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Review

Lead (Pb) Pollution in Soil: A Systematic Review and Meta-Analysis of Contamination Grade and Health Risk in Mexico

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Abstract: Lead (Pb) is a toxic metal associated with several health disorders. The mining and Pb battery industry are related to Pb increase in air, water, and soil. Mexico is an important worldwide Pb producer; however, reviews on environmental Pb contamination in Mexico are insufficient. Since Pb remains stable in soil and its concentration is an indicator of Pb exposure, this systematic review focused on reports of Pb concentrations in soil from Mexico published in 2010–2023. The retrieved reports were ordered, and contamination grade and health risk were estimated for location. From 36 retrieved reports, 24 were associated with mining Pb pollution, while a unique report mentioned the battery industry. The publications evaluated mining (13), agricultural (11), and residential (16) soils. Pb concentrations in soil were higher than the allowed limits in more than half of the reports. According to the Pb concentrations in soil, the locations evaluated in Mexico presented a contamination grade from heavily contaminated to extremely contaminated and health risks results suggested severe hazards, particularly for children. This work can guide other researchers to identify potentially contaminated but understudied Mexican locations.

Keywords: soil; mining; agricultural; residential; heavy metal; lead; Mexican territory

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Citation: Briseño-Bugarín, J.; Araujo-Padilla, X.; Escot-Espinoza, V.M.; Cardoso-Ortiz, J.; Flores de la Torre, J.A.; López-Luna, A. Lead (Pb) Pollution in Soil: A Systematic Review and Meta-Analysis of Contamination Grade and Health Risk in Mexico. *Environments* **2024**, *11*, 43. https://doi.org/10.3390/environments11030043

Academic Editor: Gianniantonio Petruzzelli

Received: 4 January 2024
Revised: 18 February 2024
Accepted: 19 February 2024
Published: 25 February 2024

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1. Introduction

Based on toxicity and potential for human exposure, lead (Pb) is among the 10 chemicals of public health concern according to the World Health Organization (WHO) [1] and is the second on the Substance Priority List 2022 of the Agency for Toxic Substances and Disease Registry (ATSDR) [2]. Although Pb naturally occurs in the Earth's crust, anthropogenic sources, namely mining, ores smelting, coal burning, and the battery industry, release Pb into the air, soil, and/or water [3]. In the soil, speciation and mobility of Pb depends on soil composition since Pb may occur as a free metal ion or complexed with inorganic and organic constituents [4]. Galena (PbS) is the most common ore mineral because Pb has high affinity with sulfur [5]. Soil components such as hydrous ferric oxide (HFO) and organic matter increase the soil's surface capacity to adsorb Pb [6]. Since Pb in soil remains stable for a long time, it may bioaccumulate in plants and agricultural products generating food chain contamination [7]. Concentration of Pb in soil from urban areas is an indicator of community Pb exposure [8]. In humans, Pb exposure occurs through ingestion of contaminated water and food, dust inhalation, and dermal contact [9], and is related to early life effects like preterm birth, in utero growth restriction, decreased birth weight, birth defects, and cognitive impairment and results in delayed onset of diseases such as obesity, infertility, cancer, metabolic alteration, autoimmune disorder, mental disease, and cardiovascular and neurodegenerative disorders [10].

Since Pb is malleable, ductile, and resistant to corrosion [11], it has been widely used in the battery industry, machinery manufacturing, and medicine, resulting in increased world

Pb production [12]. Refined Pb has been obtained from mined ore since ancient times, but since the early 1980s, it has also been recovered from used Pb products (e.g., Pb-acid batteries) by secondary smelting [13]. China, Australia, and the United States (US) are, respectively, the first-, second-, and third-largest world producers of Pb according to the US Geological Survey [14]. Concentrations of Pb in soil have been evaluated in China [15,16], Australia [17–19], and the US [20,21], highlighting the grade of Pb contamination in these countries. Mexico was the fourth-largest world producer of Pb in 2022 [14] and the first Pb ore exporter in 2021 conforming to The Observatory of Economic Complexity [22]. The political division of México consists of 32 states (Figure 1): nine states, namely Coahuila (COA), Durango (DUR), Guerrero (GRO), Morelos (MOR), Oaxaca (OAX), Querétaro (QUE), Sinaloa (SIN), Sonora (SON) and Zacatecas (ZAC), have been Pb mining producers [23]; five states, such as Baja California Norte (BCN), Nuevo León (NLE), Puebla (PUE), Tamaulipas (TAM), and Tlaxcala (TLA), produce Pb by secondary smelting from Pb-acid batteries [24]; and eight states, including Aguascalientes (AGU), Chihuahua (CHH), Estado de México (MEX), Guanajuato (GUA), Hidalgo (HID), Jalisco (JAL), Michoacán (MIC), and San Luis Potosí (SLP), produce Pb by mining and Pb battery recycling facilities [23,24]. Since both activities are distributed in the Mexican territory and they are related to environmental contamination as well as health risks, it is relevant to review the studies of Pb pollution performed in Mexico. However, reviews focused on Pb contamination in the entire Mexican territory are scarce. Thus, this systematic review aimed to collect reports from 2010 to 2023 regarding Pb and soil in Mexican territory. Additionally, we conducted a meta-analysis of contamination grade and health risk in Mexican states to uncover underserved regions.

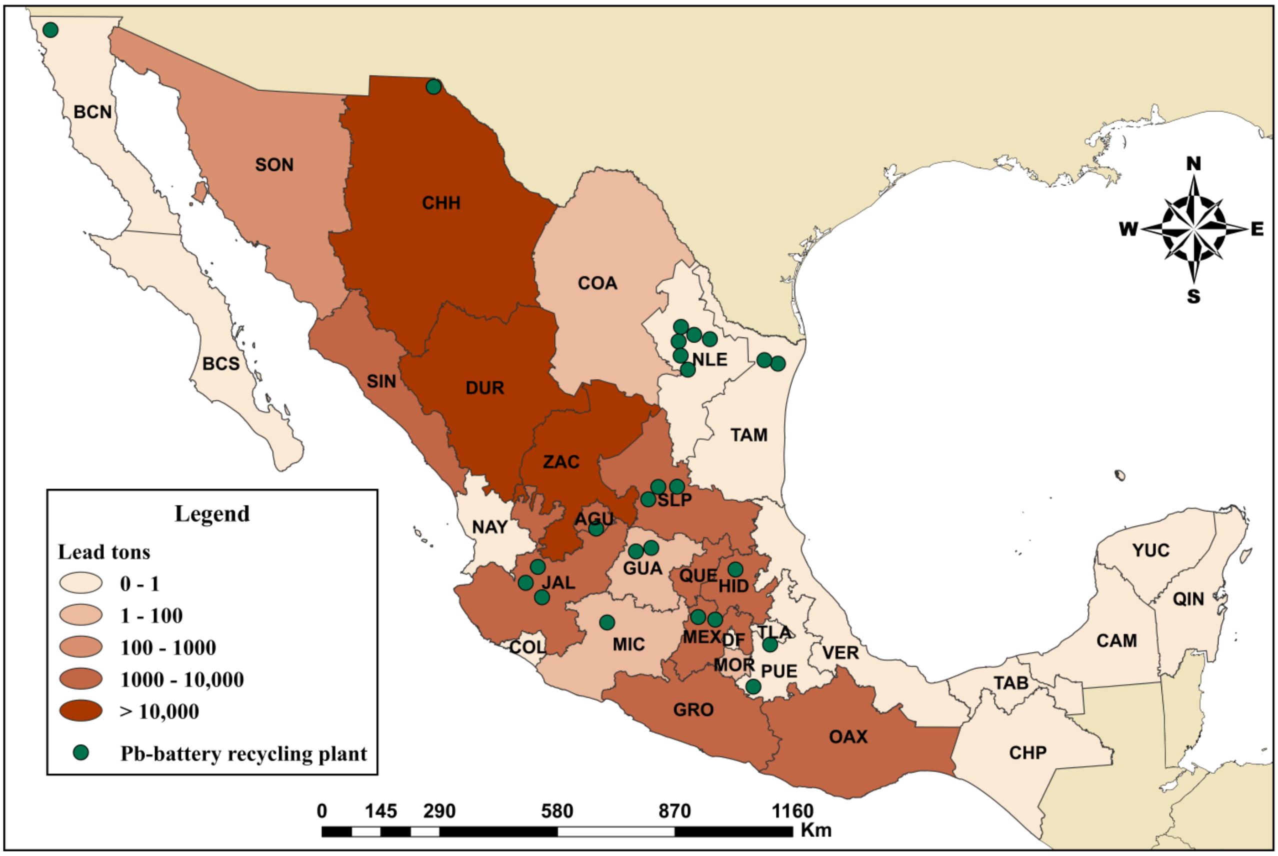

Figure 1. Lead (Pb) mining and Pb battery recycling industries in Mexico. The inner box indicates the mining Pb production from 2010 to 2022. Pb production is depicted as color intensity on the map. The green circles indicate the Pb battery recycling plants located in each state. Image created by ArcMap 10.3.1 software using data from National Institute of Statistic and Geography INEGI [19] and Commission for Environmental Cooperation CEC [20].

2. Materials and Methods

2.1. Study Design and Search Strategy

The research questions of this study were: "In which Mexican states has Pb been quantified in soil?" and "What are the Pb contamination levels and the health risk at these sites?". Thus, our systematic review focused on studies of Pb quantification in Mexican soil following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [25]. The inclusion criteria were (1) reports of Pb quantification in Mexican soil, (2) original research articles, (3) articles published from January 2010 to May 2023, and (4) works written in English or Spanish language. Exclusion criteria were (1) Pb isotope identification, (2) studies of non-Mexican soil samples, and (3) reviews or non-research articles. The search strategy consisted of using the keywords and Boolean operators "Lead OR Pb OR Plumbum AND Soil AND Mexico" in the research databases PubMed and ScienceDirect. Publication date and language filters were adjusted as January 2010 to May 2023 and English or Spanish.

2.2. Data Collection and Categorization

Data search, collection, and analysis were performed from March to June 2023. Titles and abstracts were reviewed, selecting publications by the inclusion and exclusion criteria described in Section 2.1. Data such as sampling location and method, sample size, and Pb quantification procedure were obtained from material and methods, while Pb concentrations were extracted from the results. The information retrieved was organized into three categories (mining, agricultural, and residential) according to the land use where the sampling was performed.

2.3. Data Analysis

2.3.1. Contamination Grade by Geoaccumulation Index (Igeo)

The geoaccumulation index (I_{geo}) allows us to estimate the Pb contamination grade in soil based on a reference value and the concentration measured in a soil sample [26]. We estimated I_{geo} for each concentration using the formula described by Muller (1969) [27]:

$$I_{geo} = \log_2 (Cs/1.5Bs) \tag{1}$$

where Cs is the Pb (mg/kg) quantified in soil and Bs is the geochemical background (27 mg/kg) obtained from the global soil background values [28], while 1.5 was used as a correction factor. The mean, median, or maximum Pb concentration was used for I_{geo} estimation (Tables S1–S3). When two or more authors mentioned the same location, the I_{geo} average was obtained. The I_{geo} value and its respective contamination grade are described in Table 1.

Table 1. Contamination grade based on the geoaccumulation index (I_{geo}) [27].

Grade	I_{geo} Value	Soil Quality
0	≤ 0	Uncontaminated
1	$0 < I_{geo} < 1$	Uncontaminated to moderately contaminated
2	$1 < I_{geo} < 2$	Moderately contaminated
3	$2 < I_{geo} < 3$	Moderately to heavily contaminated
4	$3 < I_{geo} < 4$	Heavily contaminated
5	$4 < I_{geo} < 5$	Heavily to extremely contaminated
6	>5	Extremely contaminated

2.3.2. Contamination Grade by Ecological Risk Index (ERI)

The ecological risk index (ERI) represents the risk of affecting living organisms and the environment with a toxic metal, evaluating the sensitivity of different ecosystems to toxic contaminants [29]. The ERI was estimated using the following formula [30]:

$$ERI = [(Ts)(Cs)]/Bs \quad (2)$$

where Ts indicates the Pb toxicity factor equal to five reported by Hakanson (1980) [30], Bs is the Pb background in soil (27 mg/kg), and Cs represents the Pb concentration measured in the soil. The ERI for each report was estimated (Tables S1–S3) using the mean, median, or maximum Pb concentration. The ERI depicts the risk as low (≤50), moderate (50–100), high (100–150), very high (150–200), and extreme (>200).

2.3.3. Statistical Analysis of Contamination Grade

To compare the contamination grade among mining, agricultural, and residential land uses, the I_{geo} and ERI values were averaged per land use and analyzed by One Way Analysis of Variance on Ranks. Statistical analysis and graphs were performed in SigmaPlot 12.0.

2.3.4. Health Risk by Exposure Estimation

The health risk assessment estimates the possible adverse health effects in people exposed to pollutants [31]. Non-carcinogenic and carcinogenic effects are included in a health risk evaluation considering the pollutant exposure grade. Since Pb exposure occurs via oral, dermal, and inhalation routes, the average daily intake (ADI) of Pb was determined for each route. The mean, median, or maximum Pb concentration in the range was used to estimate the ADI for each report. The ADIs were calculated for both adults and children using the formulas and parameters in Table 2 reported by Kan et al. (2021) [15]:

$$ADI_{oral} = [(Cs)(IR)(ED)(EF)(FI)]/[(BW)(AT)] \times 10^{-6} \quad (3)$$

$$ADI_{dermal} = [(Cs)(SA)(AF)(ABS)(ED)(EF)]/[(BW)(AT)] \times 10^{-6} \quad (4)$$

$$ADI_{inhalation} = [(Cs)(ED)(EF)(ET)]/[(PEF)(BW)(AT)] \quad (5)$$

2.3.5. Non-Carcinogenic and Carcinogenic Risk Assessments

The non-carcinogenic risk was estimated separately for oral, dermal, and inhalation exposures by the target hazard quotient (THQ) using the following formula:

$$THQ = ADI/RfD \quad (6)$$

where ADI is the value obtained in Section 2.3.4 for each exposure route and RfD corresponds to a reference Pb dose. RfDs were 0.0035, 0.000525, and 0.00352 mg/kg/day for oral, dermal, and inhalation routes, respectively [32,33]. The hazard index (HI) was estimated by adding the oral, dermal, and inhalation THQ values. The HI (Tables S1–S3) evaluates the general non-carcinogenic risk. HI < 1 indicates a lower probability of non-carcinogenic effects, HI > 1 represents a greater possibility of non-carcinogenic effects, and HI > 10 suggests a serious chronic health impact.

The carcinogenic risk was calculated for oral exposure by the cancer risk index (CRI) using the following formula:

$$CRI = ADI_{oral}\ (CSF) \quad (7)$$

where ADI_{oral} was obtained in Section 2.3.4 and CSF (0.0085 mg/kg/day) depicts the cancer risk per unit of Pb dose (i.e., cancer slope factor) [33]. CRI was estimated for each location based on Pb concentration (Tables S1–S3). The permissible CRI value is 1×10^{-6} for a single carcinogenic metal [34].

Table 2. Parameters to obtain the average daily intake (ADI). Modified from Kan et al. (2021) [32].

Parameter	Description	Substituted Value
Cs	Pb concentration identified in soil	* mg Pb/kg determined in each report
IR	Ingestion rate of soil	100 mg/day for adults 200 g/day for children
ED	Exposure duration	24 years for adults 6 years for children
EF	Exposure frequency	350 days/year
FI	Factor ingestion	1
BW	Body weight	63 kg for adults 29 kg for children
AT	Average exposure time	ED $\times$ 365 days for non-carcinogen 76.6 $\times$ 365 days for carcinogens
SA	Skin surface area exposed	5700 cm^2 for adults 2800 cm^2 for children
AF	Adherence factor	0.07 mg/cm^2 h for adults 0.2 mg/cm^2 h for children
ABS	Dermal absorption factor	0.001
ET	Exposure time	8 h/day
PEF	Emission factor	1.36×10^9 m^3/kg

* Substituted value was the Pb concentration in soil reported.

3. Results and Discussion

3.1. Reports Retrieved

The identification, screening, and selection of reports are described in Figure 2. From 40,079 reports, 39,729 were excluded by automatic filters, 350 were manually screened, and 36 were selected for this study. All 36 follow the guidelines of the U.S. Environmental Protection Agency (USEPA) and/or the Mexican regulation NMX-AA-132-SCFI-2006 [35] for sample collection as well as for Pb determination. Sampling was carried out from 0 to 30 cm deep as the official guidelines indicate. The methods for Pb quantification included flame atomic absorption spectrometry (FAAS), atomic absorption spectrometry with graphite furnace (AAS-GF), inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma optical emission spectroscopy (ICP-OES), and X-ray fluorescence (XRF).

A total of 13 reports evaluated soil from mines or tailings, 14 analyzed agricultural or residential areas related to mining, 11 identified Pb in agricultural or residential soil but in relation to other sources than mining, and a unique report evaluated Pb on residential land in relation to a battery factory in NLE. In recent years, the number of Pb battery recycling facilities has increased in Mexico. Since environmental pollution caused by this activity has becoming more frequent, it is necessary studies of environmental risks associated with this activity for achieving pollution control [36].

3.2. Data Collected

The information collected was organized into mining, agricultural, and residential soils. Figure 3 depicts Mexican states related to mining (2010–2022) and/or Pb battery recycling, reports number per state, and the land use mentioned. Mexican states related to Pb mentioned in the reports were AGU, BCN, CHH, COA, DUR, GRO, GUA, HID, MOR, NLE, PUE, QUE, SLP, SON, TLA, and ZAC. Soil from "San Antonio" and "Ensenada de Muertos" mines in Baja California Sur (BCS) was evaluated by Méndez-Rodríguez and Alvarez-Castañeda (2016) [37], but we did not find data on Pb production in the Mexican National Institute of Statistic and Geography [23]. However, an official government report indicates that BCS had its last Pb production in 1957 [38]. In contrast, no reports from OAX and SIN, Pb mining producers; TAM, Pb battery recycler; and JAL, MEX, and MIC, with both mines and recycling facilities, were found using the search strategy described in Section 2.1. Totals of 13, 11, and 16 reports described mining, agricultural, and residential soil samples, respectively. The most studied state was SLP, with ten reports by diverse authors, followed by HID, mentioned in five reports, SON, reported by four authors, CHH, by three, and COA, DUR, GRO, NLE, QUE, and ZAC with two publications each, while AGU, BCN, BCS, GUA, MOR, PUE, and TLA were studied in one report each. Interestingly, ZAC and CHH had few reports considering that both produce a greater amount of Pb than SLP [23]. From all retrieved reports, the Pb concentration in soil was registered and ordered in tables by land use, then contamination grade and health risk were determined for each report.

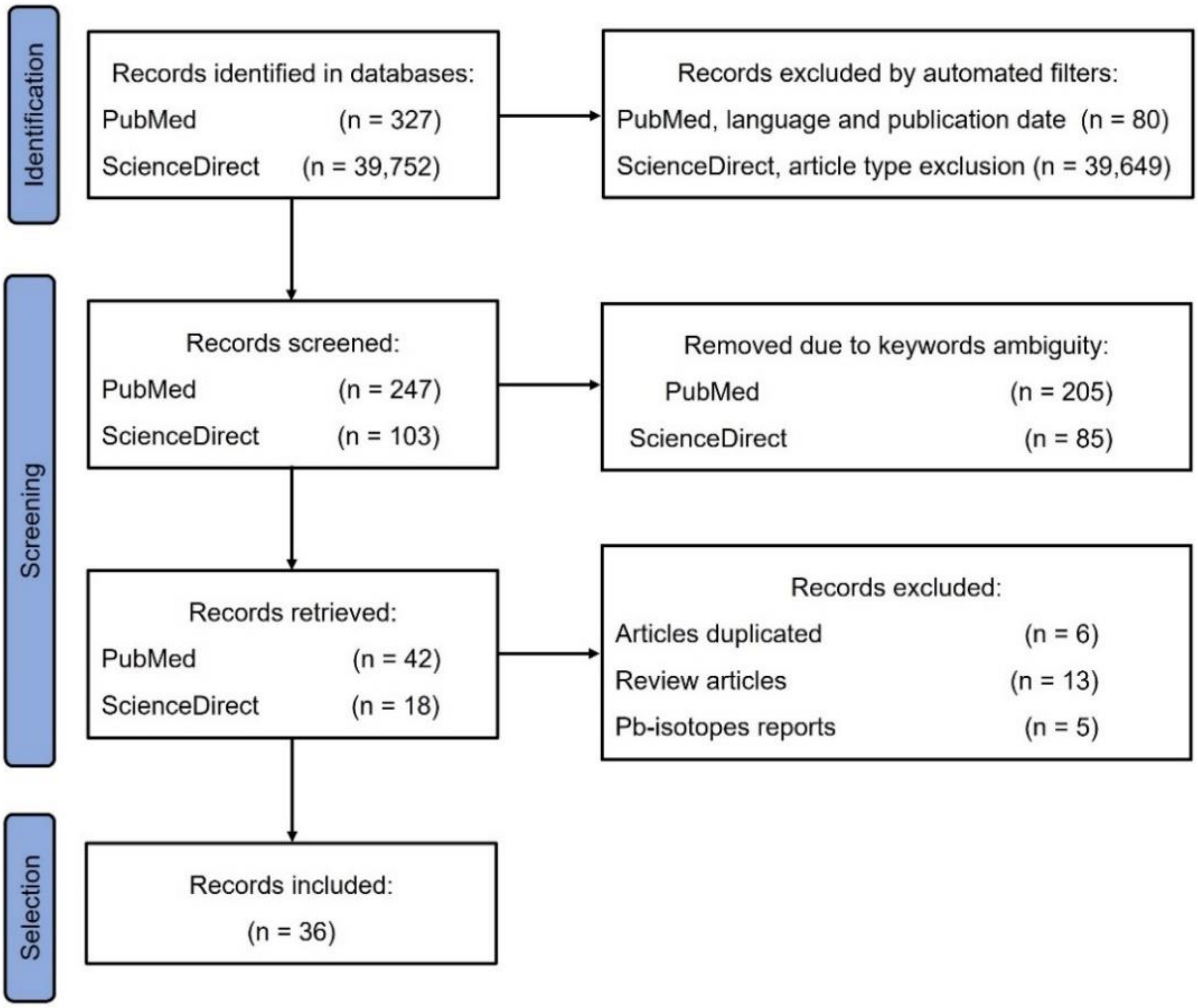

Figure 2. Flow chart of report selection.

3.3. *Lead (Pb) Concentrations in Mining, Agricultural, and Residential Land*

The uncontaminated soil presents an average of 16 mg Pb/kg, with a range from 2 to 200 mg Pb/kg [39]. The official environmental regulations in each country determine the maximum permissible concentration of Pb in soil. The Mexican Norm NOM-147-SEMARNAT-2004 permits 800 mg Pb/kg for mining soil and 400 mg Pb/kg for both agricultural and residential land [40]. Table 3 summarizes the mining/tailing studies where the highest Pb concentration was 21,288 mg/kg, identified in San Felipe de Jesús (SON), a value 26.6-fold higher than Mexican standards. Loredo-Portales et al. (2020) [41] reported that the analyzed tailing is located 0.5 km from

San Felipe de Jesus, a small town with approximately 400 inhabitants. They also evaluated agricultural soil nearby, identifying 1673.3 mg Pb/kg, a concentration 4.2 times higher than the Mexican norm. In Table 4, Vetagrande (ZAC) was the locality with the highest Pb concentration (7516.6 mg Pb/kg) in agricultural soil, 18.8-fold higher than the allowed limit. The authors Barajas-Aceves and Rodríguez-Vázquez (2013) mention that in Vetagrande soil, bean, corn, and chili has been cultivated for 24 years [42]. Regarding residential areas, 21,179 mg Pb/kg was quantified <1.5 km from a Pb smelter in Torreón (COA), exceeding the standard value by 52.9 times (Table 5). To evaluate the Pb impact on locations, the contamination grade and the human health risk were calculated for each report.

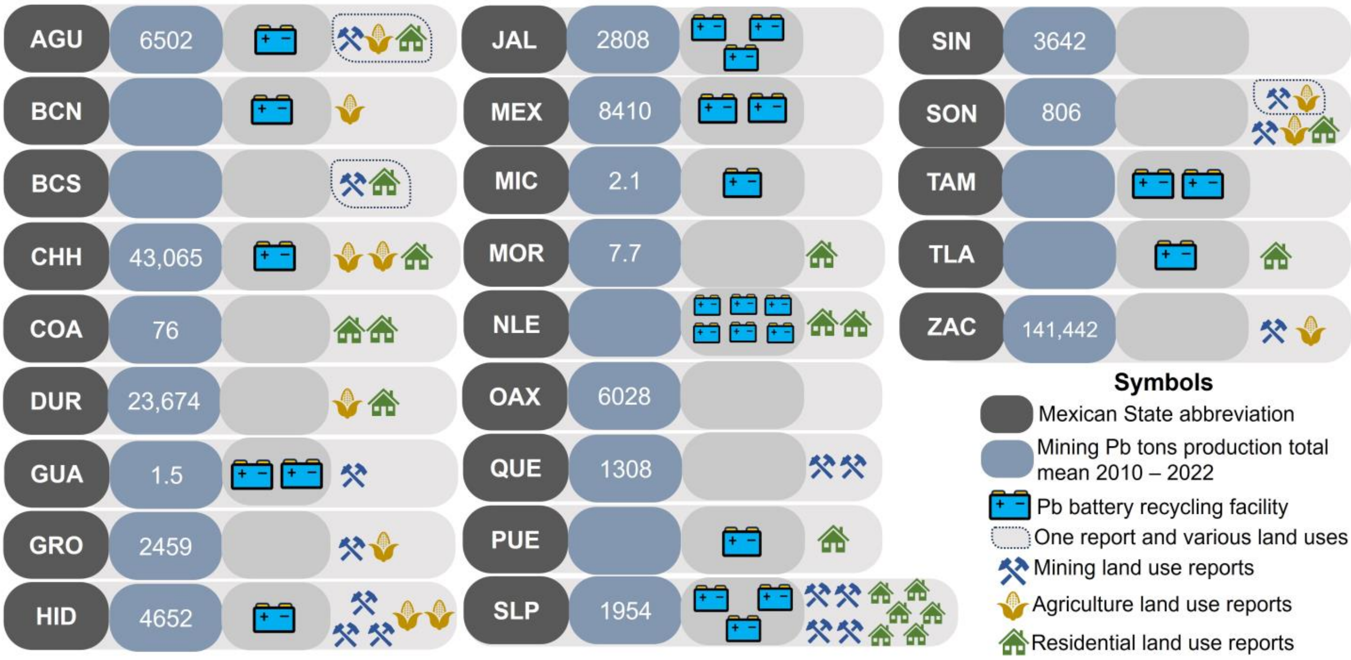

Figure 3. Mexican states' mining Pb production, Pb battery facilities, and Pb pollution reports. Aguascalientes (AGU), Baja California Norte (BCN), Baja California Sur (BCS), Chihuahua (CHH), Coahuila (COA), Durango (DUR), Estado de México (MEX), Guanajuato (GUA), Guerrero (GRO), Hidalgo (HID), Jalisco (JAL), Michoacán (MIC), Morelos (MOR), Nuevo León (NLE), Oaxaca (OAX), Puebla (PUE), Querétaro (QUE), San Luis Potosí (SLP), Sinaloa (SIN), Sonora (SON), Tamaulipas (TAM), Tlaxcala (TLA), and Zacatecas (ZAC) are depicted. The mean of Pb mining production (tons) during 2010–2022 (bluish gray) and the Pb battery recycling facilities in each state are represented (battery symbol). The number of land-use symbols indicates the quantity of reports retrieved per State.

Table 3. Pb concentrations in mining and/or tailings land.

Location	Characteristics and Distance from the Pollution Source	Range; Median, or Mean ± SD (mg/kg)	References
AGU, Asientos	Dry season, 10 m *	164.6	[43]
	Rainy season, 10 m *	2309.5	[43]
BCS, Los Planes	"San Antonio" mine	7.1 ± 1.9	[37]
	"Ensenada de Muertos" mine	3.9 ± 0.2	[37]
HID, Zimapán	20 m **	610.0 ± 5.0	[44]
	30 m **	505.5 ± 61.5	[44]
	Tailing	2211.6 ± 232.5	[45]
	5–45 m *	268.0–996.0; med 693.6	[46]

Table 3. *Cont.*

Location	Characteristics and Distance from the Pollution Source	Range; Median, or Mean ± SD (mg/kg)	References
GRO, Taxco	5–45 m *	89.0–2859.0; med 832.4	[46]
GUA, Pozos	5–35 m *	58.0–469.0; med 243.0	[46]
GUA, Xichú	5–35 m *	111–12,966; med 1171.3	[46]
QUE, Maconí	5–45 m *	70–234; med 126.6	[46]
QUE, Peñamiller	"La Estrella" mine	1.0–2.8; med 1.4	[47]
SLP, Cedral	Currently active mining	2682.4–18,537.3; 4327.0 ± 3015.6	[48]
SLP, Cerro de San Pedro	Current and historical tailings	281.7–19,549.3; 4220.0 ± 3793.3	[48]
SLP, Charcas	Historical mining 442 years ago Mine	42.1–17,861.2; 12,929.6 ± 4689.0 <400.0	[48] [49]
SLP, Villa de la Paz	Current and historical tailings Tailing Hill Rosettophyllous desert in soil Microphyllous desert in soil	189.2–5088.3; 907.8 ± 996.7 555.0 5488.0 117.9–487.1 428.1–2226.8	[48] [50] [50] [51] [51]
SON, Nacozari de García	Abandoned tailings II Abandoned tailing III	21.4–122.4, 70.0 ± 28.3 2.5–33.9; 14.1 ± 9.5	[52] [52]
SON, San Felipe de Jesús	Sulfide-rich tailings Oxide-rich tailings	9720.0–23,400.0; med 21,288.0 8960.0–23,400.0; med 14,763.0	[41] [41]
ZAC, Vetagrande	"Jal Viejo" tailing Mining soil with *Reseda Luteola* L. Mining soil with *Asphodelus fistulosus* L.	3984.0 ± 306 853 ± 250 2656 ± 151	[53] [53] [53]

*, distance from mine; **, distance from tailing; med, median; SD, standard deviation. AGU, Aguascalientes; BCS, Baja California Sur; GUA, Guanajuato; GRO, Guerrero; HID, Hidalgo; QUE, Querétaro; SLP, San Luis Potosí; SON, Sonora; ZAC, Zacatecas.

Table 4. Pb concentrations in agricultural land.

Location	Characteristics and Distance from the Pollution Source	Range; Median or Mean ± SD (mg/kg)	References
AGU, Asientos BCN, Cerro Prieto	1600 m *	369.7–374.7; med 372.2	[43]
	Geothermal station	14.7–25.8; med 19.9	[54]
CHH, Aldama CHH, Juarez Valley	Walnut orchards near mine Juarez Valley (agrochemicals)	1–47.4; med 30.5 23.4 ± 6.4	[55] [56]
DUR, Santiago Papasquiaro	Forest soil impacted by mine tailing	26.5–768.6; 256.8 ± 166.8	[57]
GRO, Santa Rosa	3000 m ** 400 m ** 40 m **	229.6 ± 50.6 59.9 ± 0.1 3269.7 ± 53.7	[58] [58] [58]
HID, Zimapán	20 m ** 30 m ** 100 m ** Soil from terrestrial plants Soil from wetlands and aquatic plants	505.5 ± 61.5 674.0 ± 3.5 365.0–3884.0; 1722.8 ± 1277.7 201.0–3991.0; 2019.2 ± 1138.6	[59] [59] [60] [60]
SON, San Felipe de Jesús	Soil adjacent mine tailings	106.0–4630.0; med 1673.3	[41]
SON, Yaqui and Mayo valleys	Yaqui valley ($PbHAsO_4$ pesticide) Mayo valley ($PbHAsO_4$ pesticide)	10.0–195.0; med 40.1 9.0–33.0; med 23.2	[61] [61]
ZAC, Vetagrande	Agricultural and rangeland soils near mines	7516.6 ± 456.3	[42]

*, distance from mine; **, distance from tailing; med, median; SD, standard deviation. AGU, Aguascalientes; BCN, Baja California Norte; CHH, Chihuahua; DUR, Durango; GRO, Guerrero; HID, Hidalgo; SON, Sonora; ZAC, Zacatecas.

Table 5. Pb concentrations in residential land.

Location	Characteristics and Distance from the Pollution Source	Range; Median or Mean ± SD (mg/kg)	References
AGU, Asientos	800 m *, residential zone	33.2–44.9; med 39.0	[43]
	1600 m *, residential zone	82.3–98.8; med 90.5	[43]
BCS, Los Planes	"El Sargento" town, 10 km *	5.2 ± 0.5	[37]
	"Brisamar" town, 40 km *	0.4 ± 0.4	[37]
CHH, Chihuahua	600 m from "Ávalos" Pb smelter	62–4716; med 1499	[62]
COA, Torreón	<1.5 km from Pb smelter	25–21,179	[63]
	>1.5 km from Pb smelter	24.0–589.0	[63]
	Pb smelter plant	130–12,050; med 374.0	[64]
DUR, Durango	"Cerro de Mercado" mining district	21.6–107.3	[65]
MOR, Tlayacapan	Pottery workshops	165.0–916.0; med 195.0	[66]
NLE, Monterrey	Battery factory	8.0–6064.0; med 83.4	[67]
	Industrial zones	224.0–1230.0; 455.0 ± 204.0	[68]
PUE, Popocatépetl	Volcanic soil	3.6–60.3	[69]
SLP, Cedral	Old mines and tailings	98–4225; med 263	[62]
SLP, Cerro de San Pedro	Urban zone mining activity	11,124.5–18,537.8; med 6485.1	[70]
SLP, Las Terceras	Brick-kiln area	19.9–611.5; med 60.5	[71]
SLP, Morales	Formerly Pb-concentrate production	62–5187; med 570	[62]
SLP, San Luis Potosí	Industrial, and vehicular traffic zones	25.0–435.0; 108.0 ± 105.0	[72]
SLP, Villa de la Paz	Urban areas near mining activity	37.0–16,991.0; 458.0 ± 4567.0	[73]
	Urban zone mining activity	466.1–3486.4; med 1053.7	[70]
	Zone near tailing	13–754; 373.4 ± 278.6	[74]
SON, Hermosillo	Traffic paint and urban topsoils	34.0–173.0; med 59.9	[75]
TLA, Trinidad Tenexyecac	Pottery area	411–2740; med 1126	[62]

*, distance from mine; med, median; SD, standard deviation. AGU, Aguascalientes; BCS, Baja California Sur; CHH, Chihuahua; COA, Coahuila; DUR, Durango; MOR, Morelos; NLE, Nuevo León; PUE, Puebla; SLP; San Luis Potosí; SON, Sonora; and TLA, Tlaxcala.

3.3.1. Contamination Grade in Mining, Agricultural, and Residential Land

Pollution monitoring is important to assess the exposure risk for humans and ecosystems, particularly in mines or industrial zones [76]. In Figure 4, the contamination grade is represented by I_{geo} and ERI values obtained for mining, agricultural, and residential land in Mexico. Mining land locations, namely Cerro de San Pedro, Cedral, Charcas, San Felipe de Jesús, and Vetagrande, were extremely contaminated ($I_{geo} > 5$) with extreme ecological risk (ERI > 200). Residential areas and ecosystems surrounding mines or storage tailings have environmental risks attributable to pollutant releases, groundwater contamination by leakages, or failures in tailing dams [77]. Indeed, agricultural soil from San Felipe de Jesús and Vetagrande presented extreme contamination, confirming possible pollutant distribution from mines or tailings to nearby areas. Agricultural soil near mines accumulates polluting compounds and eventually contaminates crops [78], representing a potential risk to human health [79]; the Mexican norm allows 400 mg Pb/kg in agricultural soil, while Canadian standards recommend 140 mg Pb/kg as a maximum limit [80]. High Pb concentration in soil suggests an increase in the metal mobility and a higher probability of bioaccumulation. Muñoz et al. (2021) identified, in Vetagrande (ZAC), vegetables with Pb concentrations greater than the limits (0.1 mg Pb/kg) established by the Food and Agriculture Organization of the United Nations (FAO); the vegetables analyzed by Muñoz were garlic (*Allium sativum*, 3.0 mg Pb/kg), carrot (*Daucus carota,* 5.0 mg Pb/kg), and bell pepper (*Capsicum annuum*, 9.6 mg Pb/kg) [81].

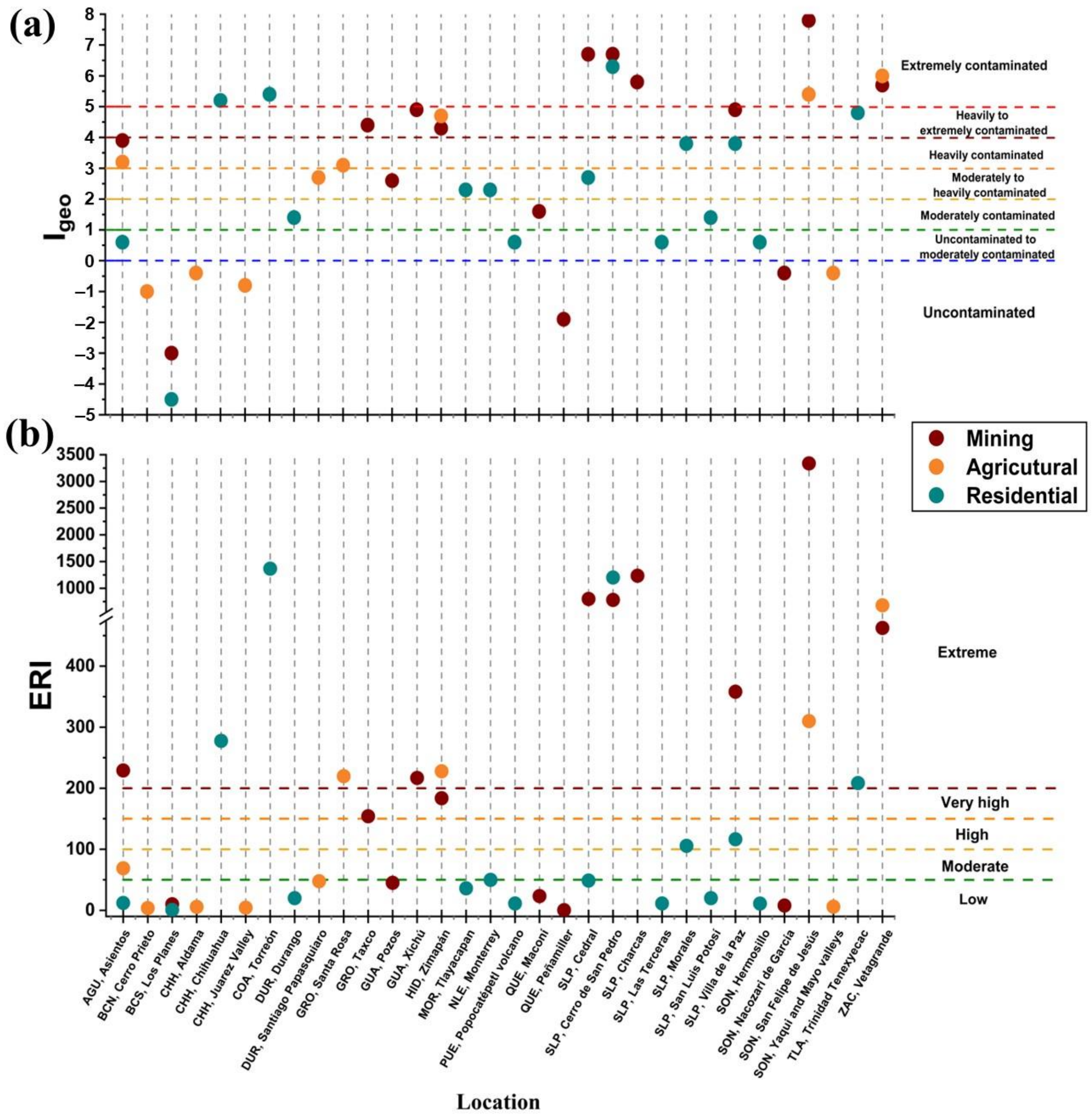

Figure 4. Contamination grade in Mexican locations. (**a**) Geoaccumulation index (Igeo) and (**b**) ecological risk index (ERI) are represented in the scheme. Circles in red, orange, and green indicate mining, agricultural, and residential land, respectively, in Mexican locations. AGU, Aguascalientes; BCN, Baja California Norte; BCS, Baja California Sur; CHH, Chihuahua; COA, Coahuila; DUR, Durango; GRO, Guerrero; GUA, Guanajuato; HID, Hidalgo; MOR, Morelos; NLE, Nuevo León; PUE, Puebla; QUE, Querétaro; SLP, San Luis Potosí; SON, Sonora; TLA, Tlaxcala; and ZAC, Zacatecas.

Contamination evaluated in residential areas was related to the industry (Pb smelter, battery factory, brick kiln, etc.), pottery, traffic paint, and volcano proximity. One clear example is the extreme contamination and ecological risk determined in Chihuahua and Torreón related to Pb smelter facilities. Localities with extremely contaminated mining land, namely Cerro de San Pedro and Villa de la Paz, also presented extreme contamination and ecological risk in residential areas. We analyzed if contamination grade was related to land-use, and results indicated that there is no significant difference among contamination in mining, agricultural, and residential soils (Figure S1). The contamination grade and ecological risk identified in the entire Mexican territory are showed in Figure 4.

3.3.2. Health Risk in Mining, Agricultural, and Residential Land

The health risk was determined by the non-carcinogenic and carcinogenic risks. The health risks for adults and children were estimated, ordered by land use, and are summarized in Table 6. Localities extremely contaminated (Figure 4) presented a HI value > 10 for children, suggesting a serious non-carcinogenic risk. Children are particularly vulnerable because they gastrointestinally absorb Pb efficiently, spend time on dusty floors, and are exposed by hand–mouth behavior [82]. Exposure to Pb in early life is associated with metabolic syndrome [83], nervous system disorders, kidney and liver damage, auditory impairment, gastrointestinal alterations, decreased intelligence quotient, and behavioral disorders [84]. Particularly, residential zones such as Trinidad Tenexyecac, Cerro de San Pedro, Morales, Torreon, and Chihuahua should be monitored to confirm such risk in children. Non-carcinogenic risk for adults was mostly interpreted as a greater possibility of non-carcinogenic effects; Pb in adults is related to Alzheimer's disease, reproductive toxicity, and progression of cancer [85]. Finally, the carcinogenic risk was evaluated in mining, agricultural, and residential zones. The results represented in Table 6 as CRI values exceeded the recommended value for a single carcinogenic metal. The population living in areas close to mines and areas of Pb smelting and brick pottery presented higher CRI values. Of all the reports, "El Sargento" town, Los Planes, Baja California Sur, located to 10 km from a mine, did not present a cancer risk.

Table 6. Hazard and cancer risk indexes in mining, agricultural, and residential soils.

Location	Mining				Agricultural				Residential			
	HI		CRI (10^{-6})		HI		CRI (10^{-6})		HI		CRI (10^{-6})	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
AGU, Asientos	5.5	23.9	50.1	54.5	1.7	7.2	15.1	16.4	0.3	1.2	2.6	2.9
BCN, Cerro Prieto	---	---	---	---	0.1	0.4	0.8	0.9	---	---	---	---
BCS, Los Planes	0.0	0.1	0.2	0.2	---	---	---	---	0.0	0.1	0.1	0.1
CHH, Aldama	---	---	---	---	0.1	0.6	1.2	1.3	---	---	---	---
CHH, Chihuahua	---	---	---	---	---	---	---	---	6.7	28.9	60.8	66.0
CHH, Juarez Valley	---	---	---	---	0.1	0.5	1.0	1.0	---	---	---	---
COA, Torreón	---	---	---	---	---	---	---	---	33.0	142.1	299.2	325.0
DUR, Durango	---	---	---	---	---	---	---	---	0.5	2.1	4.4	4.7
DUR, Santiago Papasquiaro	---	---	---	---	1.1	4.9	10.4	11.3	---	---	---	---
GRO, Santa Rosa	---	---	---	---	5.3	22.8	48.1	52.2	---	---	---	---
GRO, Taxco	3.7	16.0	33.7	36.6	---	---	---	---	---	---	---	---
GUA, Pozos	1.1	4.7	9.9	10.7	---	---	---	---	---	---	---	---
GUA, Xichú	5.2	22.5	47.5	51.6	---	---	---	---	---	---	---	---
HID, Zimapán	4.5	19.1	40.2	43.7	5.5	23.7	49.9	54.2	---	---	---	---
MOR, Tlayacapan	---	---	---	---	---	---	---	---	0.9	3.8	7.9	8.6
NLE, Monterrey	---	---	---	---	---	---	---	---	1.2	5.2	10.9	11.9
PUE, Popocatépetl volcano	---	---	---	---	---	---	---	---	0.3	1.2	2.4	2.7
QUE, Maconí	0.6	2.4	5.1	5.6	---	---	---	---	---	---	---	---
QUE, Peñamiller	0.0	0.0	0.1	0.1	---	---	---	---	---	---	---	---

Table 6. *Cont.*

Location	Mining				Agricultural				Residential			
	HI		CRI (10^{-6})		HI		CRI (10^{-6})		HI		CRI (10^{-6})	
	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children	Adult	Children
SLP, Cedral	19.3	83.3	175.4	190.5	---	---	---	---	1.2	5.1	10.7	11.6
SLP, Cerro de San Pedro	18.8	81.2	171.1	185.8	---	---	---	---	29.0	124.8	262.9	285.5
SLP, Charcas	29.8	128.3	270.2	293.5	---	---	---	---	---	---	---	---
SLP, Las Terceras	---	---	---	---	---	---	---	---	0.3	1.2	2.5	2.7
SLP, Morales	---	---	---	---	---	---	---	---	2.5	11.0	23.1	25.1
SLP, San Luis Potosí	---	---	---	---	---	---	---	---	0.5	2.1	4.4	4.8
SLP, Villa de la Paz	8.6	37.2	78.4	85.1	6.1	26.2	55.0	59.8	2.8	12.1	25.5	27.7
SON, Hermosillo	---	---	---	---	---	---	---	---	0.3	1.2	2.4	2.6
SON, Nacozari de García	0.2	0.8	1.7	1.9	---	---	---	---	---	---	---	---
SON, San Felipe de Jesús	80.5	346.9	730.7	793.7	7.5	32.2	67.8	73.7	---	---	---	---
SON, Yaqui and Mayo valleys	---	---	---	---	0.2	0.6	1.3	1.4	---	---	---	---
TLA, Trinidad Tenexyecac	---	---	---	---	---	---	---	---	5.0	21.7	45.6	49.6
ZAC, Vetagrande	11.2	48.1	101.2	110.0	16.4	70.7	149.0	161.8	---	---	---	---

---, no report found; CRI, cancer risk index; HI, hazard index; AGU, Aguascalientes; BCN, Baja California Norte; BCS, Baja California Sur; CHH, Chihuahua; COA, Coahuila; DUR, Durango; GRO, Guerrero; GUA, Guanajuato; HID, Hidalgo; MOR, Morelos; NLE, Nuevo León; PUE, Puebla; QUE, Querétaro; SLP, San Luis Potosí; SON, Sonora; TLA, Tlaxcala; and ZAC, Zacatecas.

4. Conclusions

In this systematic review, we retrieved 36 reports of Pb quantification in mining, agricultural, and residential soil in Mexico. Interestingly, the reports mentioned 16 Mexican states out of 22 related to Pb mining and/or Pb battery recycling. Most of the reports correlated the Pb concentration in soil with mining, whereas a unique article mentioned the battery industry. San Luis Potosí (SLP) was the most reported state. The meta-analysis performed allowed us to identify extreme Pb contamination grades in residential land from Cerro de San Pedro and Villa de la Paz in SLP, Chihuahua in Chihuahua, and Torreon in Coahuila, while in studies of agricultural soil, extreme contamination was recognized in Cerro de San Pedro, Cedral, Charcas, and Villa de la Paz (SLP), San Felipe de Jesús in Sonora, and Vetagrande in Zacatecas. Contamination grades coincide with a high health risk, particularly for children. Thus, the results presented in our work can guide other researchers and Mexican authorities to identify regions in the Mexican territory that require attention and immediate remediation in order to reduce the health risks in the Mexican population.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments11030043/s1, Figure S1: Igeo and ERI values (a and b, respectively) averaged and graphed to compare Pb contamination by land uses; Table S1: Indexes of geoaccumulation, ecological risk, hazard, and cancer risk in mining/tailing soils; Table S2: Indexes of geoaccumulation, ecological risk, hazard, and cancer risk in agricultural soils; Table S3: Indexes of geoaccumulation, ecological risk, hazard, and cancer risk in residential soils.

Author Contributions: Conceptualization, J.B.-B., X.A.-P. and A.L.-L.; methodology, J.B.-B. and X.A.-P.; software, V.M.E.-E.; validation, J.A.F.d.l.T. and A.L.-L.; formal analysis, J.B.-B. and X.A.-P.; investigation, J.B.-B. and X.A.-P.; resources, A.L.-L.; data curation, J.B.-B. and X.A.-P.; writing—original draft preparation, J.B.-B. and X.A.-P.; writing—review and editing, J.B.-B. and X.A.-P.; visualization, J.C.-O. and J.A.F.d.l.T.; supervision, J.B.-B. and A.L.-L.; project administration, A.L.-L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All the datasets are not publicly available due to the large amount of data collected; however, specific datasets are available upon request to the corresponding author.

Acknowledgments: The authors thank the Consejo Nacional de Humanidades, Ciencias y Tecnologías (Conahcyt) postdoctoral fellowship given to J.B-B, (CVU 703216), X. A-P. (CVU 331982) and V. M. E-E. (CVU 416160).

Conflicts of Interest: The authors declare no conflicts of interest.

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