municipality of Villapinzón of *Lycianthes lycioides (L.) Hassl.* in leaves, stems, roots, and soil, respectively; while for the samples collected in the municipality of Tenjo the values were 3.01, 3.18, 3.77 and 4.60 mg/kg, respectively. The difference in metal concentrations was associated with the contamination of the Bogotá river with discharge from tanneries [75]. Likewise, in the municipality of Villapinzón, department of Cundinamarca, different species of lichens were evaluated as bioindicators, which presented a range of 4.1 to 25.8 ppm of lead [76].

### **Lead Levels in Soil**

Currently, the country does not have a regulation on soil quality, therefore lead levels obtained were compared with international standards. Also, it is necessary to take into account that the concentration of the different chemical elements present in the soil is the result of its geological formation and the interaction of natural factors, and thus the identification of toxic elements in it does not necessarily suggest contamination processes. [77].

In soils for agricultural use, the content of metals such as lead is a threat to human health due to its incorporation into the food chain. Soils can become contaminated as a consequence of the deposition of industrial atmospheric emissions, application of pesticides and fertilizers, or by contact with contaminated irrigation water [78]. As an example of the last case, an average concentration of 15.11 mg/kg in summer (dry season) and 14.52 mg/kg in winter (rainy season) was found in soils dedicated to rice cultivation, irrigated with water from the Guatiquía River [77], which correspond to values within the natural range of 10 to 30 mg/kg [78]. Similar results were found for the common chard (*Beta vulgaris L.*) which, with a lead level in the soil of 14.7 mg/kg, showed optimal growth without physiological alterations [7]. On the other hand, the lowest Pb values were reported in soils of rice, cotton, and pasture crops irrigated with water from the Sinú River, with maximum values of 0.059, 0.072, and 0.083 mg/kg, respectively [78], exceeding the reference level for uncontaminated soils in Colombia of 0.012 mg/kg and classified as moderately contaminated [79].

Regarding urban soils, the Pb content in road sediments in the city of Bogotá was studied and it was determined that the highest concentrations occur in particles smaller than 63 µm and during the dry season, with mean values of 107, 84, 97 and 69 mg/kg for the localities (districts) of Fontibón, Barrios Unidos [80], Kennedy, and Puente Aranda [81], respectively.

These areas are recognized as industrial zones and exceed the limit of 60 mg/kg established by the legislation of Catalonia (Spain) but are below Canadian regulations (140 mg/kg). Similar results were obtained in the municipality of Soacha, with a concentration of 99 and 258 mg/kg for the urban center and the main road [82]. The aforementioned levels are a consequence of the emission of combustion gases, fuel and/or lubricant leaks, wear of tires and/or brakes, rust and car body rust, as well as resuspension of atmospheric particles due to vehicular traffic [83]. Similarly, Trujillo-González et al. [84] analyzed the lead content in road sediment samples from the city of Villavicencio, as categorized into three sectors: residential, commercial, and road infrastructure. The commercial sector presented an average value of 1289.4 mg/kg, followed by the main road with 87.5 mg/kg, and the residential area with 26 mg/kg. According to both studies, a higher lead content is evidenced in road sediments in industrial urban areas due to their vehicular density and the contribution of atmospheric emissions that are deposited on the ground. This puts the health of local inhabitants at risk since the wind and the turbulence generated by the traffic can resuspend and transport the particulate matter [82].

## **Air Pollution**

Colombian legislation [85] establishes as the maximum permissible levels in air for unconventional pollutants with carcinogenic effects, such as Pb, values of 0.5 and 1.5  $\mu\text{g}/\text{m}^3$  in terms of annual exposure and in 24 hours, respectively. In the locality (district) of Puente Aranda, in the city of Bogotá, daily average concentrations of 1.445 and 3.926  $\mu\text{g}/\text{m}^3$  were found for the first monitoring campaign (June-July 2005), 1.386 and 4.994  $\mu\text{g}/\text{m}^3$  for the second (October-November 2005), and 0.746 and 3.880  $\mu\text{g}/\text{m}^3$  for the third (April-May 2006). The highest values, which exceed more than twice the limit established in Colombian regulations, correspond to an area close to a mass transportation main line and to 6 main roads associated with an industrial area with high traffic flow, in which wind also converges and subsequently drags pollutants to the place [86]. However, in a following study [87] an annual average level of 0.025  $\mu\text{g}/\text{m}^3$  and a daily maximum of 1.48  $\mu\text{g}/\text{m}^3$  were identified, associated with high-temperature industrial emissions, such as those coming from metallurgical processes, fossil fuel combustion, incineration of industrial waste, and industries related to steel, ceramics, glass, and paint manufacturing.

Similar results were found in the sampling of different areas of the city of Medellín where 360 children resided, all under 5 years of age and with respiratory diseases, obtaining values between 0.099 and 1.464  $\mu\text{g}/\text{m}^3$  for Andalusia, Robledo, downtown Medellín, Castilla, Belén de los Alpes, Guayabal, Estadio, and Santa Elena. The previous results are directly related to amounts of particulate matter PM10 and PM2.5 that exceed the limits established by

Colombian regulations [85], which in turn increases the risk of respiratory infections by 49.3 % [88].

On the other hand, in the department of La Guajira, lead concentrations were evaluated in daily samplings of PM10 and PST in a high vehicular traffic area in the city of Rioacha, with average values of 7.9 and 4.1 ng/m<sup>3</sup>; far below the limit established for daily exposure [89]. Likewise, Fagundo and Doria [90] compared the lead levels associated with PM10 in the city of Rioacha (control) with an open-pit coal mining activity area in the municipalities of Hatonuevo, Albania, and Barrancas. Annual values of 0.006 and 0.02 µ/m<sup>3</sup> were found in the last two sites, in contrast to the control zone, where the metal was not detected. Lead concentrations were higher in the dry season, favored by the resuspension of particles caused by the wind, excavation activities, extraction, material transport, and vehicular traffic. Similar cases were found in Manizales due to the proximity to industrial emissions, which were associated with thyroid cancer [91] and in Medellín due to emissions from the incineration of hazardous waste [92].

Lead concentration in the air can also be assessed from inside infrastructure. Thus, for example, in the study by Fuentes and Falla [93], it was determined that exposure to lead inside kindergartens in the localities (districts) of Puente Aranda, Fontibón, and Kennedy in the city of Bogotá is above the reference dose established by the EPA ( $> 1.0 \times 10^{-7}$  mg/kg-day), associated with high traffic areas, the presence of live barriers, and proximity to industries.

## **Water Contamination**

Lead concentrations have been reported in sediments in the mangroves located at the river mouth of the Sevilla River in the Ciénaga Grande of Santa Marta [74]. Lead levels have also been reported in the streambed of the Sinú River, an area known for its intense agricultural, fish and livestock farming activity. Values reported varied between 10.10-26.89 mg/kg in the rainy season and 13.95-28.08 mg/kg in the dry season, which surpass the reference value of 9 mg/kg and resemble slightly contaminated sediments (25.4-63.4 mg/kg) as reported by secondary sources [94]. Likewise, Tejeda-Benítez et al. [95] analyzed sediment samples in the Magdalena River, finding an average Pb concentration of 12.1 µg/g and maximum values of 18.1 µg/g downstream from the city of Neiva, 18 µg/g in the municipality of Gamarra and 16.8 µg/g in the city of Barranquilla, with concentration factors of 1.29, and 1.2, this indicates a moderate level of contamination associated with activities such as agriculture, fishing, and mining in the first two places, while in the city of Barranquilla the petrochemical, metallurgical, construction, and port industries stand out as sources. Additionally, fluvial sediments, along with their pollutants, are carried by the Magdalena River to the bays of Cartagena and Barbacoas —with lead levels of up to 23.03 µg/g and 13.03 µg/g, respectively

[96]. Although these figures do not exceed the value of 31  $\mu\text{g/g}$  defined as the minimum effect level for aquatic organisms, they can affect the health and diversity of the coral reef communities in the Rosario Islands.

Regarding lentic ecosystems, in 2006 lead concentrations were determined in the sediments of the La Fe reservoir, located in the department of Antioquia, with mean values of 31.66  $\mu\text{g/g}$  near the dam and 21.39  $\mu\text{g/g}$  in the tail-end of the reservoir, associated with the agricultural and livestock activities developed along the channels that feed it [97]. Similarly, in the Ciénaga de Ayapel wetland complex, Rúa Cardona et. al [98] reported lead levels between 1.09-11.87  $\mu\text{g/g}$ . The maximum value reported occurred in the center of the Ciénaga de Ayapel, which receives the water from streams contaminated by activities such as agriculture, livestock farming, mining, untreated wastewater discharge, and transportation of boats. In this case, the authors took 2.39  $\mu\text{g/g}$  as a reference level, as found in sediment samples from the Formación Betulia near the urban center of the municipality of Ayapel. This shows an enrichment of Pb in the wetland complex, since 91 % of the samples exceed this level. In contrast, the lead levels determined by Romero Núñez et al. [99] in the Ayapel, Loricá, and Betancí marshes are well below the reference level, with values close to 0.2  $\mu\text{g/g}$ .

On the other hand, it was found that the sediments of the bays of Cartagena and Barbacoas, affected by the pollution plumes of the rivers that flow into them, were below the permissible limits [100], while the marine sediments in the Gulf of Urabá, into which the waters of the Atrato, León, Turbo, and Caimán rivers flow, and which are contaminated by activities such as gold mining, banana plantations, extensive cattle farming, and discharge of domestic wastewater, had Pb levels of 0.17-6.93  $\mu\text{g/g}$  [101], which are below the reference value for the earth's crust (12.5  $\mu\text{g/g}$ ). In the bay of Cispatá, the economy is based on fishing, with contributions from wood production, the growth of tourism, and an oil port 12 km away. Here, it was reported a maximum Pb concentration of 1.39  $\mu\text{g/g}$ , associated with runoff contaminated with agrochemical residues and domestic wastewater [96]. In another study, levels between 5.7 and 22.4  $\mu\text{g/g}$  of lead were found in marine sediments in the port of the city of Santa Marta, associated with the load and transportation of coal [102]. These values are below the limits established for marine sediments in the North American (450  $\mu\text{g/g}$ ) and Chinese (60  $\mu\text{g/g}$ ) regulations, but when compared with the marine sediment pollution index (MSPI) are found in the range of average and poor condition sediments.

Also, lead was reported in samples of water bodies associated with the mining activity of the department of Boyacá, with a range between 0.013-0.21 mg/L [103], exceeding the maximum limit of 0.01 mg/L established for water for human consumption [50]. Likewise, in the Las Torres stream, in the municipality of Sogamoso, there were Pb concentrations between 0.698-0.750 mg/L [104], exceeding the 0.1 mg/L limit for livestock use defined in Decree 1076 of 2015 [105]. These concentrations are the consequence of the discharges from the brick industry, coal mining, and wastewater from nearby communities [104].

**Table 1. Identification of the studied environmental matrices.**

Environmental Matrix	Reported Organisms	Study year	Location	Concentration		Reference
				Reported <sup>1</sup>	Maximum allowed	
Blood	Children	2004	Cartagena: Torices, San Francisco, Barrio Chino, Alcibia, Olaya, Bosque, Henequén and Arroz Barato	<b>1-21 µg/dL</b>	5 µg/dL	[31]
		2004-2005	Bogotá D.C. and Soacha	<b>Between 20 and 90 µg/dL</b>		[20]
		2010	North of Cali	<b>1.1-9.9 µg/dL</b>		[32]
		2014	Cartagena: Canapote, Paseo Bolívar, Ceballos, Bosque and Zaragocilla	<b>0.05-34.05 µg/dL</b>		[34]
		2015	Cartagena, Valledupar, La Paz Tasajera	< 5 µg/dL (Cartagena, Valledupar, La Paz) <b>8.9 ± 0.8 µg/dL (Tasajera)</b>		[35]
	Adults	1996	Bogotá D. C.	<b>15 a 369 µg/dL</b>	38 µg/dL	[28]
		2009-2010	Cali	> 5 µg/dL		[38]
		2012	Cali	<b>62 and 90.3 µg/dL</b>		[13]
		2013	La Mojana region: Guaranda, Sucre, Majagual and San Marcos, Montería	<b>0.15-52.46 µg/L</b>		[39]
		Objects	Paints	2014	Bogotá D.C.	<b>5-47600 ppm</b>
Food	Beef	2008-2009	Sinú and San Jorge river valleys, department of Córdoba	0.007-0.098 <sup>2</sup> µg/g	0.5 µg/g	[52]
		2014	Yondó and Barrancabermeja, Middle Magdalena	<b>0.38-0.62 and 0.22-0.24 mg/kg</b>	0,5 and 0,1 mg/kg	[53]
	Salt	2010	Bogotá D. C.	Up to 1 mg/kg	2 mg/kg	[51]

<sup>1</sup> Values highlighted in bold correspond to those above the limits established by regulations or the reference values used by each study.

<sup>2</sup> 1 µg/g is equivalent to 1 mg/Kg.

Reported Lead Levels in Different Environmental Matrices in Colombia

Environmental Matrix	Reported Organisms	Study year	Location	Concentration		Reference
				Reported <sup>1</sup>	Maximum allowed	
Drinking water	Potato	2012	Cali: communes 13, 14, 15 and 21	0.11-0.36 µg/L	10 µg/L	[49]
		2014	Tunja (Boyacá)	<b>0.085-0.150 mg/Kg</b>	0.1 mg/kg	[47]
		2015	Toledo, Norte de Santander	<b>0.01-0.38</b>	0.3 mg/kg	[48]
		2005	Chocontá and Suesca municipalities (department of Cundinamarca)	<b>7.7 and 7.3 ppm</b>	0.3 mg/kg 0.3 mg/kg	[56]
		2011-2012	Ciénaga de Mallorquín (Barranquilla)	<b>0.66-2.03 µg/g</b>		[57]
		2014	Vereda Volcán (Paipa, Boyacá)	<b>0.12-0.51 µg/g</b>		[58]
		n.d.	Urabá Gulf: Candelaria Bay, Marirrí Bay, Bocas del Roto and Bocas del Atrato	<b>0.667-23.378 mg/kg</b>		[59]
		2014	Bogotá D.C.	0.016-0.089 mg/kg		[60]
		2016	Atrato river delta	<b>0.672 to 3.110 mg kg</b>		[61]
		Alcoholic drinks	n.d.	n.d.	Rocha, Ballesta, Puerto Badel, Santa Rosa, Villanueva, Turbaco, San Basilio de Palenque, María la Baja, Arroyo Hondo, Pasacaballos municipalities (Bolívar)	<b>0.5-0.76 mg/L</b>
n.d.	Galeras, Sincé, and Morroa municipalities (Sucre)			<b>0.36-0.41 mg/L</b>		[63]
Soil	Urban soils	2010	Soacha (Cundinamarca)	<b>99 and 258 mg/kg</b>	60 mg/kg	[82]
		2010-2011	Localities (districts) of Kennedy and Puente Aranda in Bogotá D. C.	<b>97 and 69 mg/kg</b>		[81]
		2010-2011	Localities (districts) of Fontibón and Barrios Unidos in Bogotá D. C.	<b>107 and 84 mg/kg</b>		[80]
		2014	Villavicencio	<b>Commercial area 1289.4 mg/kg, main road 87.5 mg/kg</b>		[83]

Reported Lead Levels in Different Environmental Matrices in Colombia

Environmental Matrix	Reported Organisms	Study year	Location	Concentration		Reference
				Reported <sup>1</sup>	Maximum allowed	
				<b>and residential area 26 mg/kg</b>		
	Agricultural use	n.d.	Bogotá D. C.	14.7 mg/kg	10-30 mg/kg	[18]
		2011-2012	Vereda La Esperanza (Villavicencio, Meta)	15.11 mg/kg in the dry season and 14.52 mg/kg in the rainy season		[77]
		2015	Lower and middle basin of the Sinú river, between the departments of Córdoba and Antioquia	0.13 mg/kg	0.012 mg/kg	[78]
	Others	n.d.	Tenjo and Villapinzon municipalities (department of Cundinamarca)	<b>45.02 mg/kg</b>	10-30 mg/kg	[75]
	Lichens	n.d.	Villapinzon municipality (department of Cundinamarca)	4.1 to 25.8 ppm		[76]
Bioindicators	Red mangrove	2003	River mouth of the Sevilla river-Ciénaga Grande de Santa Marta	7.2 to 27.92 µg/g		[73]
	Plants	n.d.	Tenjo and Villapinzon municipalities (department of Cundinamarca)	7.63, 7.38, 7.78 mg/kg		[75]
		2008	Medellín		0.125 to 123.7 mg/kg	[66]
Bioindicators	House mice	2008	Medellín	5.02- <b>45.05 mg/kg</b>	0.5-7 mg/kg	[67]
	House mice	2010-2011	Department of Cesar: La Loma, La Jagua and Valledupar	0.18 and 0.35 µg/g		[68]
	Bats ( <i>Quiróptera</i> )	2012	Los Córdoba municipality, department of Córdoba	0.051-0.066 µg/g in liver tissue and 0.020-0.038 µg/g in muscle tissue		[71]
	Chipi Chipi (Mollusk- <i>Donax denudatus</i> )	2012-2013	Berrugas (Sucre), Cartagena (Bolívar), Riohacha (Guajira)	0.110, 0.060 and 0.100 µg/g		[70]

Reported Lead Levels in Different Environmental Matrices in Colombia

Environmental Matrix	Reported Organisms	Study year	Location	Concentration		Reference
				Reported <sup>1</sup>	Maximum allowed	
	Hummingbirds	2015	Biological Reserve El Encenillo (Guasca); Hacienda San Carlos (Zipacón); Universidad de los Andes (Bogotá)	3.25, 4.05 and 4.69 ppm		[69]
Air	Particulate matter	2005-2006	Locality (district) of Puente Aranda (Bogotá D. C.)	<b>1.445 and 3.926 µg/m<sup>3</sup> day</b>	0.5 µg/m <sup>3</sup> yearly and 1.5 µg/m <sup>3</sup> in 24 hours	[86]
		2006-2007	Andalucía neighborhood (Medellín)	<b>1.464 µg/m<sup>3</sup> day</b>		[88]
		2011-2012	Rioacha (Guajira)	7.9 ng/m <sup>3</sup>		[89]
	Particulate matter	2013	Albania and Barrancas municipalities (department of La Guajira)	0.006 and 0.02 µg/m <sup>3</sup>		[90]
		2015-2016	Bogotá D. C.	0.025 µg/m <sup>3</sup> yearly and daily maximum of <b>1.48 µg/m<sup>3</sup></b>		[87]
Water	Water bodies	2013	Las Torres stream, Sogamoso (municipality, department of Boyacá)	<b>0.75 mg/L</b>	0.1 mg/L for livestock farming use	[104]
		n.d.	Boyacá	<b>0.013-0.21 mg/L</b>	0.01 mg/L for human consumption	[103]
	Sediments	2006	Catchment area of the La Fe reservoir, (department of Antioquia)	<b>31.66 µg/g</b>		[97]
		2006-2008	Ayapel marsh [department of Córdoba]	1.090- <b>11.870 µg/g</b>	2.39 µg/g	[98]
		2008	Ayapel, Lorica, and Betanci wetlands (department of Córdoba)	0.2 µg/g		[99]
Water	Sediments	2007-2008	Sinú river basin	<b>10.10-26.89 mg/kg in the rainy season</b> <b>13,95-28,08 mg/Kg in the dry season</b>	9 mg/Kg	[94]
		2009	Urabá Gulf	0.17-6.93 µg/g	12.5 µg/g	[101]
		2010-2011	Cispatá bay	1.39 µg/g		[96]

*Reported Lead Levels in Different Environmental Matrices in Colombia*

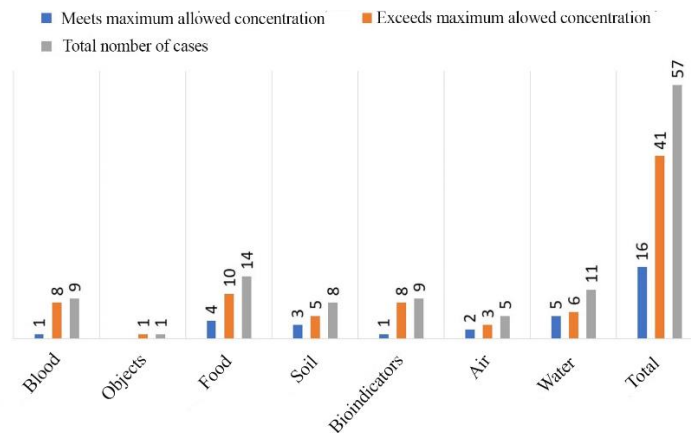
Environmental Matrix	Reported Organisms	Study year	Location	Concentration		Reference
				Reported <sup>1</sup>	Maximum allowed	
		2011	Santa Marta port	5.722.4 µg/g	60 µg/g	[102]
		2013	Magdalena river	Neiva (18.1 µg/g), Gamarra (18 µg/g) Barranquilla (16.8 µg/g)	FC = moderate contamination	[95]
		2013	Cartagena and Barbacoas bays	0.59-23.03 µg/g	31 µg/g	[100]

**Source: Own source.**

The table above shows reports of specific cases, so it cannot be assumed they are generalizable to the country. Even so, it should cause alarm that 41 of the 57 reported cases, that is, 72 %, show lead concentrations above the norm. These percentages, as summarized in figure 4, amount to 89 % for blood samples in adults and children, 71 % for food, 63 % for soil, 89 % for bioindicators, 60 % for air and 55 % for water. It can be noticed that the maximum values in most cases exceeded the acceptable levels, evidencing a greater risk of poisoning in activities related to battery recycling, consumption of contaminated food, ingestion of paint particles, and projectiles lodged in the human body. This situation is aggravated by a lack of regulations in the country related to environmental exposure to lead.

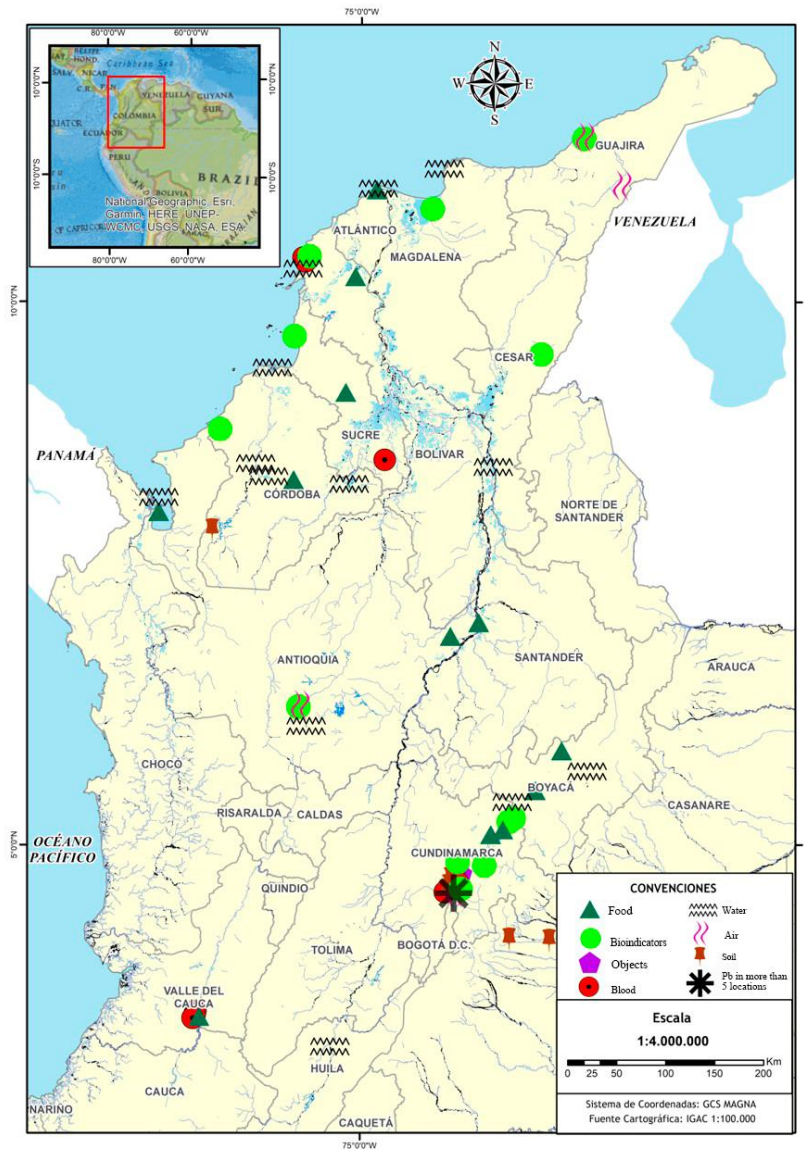
Given the complex relationships and the transport of pollutants in the environment, water sources in rural areas become areas of interest for a comprehensive analysis of different substances, taking into account that many of these sources are used in the irrigation of crops and in the water supply to communities, without purification systems that include the removal of heavy metals.

**Figure 4. Cases reported according to compliance or not with the maximum permitted concentrations**



**Source: Own source.**

Figure 5. Geographic location of the lead reports in Colombia



Source: own source.

## Conclusions

The studies analyzed show that lead is distributed in Colombia across all environmental matrices: blood in humans, food, soil, bioindicators, air, and water. The percentages that are above the permissible values for each one are 89 %, 71 %, 63 %, 89 %, 60 % and 55 %, respectively. These data allow us to estimate that lead poisoning could become a large-scale ecological and public health problem in the country, given its availability in the different environmental matrices.

There is a greater risk for the population of vulnerable groups (children, the elderly and pregnant women) of low socioeconomic status and for those who live in the vicinity of car battery manufacturing or recycling industries, foundries or metalworking factories, facilities for the disposal of hazardous waste, or are close to particulate matter (PM10), oil refineries, extraction wells, industrial discharges, and for those who consume contaminated food or beverages. Despite this, there is evidence of little research on the subject.

For this reason, it becomes necessary to carry out new studies that provide a broader vision of this situation at a national level and that, in addition to determining concentrations, carry out an assessment of the health risk in different exposure scenarios, in such a way that they can guide public policies and regulatory adjustments that benefit citizens and ecosystems. Furthermore, these studies should increase the geographic coverage. Figure 5 shows that the existing studies are located in the areas of greatest economic activity and industrial concentration in the country, showing a clear information gap in the Pacific Coast, Orinoquía and the south of the country, places where there may also be contamination by lead.

Although it was found that 72 % of the studies reported lead concentrations that exceeded the values defined by the regulations, it must be considered that the results presented follow the inclusion and exclusion criteria defined. Although these criteria were adopted to present as realistic a picture as possible, changing them would have yielded different results. For example, taking information from studies with secondary information or that did not report the specific place of the sample would have yielded a greater amount of data, but the information reported in this article would have had less rigor and geolocation of the studies would not have been possible. Similarly, if articles prior to 1995 had been included, the lead conditions allowed in gasoline would have been different from the current ones and they would have been estimated with methods not comparable to the most recent ones. Likewise, including studies without specific concentrations of lead would have given us a greater geographic panorama, but it would not have allowed us to know if the concentrations represent any risk.

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