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Potentially toxic elements and Pb isotope data of regional food from the Sonoran River basin: Tracing the nature of the sources

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ABSTRACT

The upper Sonora River basin in northwestern Mexico is a region with active and historical mining, as well as vigorous agricultural and livestock activity. The Buenavista del Cobre mine spill that occurred in 2014 raised major concerns among residents, including food safety. In this study, potentially toxic elements, PTE, (Al, As, Ba, Cd, Cr, Cu, Fe, Ni, Pb, Zn, and Tl) and Pb isotope ratios were measured in samples of regional foods and food products [beef chorizo, shredded beef jerky, beef liver, beef top round, farmer's cheese, and red chili (powdered dried mild pepper)] collected from representative sites along the basin. Compared to international guidelines, only two out of 20 beef samples exceeded the Pb limit of 0.1 mg/kg set by FAO/WHO and the EU, mainly in prepared products (chorizo, shredded beef jerky). One liver sample exceeded the FAO/WHO Pb limit of 0.2 mg/kg. For red chili, one sample exceeded the Pb guideline of 0.6 mg/kg (FAO/WHO). Overall, Pb levels did not surpass FAO/WHO recommendations. Pb isotope compositions in most food samples align with the range of North American rocks, indicating limited influence from mining. Variability in Pb isotope composition may be related to preparation methods and geogenic anomalies. Although the mine spill represented a major environmental disturbance, PTE concentrations measured in foods and food products are consistent with the geochemical background of the basin. This interpretation is supported by Pb isotope compositions, indicating that Pb in food and food products primarily originates from natural sources, with no clear evidence of significant contributions from mining activities.

Keywords: Potentially Toxic Elements; regional food; Pb isotopes; traceability; Sonora River basin; Mexico

RESUMEN

La cuenca superior del río Sonora, en el noroeste de México, es una región con minería activa e histórica, así como con una intensa actividad agrícola y ganadera. El derrame en la mina Buenavista

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del Cobre, ocurrido en 2014, generó gran preocupación entre las comunidades, incluida la seguridad alimentaria. En este estudio, se midieron elementos potencialmente tóxicos, EPT, (Al, As, Ba, Cd, Cr, Cu, Fe, Ni, Pb, Zn, y Tl) y las razones isotópicas de Pb en muestras de alimentos y productos alimenticios regionales (chorizo de res, machaca (carne seca) de res, hígado de res, pulpa de res, queso fresco y chile colorado) recolectadas en sitios representativos a lo largo de la cuenca. En comparación con las directrices internacionales, solo dos de 20 muestras de carne de res superaron el límite de Pb de 0.1 mg/kg establecido por la FAO/OMS y la UE, principalmente en productos preparados (chorizo, machaca). Una muestra de hígado superó el límite de Pb de la FAO/OMS (0.2 mg/kg). Para el chile colorado, una muestra excedió la directriz de Pb de 0.6 mg/kg (FAO/OMS). En general, los niveles de Pb no sobrepasaron las recomendaciones de la FAO/OMS. Las composiciones isotópicas de Pb en la mayoría de las muestras de alimentos coinciden con el rango de rocas de Norteamérica, lo que indica una influencia limitada de la minería. La variabilidad en la composición isotópica de Pb puede estar relacionada con los métodos de preparación y anomalías geogénicas. Aunque el derrame en la mina representó un importante desastre ambiental, los EPT en alimentos y productos alimenticios son consistentes con el fondo geoquímico de la región. Esta interpretación es apoyada por las composiciones isotópicas de Pb, lo que indica que el plomo en los productos alimenticios es de fuente natural (geogénico), y no hay evidencia clara de aporte de Pb asociado a actividad minera.

Palabras clave: *elementos potencialmente tóxicos; comida regional; isótopos de plomo; trazabilidad; cuenca del río Sonora; México*

INTRODUCTION

Rapid industrial development has significantly increased the pollution by potentially toxic elements (PTE) in the environment (Jiang *et al.*, 2017). PTE are considered hazardous due to their capacity for bioaccumulation, biomagnification, toxicity, and environmental persistence. When present in high concentrations, they can impact the quality of water bodies, the atmosphere, soil, and living organisms (Li *et al.*, 2014; Boente *et al.*, 2020; Rehman *et al.*, 2020). Some elements (*e.g.*, Cu, Fe, Zn) are essential for organisms due to their fundamental biological roles and participation in various enzymatic reactions (Rodríguez-Marín *et al.*, 2019). However, relatively high concentrations can be harmful for organisms (Kamunda *et al.*, 2016; Bonanno *et al.*, 2017; Zhou *et al.*, 2020). In contrast, elements such as As, Cd, Cr, Hg, Pb, and Tl lack confirmed biological functions in organisms and can be toxic, even at low concentrations.

PTE can originate from both geogenic (*e.g.*, rock erosion, pedogenesis, volcanism) or anthropogenic sources (*e.g.*, mining, agriculture, industrial emissions, urban effluents) (Loredo *et al.*, 2003; Ihedioha *et al.*, 2017; Marrugo-Negrete *et al.*, 2017; Duan *et al.*, 2020). Mining, while economically important from the local to the global level, generates large amounts of waste, for instance, mine tailings containing As, Cd, Cu, Hg, Pb, Sb, Sn, and Zn (Anawar, 2015). Moreover, PTE can persist in the environment for centuries after ceasing mining operations (Coelho *et al.*, 2012; Peña-Ortega *et al.*, 2019). Other significant PTE sources include the growing industrial and urban activities, contributing pollutants to air, soil, and water (Pan *et al.*, 2018; Ali *et al.*, 2019; Müller *et al.*, 2020).

Once in the environment, PTE can interact with humans through inhalation, dermal absorption, and ingestion. The latter is the main route of PTE exposure due to consuming food contaminated with PTE (Bi *et al.*, 2018; Khan *et al.*, 2020). Therefore, monitoring PTE concentrations in edible products is crucial, particularly in regions with mining activities (*e.g.*, Liu *et al.*, 2010; Alturiqui *et al.*, 2012; Zhao *et al.*, 2016; Wang *et al.*, 2019).

Identifying contaminating sources is challenging (Cheng & Hu, 2010). Isotope geochemistry, particularly Pb isotope systematics, provides an effective tool for tracking Pb sources in the environment. Pb has four naturally occurring stable isotopes (^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb); ^{204}Pb is non-radiogenic, while ^{206}Pb, ^{207}Pb, and ^{208}Pb are the decay products of ^{238}U, ^{235}U, and ^{232}Th, respectively (Dickin, 2018). A particularity of the Pb isotopic ratios is the lack of fractionation during emission, transport, and deposition processes, enabling source identification (geogenic *vs.* anthropogenic) and tracing of PTE in environmental media (Yoo *et al.*, 2014; Brewer *et al.*, 2016; Lee *et al.*, 2019; Mihaljevič *et al.*, 2019; Yu *et al.*, 2024).

The upper basin of the Sonora River (Figure 1) is a region historically linked to mining, agriculture, and livestock farming. The region includes significant mining operations such as the Buenavista del Cobre (Cu-Mo) mine in Cananea, the Las Chispas mine, the Santa Elena (Au) mine in Banámichi, and the San Felipe de Jesús area (Cu, Pb, Zn, and Au). Previous studies have assessed the environmental impact of mining in this region, particularly after the Buenavista del Cobre mine spill in 2014 (*e.g.*, Aguilar-Hinojosa *et al.*, 2016; Díaz-Caravantes *et al.*, 2016; Calmus *et al.*, 2018; Rivera-Uria *et al.*, 2018; Escobar-Quiroz *et al.*, 2019; Romero-Lázaro *et al.*, 2019; Romo-Morales *et al.*, 2020). Dispersion, bioaccessibility, and toxicity of historic mine tailings have also been examined (Del Rio-Salas *et al.*, 2019; Loredo-Portales *et al.*, 2020).

While mining and agriculture are vital to economic development, they can contribute to the release of PTE into the environment, posing risks to ecosystems and human health. The presence of PTE in food is a growing concern in the region due to its potential public health implications. Dietary exposure to PTE requires careful assessment, especially considering the dietary habits of the Mexican population (*e.g.*, Galeana-Pizaña *et al.*, 2023). Elevated concentrations of PTE may exacerbate the country's burden of non-communicable diseases, such as type 2 diabetes and cardiovascular disease (Reyes-Pablo *et al.*, 2020; Villerías Alarcón, I., & Juárez Gutiérrez, 2021), by increasing vulnerability, inducing oxidative stress, or causing direct damage to key organs such as the kidneys or liver (Niede & Benbi, 2022).

This research evaluates the PTE concentrations in regional food products most commonly consumed in settlements located in the Sonoran River basin. Here, Pb isotope measurements are incorporated to estimate the contributions of anthropogenic and geogenic sources in food products. Studied products include beef (*i.e.*, chorizo, liver, top round, and shredded beef jerky), farmer's cheese, and red chili. These products are not only consumed on a daily basis but also have deep cultural roots in these communities (Sandoval-Godoy & Camarena-Gómez, 2012). Beyond the scientific importance, this study has significant social implications, since Pb isotope systematics allow differentiation between natural and anthropogenic sources of contamination, offering insight for future assessments of risk associated with the consumption of locally produced foods. Moreover, this

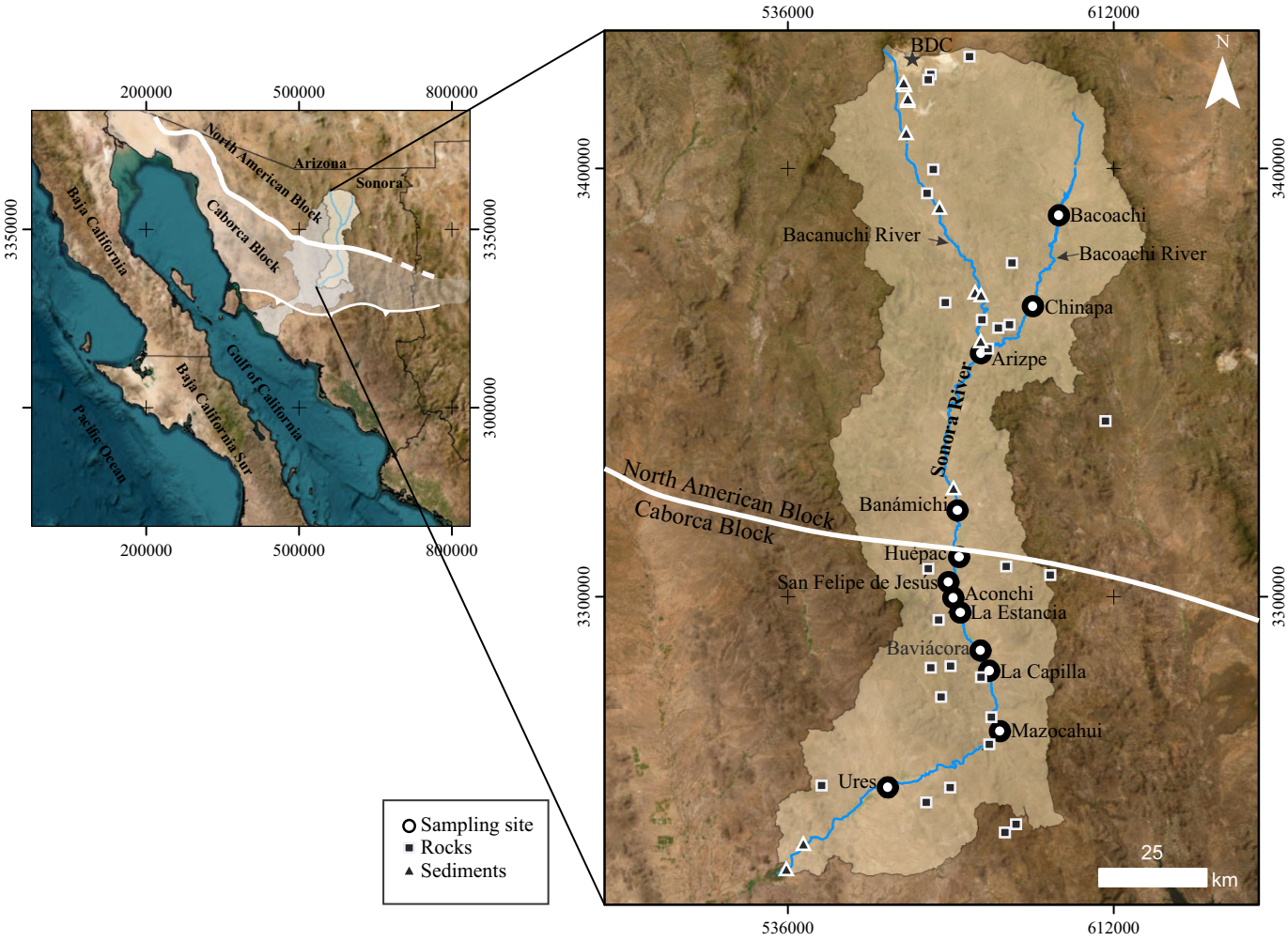


Figure 1. Location map of the upper Sonora River basin showing sampling locations. Inset showing the limits of the basements of the North American and Caborca blocks. BDC: Buenavista del Cobre.

research can help to strengthen trust in local foods and food products and empower affected communities by keeping them informed and engaged in environmental and public health decision-making processes.

ENVIRONMENTAL FRAMEWORK

Site description

The Sonora River is born east of Cananea at an altitude of 2400 m a.s.l. and flows south along 294 km. The Sonora River basin region comprises an area of ~27000 km^2 and is characterized by a subhumid climate in the northern part, becoming more arid in the lower part (Pérez-Quezadas *et al.*, 2021). It has bimodal precipitation, with a winter period consisting of frontal systems and a summer period with convective storms (Robles-Morua *et al.*, 2015). Much of the precipitation in the Sonora River basin is associated with the North American monsoon, which occurs from early July to mid-September (Pérez-Quezadas *et al.*, 2021). Topographic differences in the area result in a wide range of mean annual precipitation, from 350 mm/year in the southern part of the basin to 700 mm/year in the northern part (Robles-Morua *et al.*, 2015). During most of the year, the Sonora River may represent the only source of surface water for living beings in the region, as well as for the development of productive activities.

Geology of the region

The Sonora River basin is located on the southwestern margin of the North American craton, where the Proterozoic basement is composed of crystalline rocks from the Mazatzal and Yavapai provinces, which were accreted 1.63 Ga (Iriondo & Premo, 2011). The Mazatzal province is characterized by the Pinal Schist, which has an age of 1.69 to 1.64 Ga (Anderson & Silver, 2005; Page *et al.*, 2010) and was intruded by Mesoproterozoic plutons, such as the 1.44 Ga Cananea granite (Anderson & Silver, 1977; Noguez-Alcántara, 2008). The Yavapay province is characterized by metamorphic rocks that were intruded by the 1.73 Ga Crestón granite (Valenzuela-Navarro *et al.*, 2005). Neoproterozoic and Paleozoic rocks are poorly represented in the upper Sonora River basin; only a few outcrops are found in the Bacoachi area and west of Cananea, as well as roof pendants in the El Jaralito batholith (Roldán-Quintana, 1991) west of Baviácora. In the Hermosillo area, Paleozoic rocks are represented by intercalations of limestones and sandstones (Peña-Leal *et al.*, 1999) (Figure 2).

The tectonic evolution from the upper Permian to the Upper Miocene was mainly controlled by the subduction of the Pacific oceanic plates beneath the North American plate. In the study area, the Mesozoic rocks range from the Middle Triassic to the Upper Cretaceous. The Triassic is mainly represented by sandstones and limestones that outcrop east of Hermosillo (Peña-Leal *et al.*, 1999).

In the study area, Jurassic rocks record magmatic arc activity as well as the development of back-arc basins along the continental margin (Dickinson & Lawton, 2001; Mauel *et al.*, 2011). During the Early Cretaceous, shallow marine sedimentary rocks of the Bisbee Group were deposited during marine transgression from the Gulf of Mexico. During the Late Cretaceous and Paleocene, intense igneous activity occurred along the North American Cordillera between 80 and 40 Ma, known in Sonora as the Cretaceous-Eocene Mexican Magmatic Arc (Valencia-Moreno *et al.*, 2021); this event is well represented in the study area, mainly by the Aconchi batholith and the volcanic rocks of the Tarahumara and Mesa formations. The igneous activity continued during the Cenozoic, corresponding to the westernmost manifestations of the Sierra Madre Occidental volcanic province (González-León *et al.*, 2011). During the late Oligocene-Miocene (Gans, 1997; González-León *et al.*, 2010), the Basin and Range extensional event thinned the crust, resulting in N-S to NNW-SSW elongated ranges and valleys bounded by normal faults. The extension was characterized by exhumation controlled by low-angle normal fault activity, marked by a high erosion rate and the supply of the large volumes of clastic sediments of the Báucarit Formation and the Sonora Group (Grijalva-Noriega & Roldán-Quintana, 1998; González-León *et al.*, 2010).

METHODOLOGY

Elemental concentrations

A total of 40 samples of foods and food products were collected from the upper Sonora River basin from the most representative settlements along the basin: Aconchi, Arizpe, Bacoachi, Banámichi, Baviácora, Chinipa, Huépac, La Capilla, Mazocahui, Ranchito de Huépac, San Felipe de Jesús, and Ures (Figure 1b). The samples included beef chorizo (n=9), beef liver (n=3), shredded beef jerky (n=3), beef top round (n=8), farmer's cheese (n=5), and red chili (n=11). Each sample was placed in polyethylene bags and transported in coolers to a refrigerator for storage until analysis. Beef samples were washed with distilled water to remove external contamination and cut into small pieces with a stainless-steel knife.

The food samples were subjeted to acid digestion using a wet method in a closed system in 100 mL PFA digestion Savillex vessels. Around 10 g (beef and cheese) and 5 g (red chili) were weighed into Savillex containers; 10 mL of concentrated nitric acid was added, and the samples were left at room temperature for 12 hours. Subsequently, a gentle heating was applied for 3 hours until the solid particles disappeared. Then, 3 mL of 30% H_2O_2 was added at 15-minute intervals until the solutions turned from amber to clear. Next, the samples were evaporated at low temperature until reaching a volume of 5 mL. The elemental determination was carried out in triplicate using a Perkin Elmer Avio 500 ICP-OES at the Facultad de Química, Universidad Nacional Autónoma de México. For quality control, blanks, spiked blanks, certified reference material (BOVM-1), and an internal standard for continuous calibration and verification were used. The detection limits during measurements are shown in Tables 1 and 2. Element recoveries were ± 20% for all elements, except for Pb, which recoveries were within 5%.

Pb isotope ratios

In addition to the food samples, one sample of mine waste was collected from the El Lavadero, located 5 km east of San Felipe de Jesús town. Also, two river sediment samples from the Sonora River were collected, along with a pyrite sample and a porphyry rock from the Buenavista del Cobre mine. The digestion of the pyrite, tailings, and river sediment samples was done with aqua regia (double-distilled acids) for one night. The whole rock sample was digested with HF (29 M) and HNO_3 (16 M) in ultraclean Savillex screw-cap vessels at 100 °C overnight. The solution was evaporated to dryness, then HNO_3 (16 M) was added, and the mixture was heated at 100 °C overnight. The solution was evaporated, and HCl (10M) was added and kept at 100 °C overnight to ensure total digestion.

The acids used during digestion and treatment for measuring Pb isotope ratios were distilled twice in a Savillex distiller, and the solutions were prepared using ultrapure (18.2 MΩ) Milli-Q water. To determine the Pb isotope ratios, the digested samples were evaporated and dissolved in HNO_3 (8M) to perform chromatographic procedures. The digested samples were reconstituted with HNO_3 (8 M) for chromatography using Sr-Spec™ resin, following the procedures of Stegink and Rader (2024) and Del Rio-Salas *et al.* (2025). The resin was cleaned and preconditioned with HCl (8M) and HNO_3 (8M). The removal of matrix elements was performed by elution with HCl and HNO_3. Later, Pb was collected by eluting it with HCl (8M), according to the procedure reported by Deniel and Pin (2001). The Pb solution was then evaporated and reconstituted with 2% HNO_3 to perform the Pb isotope ratios measurements on a Nu Plasma II Multicollector-Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) in the Department of Earth and Atmospheric Sciences Metal Isotopes Laboratory at Indiana University-Bloomington. The isotope ratios $^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ are reported after being normalized to Galer and Abouchami (1998). All Pb isotope results were Hg-corrected, albeit the Hg correction was nominally to zero, and corrected online for mass discrimination using the known Tl ratio of the NIST-997 spike. Precision and accuracy were constrained using the NBS-981 standard (n=33), with errors during the measurements at the Indiana University-Bloomington laboratory being $^{208}Pb/^{206}Pb$ = 2.1677 (0.0001-0.0006 2σ), $^{207}Pb/^{206}Pb$ = 0.9148 (0.00003-0.0002 2σ), $^{206}Pb/^{204}Pb$ = 16.9405 (0.0014-0.0042 2σ), $^{207}Pb/^{204}Pb$ = 15.4963 (0.0012-0.0049 2σ), and $^{208}Pb/^{204}Pb$ = 36.7219 (0.0033-0.0160 2σ).

RESULTS AND DISCUSSION

Elemental concentrations

Tables 1 and 2 display the concentrations of Al, As, Ba, Cd, Cr, Cu, Fe, Ni, Pb, Zn, and Tl (mg/kg) in foods from the upper Sonora River basin. Comparing these values to the Upper Continental Crust (UCC) (Rudnick and Gao, 2003), and the local geochemical background (Calmus *et al.*, 2018) (Tables 1 and 2), the liver samples nearly tripled the Cu values. Liver samples from Aconchi and one from Ures, shredded beef jerky from Aconchi and San Felipe de Jesús, and top round samples from Baviácora, Huépac, and Banámichi, exceeded the Zn value for the UCC and the local geochemical background. One liver sample from Aconchi and red chili samples from Aconchi, Mazocahui, Banámichi, and San Felipe de Jesús exceeded the Cd value of the UCC.

The Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) through the Codex Alimentarius (FAO/WHO, 2023), the European Union (EU, 2023), and the National Food Safety Standard for Maximum Levels of Contaminants in Food GB-2762-2022 established by China (Foreign Agriculture Service [FAS], 2022) have set recommendations for the maximum permissible concentration of Pb and Cd. Specifically, the FAO/WHO sets limits of 0.1 mg/kg for Pb in beef and 0.2 mg/kg in beef liver. Likewise, the European Union recommends a maximum allowable concentration of Pb at 0.1 mg/kg in beef and 0.2 mg/kg

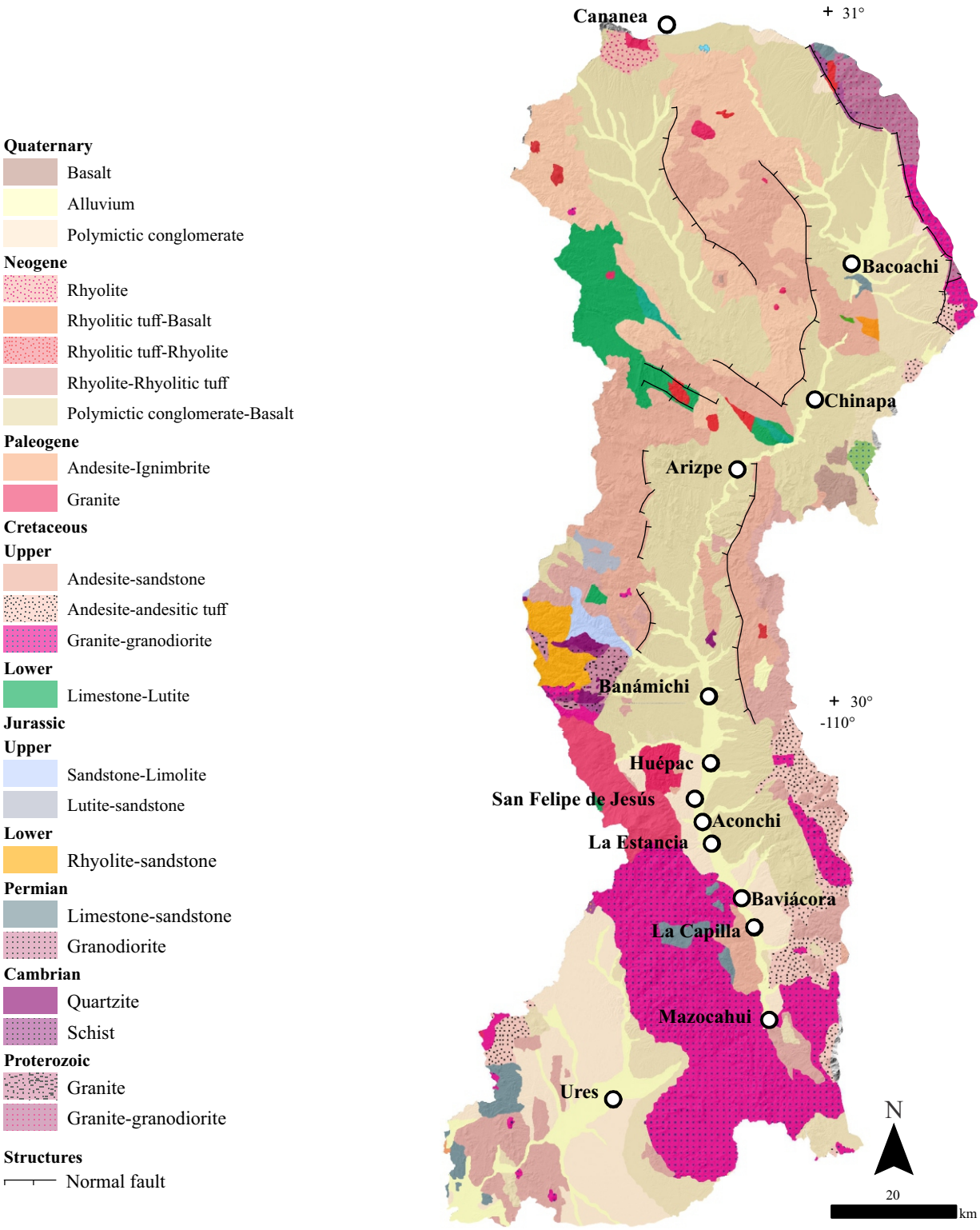


Figure 2. Geological map of the Sonora River basin. Modified from the Geological-Mining Charts of the Mexican Geological Survey (Charts H12-5, H12-6, H12-8, H12-9, H12-11, and H12-12).

Table 1. Elemental concentrations (mg/kg) in regional edible products along the Sonoran River basin, as well as the average values for the upper continental crust (UCC) and the geochemical background of the upper Sonora River basin (Bkg) from Rudnick & Gao (2003) and Calmus *et al.* (2018), respectively. DL: detection limit.

Sample		Site	Al	As	Ba	Cd	Cr	Cu	Fe	Ni	Pb	Zn	Tl
DL			*1.330*	*0.042*	*0.011*	*0.003*	*0.042*	*0.012*	*0.156*	*0.005*	*0.038*	*0.035*	*0.023*
Chorizo	C14	Bacoachi	8.50	<DL	1.30	<DL	0.23	1.41	17.05	0.13	<DL	23.11	<DL
	C15	Bacoachi	16.80	<DL	0.44	<DL	0.20	0.93	25.73	0.05	<DL	36.83	<DL
	C16	Bacoachi	11.20	<DL	0.29	<DL	0.13	0.84	16.92	0.04	<DL	23.71	<DL
	C20	Arizpe	8.10	<DL	0.28	<DL	0.91	0.76	16.31	0.50	<DL	26.69	<DL
	C41	Huépac	26.40	<DL	0.52	<DL	2.34	1.07	22.61	1.30	0.06	15.31	<DL
	C44	Banámichi	27.70	<DL	0.60	<DL	1.43	0.79	23.26	0.82	0.03	19.90	<DL
	C53	Baviácora	93.50	<DL	0.84	<DL	0.34	0.75	49.53	0.13	0.13	41.25	<DL
	C60	Aconchi	49.50	<DL	0.50	<DL	0.15	0.76	19.91	0.03	<DL	24.47	<DL
	C65	Ures	86.70	0.04	0.89	<DL	0.25	0.89	26.24	0.06	<DL	28.42	<DL
Liver	C18	Arizpe	<DL	0.04	0.34	<DL	0.17	28.83	44.71	<DL	<DL	55.84	<DL
	C55	Aconchi	1.70	<DL	0.15	0.257	0.16	61.35	44.08	0.01	<DL	68.83	<DL
	C64	Ures	2.10	0.08	0.06	<DL	0.14	75.86	42.80	<DL	<DL	73.75	<DL
Beef jerky	C17	Arizpe	9.50	<DL	0.49	<DL	2.92	1.40	245.6	0.46	0.13	62.71	<DL
	C54	San Felipe de Jesús	15.70	0.29	0.40	<DL	2.60	1.78	82.35	1.32	0.26	204.9	<DL
	C61	Aconchi	15.00	<DL	0.32	<DL	2.29	2.69	135.2	1.17	<DL	234.8	<DL
Top round	C21	Arizpe	1.50	<DL	0.09	<DL	1.01	0.61	17.88	0.53	<DL	48.14	<DL
	C26	Chinapa	3.50	<DL	0.15	<DL	0.19	0.73	16.85	0.04	<DL	54.37	<DL
	C31	Baviácora	1.10	<DL	0.06	<DL	0.21	0.76	21.81	0.02	<DL	82.88	<DL
	C39	Huépac	1.80	<DL	0.07	<DL	0.16	0.73	21.77	0.04	<DL	78.39	<DL
	C45	Banámichi	1.60	<DL	0.06	<DL	0.17	0.56	21.52	<DL	<DL	70.33	<DL
	C58	San Felipe	1.90	<DL	0.03	<DL	0.08	0.64	11.78	<DL	<DL	55.03	<DL
	C62	Aconchi	2.40	<DL	0.09	<DL	0.11	0.52	19.06	<DL	<DL	30.48	<DL
	C63	Ures	1.80	<DL	0.10	<DL	0.08	0.73	16.24	<DL	<DL	41.14	<DL
Farmer's cheese	C27	Chinapa	<DL	0.06	0.83	<DL	0.28	0.224	1.78	0.04	<DL	38.66	<DL
	C29	Baviácora	3.10	<DL	1.31	<DL	1.50	0.276	7.53	0.75	<DL	53.07	<DL
	C38	Huépac	5.70	<DL	0.96	<DL	1.39	0.175	9.84	0.68	<DL	34.70	<DL
	C43	Banámichi	4.00	<DL	0.87	<DL	0.30	0.352	5.27	0.03	<DL	52.85	<DL
	C56	San Felipe de Jesús	6.60	0.05	0.65	<DL	1.05	0.157	4.83	0.44	<DL	26.54	<DL
	UCC		*81503*	*4.8*	*628*	*0.09*	*92*	*28*	*39177*	*47*	*17*	*67*	*0.9*
	Bkg		*72665*	*17.9*	*926*	*–*	*43*	*19.7*	*28470*	*17.5*	*23.1*	*76.3*	*0.54*

Table 2. Elemental concentrations (mg/kg) in red chili along the Sonoran River basin, as well as the average values for the upper continental crust (UCC) and the geochemical background of the upper Sonora River basin (Bkg) from Rudnick & Gao (2003) and Calmus et al. (2018), respectively. DL: detection limit.

Sample		Site	Al	As	Ba	Cd	Cr	Cu	Fe	Ni	Pb	Zn	Tl
DL			*0.01*	*0.03*	*0.01*	*0.03*	*0.01*	*0.07*	*0.01*	*0.01*	*0.02*	*0.01*	*0.02*
Red chili	C13	Bacoachi	26.68	0.73	1.41	0.09	0.30	3.52	29.49	0.98	0.16	11.31	<DL
	C23	Arizpe	90.15	0.84	3.51	0.07	0.35	3.88	110.9	0.51	<DL	13.89	<DL
	C25	Chinapa	28.57	<DL	1.01	<DL	0.16	2.65	42.35	0.23	<DL	8.34	<DL
	C28	Baviácora	38.62	1.66	1.45	0.05	0.28	3.36	36.21	0.32	0.14	8.36	<DL
	C32	Aconchi	1060.80	0.99	6.03	0.11	0.65	5.07	280.4	0.65	0.32	16.25	<DL
	C34	La capilla	65.97	<DL	1.62	0.06	0.47	4.23	31.51	0.40	<DL	7.31	<DL
	C36	Mazocahui	120.07	3.51	9.24	0.12	0.50	4.61	144.6	0.51	0.63	15.68	<DL
	C37	Ures	82.01	0.68	2.46	<DL	0.36	4.17	88.20	0.38	<DL	13.64	<DL
	C42	Banámichi	20.34	0.78	2.47	0.10	0.29	5.71	68.46	0.72	0.22	15.97	<DL
	C66	San Felipe de Jesús	29.40	0.61	1.14	0.14	0.52	8.47	107.2	0.27	0.42	20.35	<DL
	C67	Ranchito de Huépac	98.36	1.22	4.01	<DL	0.45	5.23	88.06	0.43	0.40	14.68	<DL
	UCC		*81503*	*4.8*	*628*	*0.09*	*92*	*28*	*39177*	*47*	*17*	*67*	*0.9*
	Bkg		*72665*	*17.9*	*926*	*–*	*43*	*19.7*	*28470*	*17.5*	*23.1*	*76.3*	*0.54*

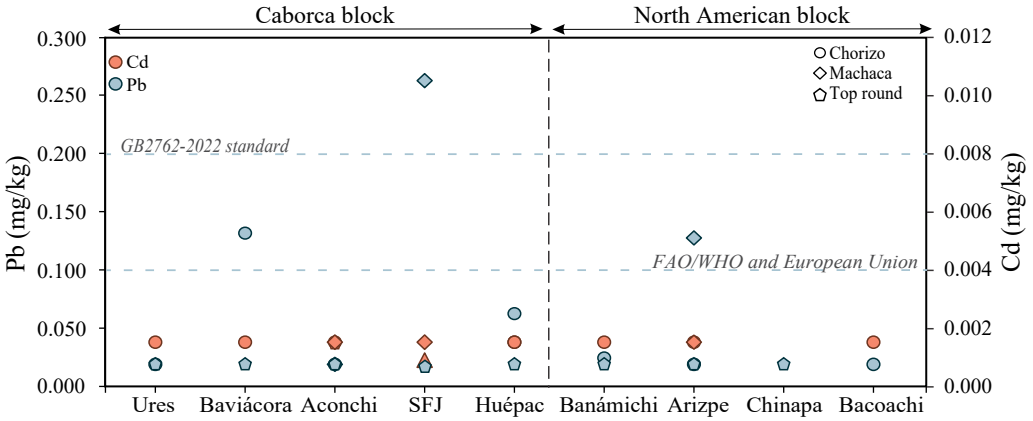


Figure 3. Concentrations of Pb and Cd in samples of beef and beef derivatives collected from Ures, Baviácora, Aconchi, San Felipe de Jesús, Huépac, Banámichi, Arizpe, Chinapa and Bacoachi. The maximum permissible content of Pb established in accordance with the EU (2023) and FAO/WHO (2023) is 0.1 mg/kg, and the National Food Safety Standard GB-2762-2022 (FAS, 2022) establishes a value of 0.2 mg/kg for meat and a value of 0.5 mg/kg for beef derivatives.

in liver, as well as a maximum limit for Cd at 0.05 mg/kg in beef and 0.5 mg/kg in beef liver (EU, 2023). Conversely, GB-2762-2022 recommends a Pb limit for beef (0.2 mg/kg), beef offal (0.5 mg/kg), beef derivatives (0.3 mg/kg), dairy derivatives (0.2 mg/kg), and spices (1.5 mg/kg), while also establishing Cd limits in beef (0.1 mg/kg), beef liver (0.5 mg/kg), and beef derivatives (0.1 mg/kg).

Based on these reference values, the Pb concentrations in chorizo samples from Bacoachi, Arizpe, Huépac, Banámichi, Aconchi, and Ures are below the maximum permissible levels set by the European Union and FAO/WHO. In contrast, the C53 chorizo sample from Baviácora exceeds this limit but remains within the limits of GB-2762-2022 (Figure 3). The Pb concentrations in shredded beef jerky samples collected from San Felipe de Jesús and Arizpe exceeded the maximum permissible values established by FAO/WHO and the European Union (Figure 3) but are below the recommended limit for beef derivates (0.3 mg/kg) according to GB-2762-2022.

Regarding Cd contents, none of the studied samples exceeded the GB-2762-2022 recommended values of 0.1 mg/kg for beef and beef derivatives or the European Union values of 0.05 mg/kg. In the case of Cd in the liver samples, none of them exceed the established maximum limit of 0.5 mg/kg (EU, 2023; FAS, 2022) (Figure 4). Cu and Zn are considered essential micronutrients. So far, no limits have been established by food safety regulations worldwide for these elements in meat and meat derivatives. However, chronic exposure to Cu may cause adverse health effects (More *et al.*, 2023; National Institutes of Health, 2024). Values for Cd, Cu, and Pb in beef products from the Sonora River region are similar to those reported for the Zhejiang Province, southeast China, where a relatively low health risk was observed (Han *et al.*, 2022).

In the case of the red chili samples, only the C36 sample from Mazocahui slightly exceeded the maximum permissible value recommended for Pb (0.6 mg/kg) established by the European Union (Figure 5). However, the value does not surpass the GB-2762-2022 recommended value (1.5 mg/kg). No permissible limits have been set for Cd, Cu and Zn in red chili. Nonetheless, these elements may cause toxic or carcinogenic effects at high doses (National Toxicology Program, 2021; More et al., 2023). Cadmium content in red chili from the upper Sonoran River basin is similar to that reported from a mining region in the Guizhou Province, southern China, with an average of ~0.06 mg/kg (Zhou & Liu, 2024).

Regarding farmer's cheese, GB-2762-2022 sets a limit of 0.2 mg/kg of Pb in dairy products and derivatives, whereas FAO/WHO establishes a limit of 0.02 mg/kg. Pb contents in the cheese samples from the upper Sonoran River basin do not exceed such limits; therefore, there is no concern associated with the consumption of these goods. No limits have been established for Cd, Cu and Zn in farmer'scheese.

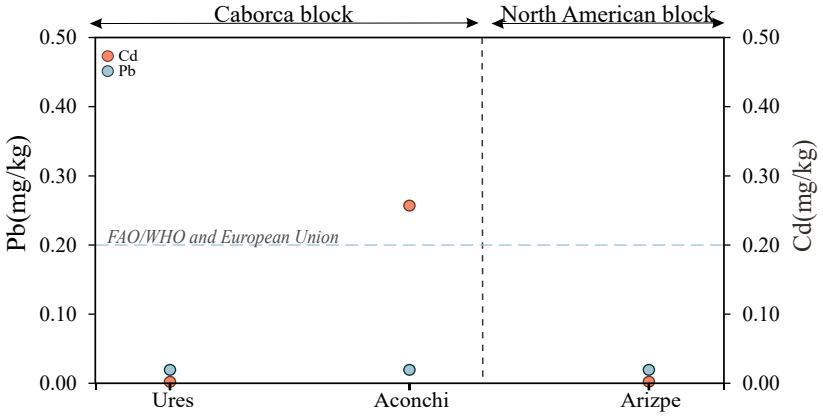


Figure 4. Concentrations of Pb and Cd in liver samples from Ures, Aconchi, and Arizpe. Maximum permissible contents of Pb (0.2 and 0.5 mg/kg) and Cd (0.5 mg/kg) established by the European Union (2023), FAO/WHO (2023), and the National Food Safety Standard GB 2762-2022 (FAS, 2022).

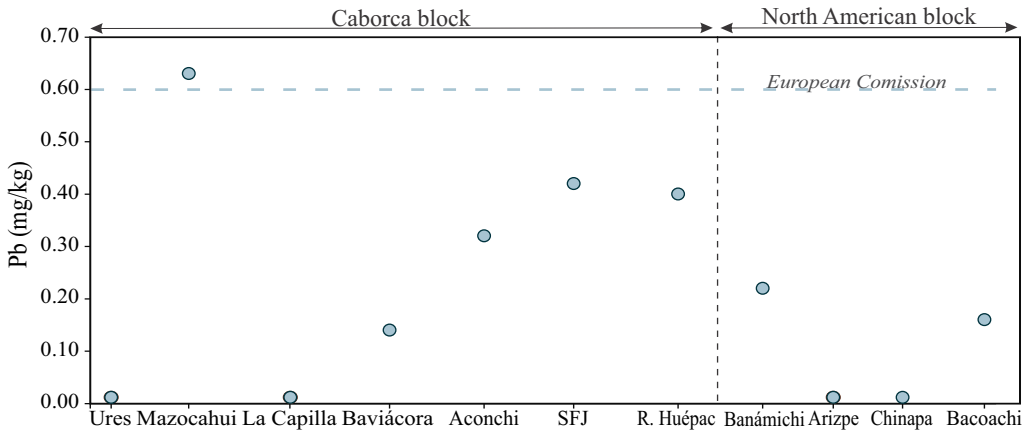


Figure 5. Concentrations of Pb in samples of red chili from Ures, Mazocahui, La Capilla, Baviácora, La Estancia, San Felipe de Jesús (SFJ), Ranchito de Huépac (R. Huépac), Banámichi, Arizpe, Chinapa, and Bacoachi. The maximum permissible Pb content (0.60 mg/kg) was established by the European Union (EU, 2023).

The relatively high values found in some foods and food products can be attributed to the natural geochemical anomalies in the region (Calmus *et al.*, 2018). However, according to the data reported in the region, the concentrations of Cu, Pb, and Zn in surface sediments along the Bacanuchi and Sonora rivers (León-García *et al.*, 2021; Figure 1) are similar to or even lower than those of the UCC. Even so, considering the element mobility reported by Aguilar-Hinojosa *et al.* (2016) in river sediments very close to the Buenavista del Cobre mine, where the 2014 spill occurred, Zn mobility is relatively high (up to 248 mg/kg), while that of Cd and Pb is practically negligible. Further south in the basin, at an abandoned mining site in San Felipe de Jesús, nearby agricultural soils showed mobile Zn concentrations of 4400–4100 mg/kg and Pb concentrations of 552–689 mg/kg; phytoaccessible fractions in these soils ranged from 380 ppm for Zn to as high as 136 mg/kg for Pb (Loredo-Portales *et al.*, 2020). In this area, the high mobility of these elements is associated with the oxidation of sulfides of the San Felipe de Jesús tailings, which are characterized by high metal concentrations (Del Rio-Salas *et al.*, 2019).

For the other elements listed in Tables 1 and 2, no international regulatory limits have been set for Cr, Ba, Al, Fe, and Ni in meat products or red chili. However, these elemental concentrations should serve as a reference for future assessments in the region in the event of any other anthropogenic incident. In the case of As, the Codex Alimentarius (FAO/WHO, 2023) recommends limits for specific products (edible fats, oils, fat and blended spreads, mineral water, rice, and salt), and such limits do not apply to the food products in this study. However, further investigations are warranted for red chili due to its relatively high As content (Table 2).

Pb isotope composition

The Pb isotope ratios of edible product samples collected in the upper Sonora River basin are listed in Table 3. Table 4 shows the Pb isotope composition of sediments from the Sonora River and mine tailings in the San Felipe de Jesús region (Del Rio-Salas *et al.*, 2024). Samples of pyrite and a porphyritic rock from the Buenavista del Cobre mine in Cananea and a galena from the inactive El Gachi mine (Del Rio-Salas *et al.*, 2024) were also considered in the study. Table 4 also includes the Pb isotope composition of the fluid spilled from the Buenavista del Cobre mine in 2014, and a sample of sediment from the Tinajas 1 dam, where the spill originated (Romo-Morales *et al.*, 2020).

Table 3. Pb isotope composition of regional edible products along the Sonoran River basin.

Sample	Type	Site	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
C1	Chorizo	San Felipe de Jesús	0.828	2.045	18.964	15.696	38.772
C4	Chorizo	Aconchi	0.836	2.061	18.761	15.68	38.662
C5	Chorizo	Ures	0.826	2.046	18.963	15.669	38.804
C12	Chorizo	Baviácora	0.833	2.062	18.825	15.681	38.813
C20	Chorizo	Arizpe	0.802	1.989	19.719	15.813	39.229
C3	Liver	Aconchi	0.849	2.094	18.413	15.641	38.549
C6	Liver	Ures	0.823	2.042	19.047	15.685	38.887
C9	Beef jerky	San Felipe de Jesús	0.832	2.058	18.858	15.696	38.809
C10	Beef jerky	Aconchi	0.813	2.007	19.373	15.752	38.876
C2	Top round	San Felipe de Jesús	0.828	2.042	18.941	15.692	38.68
C11	Top round	Aconchi	0.827	2.033	19.039	15.747	38.707
C8	Red chili	San Felipe de Jesús	0.833	2.067	18.764	15.632	38.789
C7	Red chili	La Estancia	0.826	2.049	18.984	15.683	38.899
C36	Red chili	Mazocahui	0.828	2.055	18.965	15.708	38.971
C19	Soft cheese	Arizpe	0.835	2.078	18.834	15.722	39.13
C27	Soft cheese	Chinapa	0.815	2.015	19.294	15.725	38.873
C43	Soft cheese	Banámichi	0.824	2.034	19.139	15.769	38.925

Table 4. Pb isotope composition of geogenic contributions along the Sonoran River basin and southern Arizona.

Sample	Type	Site	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Reference
SRSF-01	Sonora River sediment	San Felipe de Jesús	0.825	2.045	18.951	15.643	38.762	1
SRSF-02	Sonora River sediment	San Felipe de Jesús	0.823	2.038	19.015	15.653	38.757	1
JLAV	Mine tailings	El Lavadero	0.830	2.053	18.860	15.644	38.709	1
Py-CAN	Pyrite	Cananea	0.844	2.085	18.498	15.605	38.565	1
Por-CAN	Porphyritic rock	Cananea	0.839	2.077	18.592	15.601	38.619	1
BCS1	Mine spill	Cananea	0.819	2.03	18.657	15.746	38.765	2
STD1	Tinajas river sediment	Cananea	0.821	2.031	18.515	15.606	38.568	2
GA-12a	Galena	El Gachi	0.830	2.475	18.859	15.645	38.72	3
JNO10	Mine tailings	San Felipe de Jesús	0.83	2.053	18.86	15.644	38.709	3
JNO15	Mine tailings	San Felipe de Jesús	0.828	2.049	18.891	15.646	38.707	3
HO5	Mine tailings	San Felipe de Jesús	0.813	2.011	19.287	15.689	38.781	3
KD-GR2-13	Andesitic flow	Southern Arizona	0.838	2.059	18.557	15.564	38.226	4
D-MR2-23	Dioritic intrusion	Southern Arizona	0.839	2.067	18.546	15.562	38.35	4
QL-85-13	Quartz latite dike	Southern Arizona	0.822	2.038	18.968	15.608	38.663	4
RS-MR-53	Granodiorite	Southern Arizona	0.826	2.052	18.88	15.599	38.752	4
TWB-Pa3	Porphyritic granite	Southern Arizona	0.837	2.068	18.621	15.589	38.515	4
T32	Rhyodacite	Southern Arizona	0.851	2.104	18.253	15.542	38.409	4
7-25-09-3	El Oquimosis granite	Puerta del Sol	0.814	2.019	19.264	15.684	38.898	5
EGB12-33	El Palofierral orthogneiss	Puerta del Sol	0.808	1.996	19.408	15.68	38.731	5
EGB12-23	El Gato diorite	Puerta del Sol	0.814	2.013	19.226	15.656	38.699	5
9-27-09-2	Las Mayitas granodiorite	Puerta del Sol	0.819	2.03	19.105	15.656	38.781	5
11-21-09-3	El Garambullo gabro	Puerta del Sol	0.821	2.031	19.091	15.666	38.783	5
3-4-08-2	Granodiorite	Arizpe	0.825	2.044	19.043	15.711	38.916	6
3-3-08-1	Monzonite	Arizpe	0.828	2.044	19.038	15.755	38.917	6
9-29-09-3	Granite	Baviácora	0.809	2.006	19.4	15.696	38.923	6
10-2-09-8	Granite	Baviácora	0.801	2.006	19.615	15.706	39.347	6
10-1-09-2	Tonalite	Baviácora	0.816	2.029	19.206	15.677	38.967	6
2-27-09-8	Quartz monzonite	Cumpas	0.837	2.074	18.641	15.604	38.652	6
4-23-09-5	Tarahumara volcanic rock (Porphyritic rhyolite)	Huépac	0.813	2.018	19.284	15.675	38.914	6
9-30-09-4	Tonalite	Mazocahui	0.816	2.026	19.185	15.667	38.867	6

Data sources. 1: Present study; 2: Romo-Morales *et al.* (2020); 3: Del Rio-Salas *et al.* (2024); 4: Bouse *et al.* (1999): 5: González-Becuar *et al.* (2017); 6: González-León *et al.* (2011).

Finally, the Pb isotope composition of the lithology from the southern part of the basin (Puerta del Sol area; González-Becuar *et al.*, 2017), and the lithology located further north in the basin (González-León *et al.*, 2011), as well as the lithology from the southern state of Arizona (Bouse *et al.*, 1999), are included.

The isotope ratios $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ in the samples of edible products of animal origin averaged 19.012, 15.712, and 38.836, respectively. In contrast, the red chili samples showed averages of 18.904 ($^{206}Pb/^{204}Pb$), 15.674 ($^{207}Pb/^{204}Pb$), and 38.886 ($^{208}Pb/^{204}Pb$). Figure 6 shows the scatter diagram of $^{207}Pb/^{206}Pb$ *vs.* $^{208}Pb/^{206}Pb$, revealing a trend in the isotope values of the edible product samples with a positive slope, characterized by a correlation factor of r=0.97. This trend indicates more radiogenic lead (relatively lower values of $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$) and less radiogenic lead (relatively higher values of $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$). Figure 6 displays the fields of Pb isotope compositions of lithologies associated with the Caborca and North America blocks according to data reported in the region by Bouse *et al.* (1999), González-León *et al.* (2011), and González-Becuar *et al.* (2017).

Even though most of the food samples were obtained from settlements that lay in the Caborca block (*i.e.*, downstream of the study area), the majority of the Pb isotope composition data is located within the composition field of rocks from the North America block, except one chorizo sample from Arizpe, one farmer's cheese sample from Chinapa, and one shredded beef jerky sample from Aconchi. This suggests that the lithology of the North American block influences the isotope composition of downstream sediments because of sediment contributions from the upstream basin. Additionally, the configuration of basement rocks may explain the composition of edible products; the magmatic activity beneath the Caborca block also interacted with rocks from the North America block, imprinting the isotope composition in rocks and derivatives (*e.g.*, soils, sediments).

Figure 7 presents the Pb isotope data normalized to ^{204}Pb. The fields defining the isotope composition of rocks from the Caborca (more radiogenic) and North America (less radiogenic) blocks are also clearly defined. In contrast, the Pb composition of edible products is quite dispersed, and no logical trend or pattern is observed, which is typical of geological samples (*e.g.*, rocks, soils, sediments). This dispersion in the isotope composition data may be linked to food preparation, as the composition of Pb can be influenced by interactions with artifacts used during preparation and transportation (Nerín *et al.*, 2016; Pakdel *et al.*, 2023).

Mining activity is considered a potential source of anthropogenic PTE inputs in the study area. The dispersion of PTE is associated with mine tailings impoundments from both active and inactive facilities (Romero *et al.*, 2007; Peña-Ortega *et al.*, 2019; Rubinos *et al.*, 2021; Reddy *et al.*, 2022). The Pb isotope compositions from the Buenavista del Cobre mine mineralization, the 2014 spilled solution, and the associated sediments are shown in Figure 7 (Romo-Morales *et al.*, 2020; Del Rio-Salas *et al.*, 2024). The Pb isotope composition of the pyrite

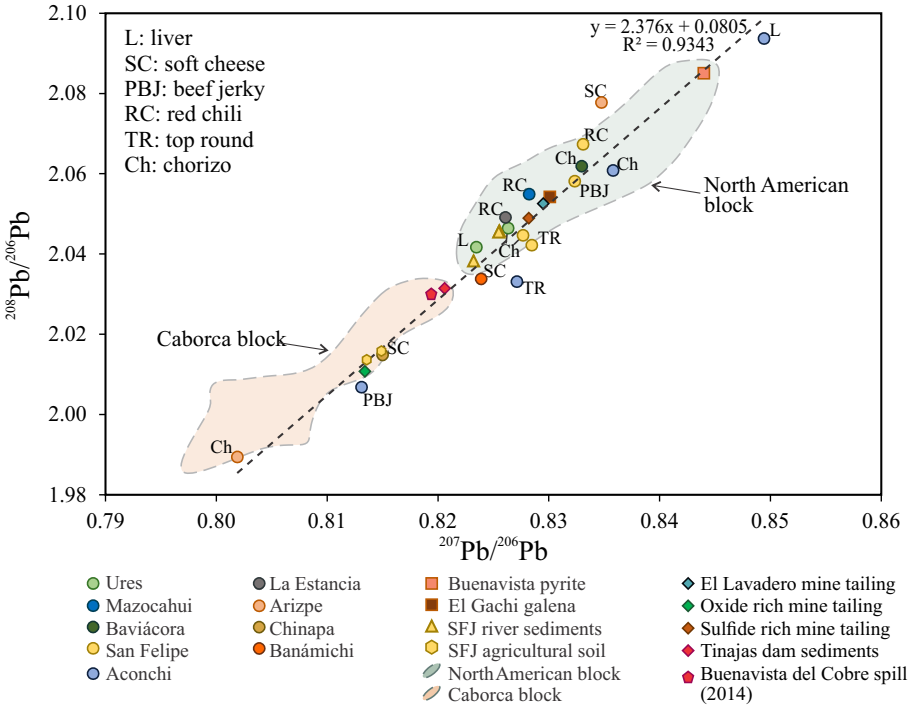


Figure 6. $^{207}Pb/^{206}Pb$ *vs.* $^{208}Pb/^{206}Pb$ diagram showing the composition of samples of edible products collected from localities in the upper Sonora River basin, and the composition of minerals, river sediments, mining waste, and lithologies of the Caborca and North American blocks.

sample related to the mineralization at the Buenavista del Cobre mine closely resembles that of the sediments containing the spilled solution. In contrast, the spilled solution exhibits a more radiogenic signature regarding the $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios, suggesting a mixture with additional components, including chemical reactants used to extract the metals of interest. This suggests that the 2014 spilled solution from Buenavista del Cobre mine has not influenced the composition of food products in the region, as indicated by the Pb composition of watercress from the study area (Romo-Morales *et al.*, 2020). Figure 7 illustrates the sulfide-rich and oxide-rich tailings from San Felipe de Jesús (Del Rio-Salas *et al.*, 2024) and the El Lavadero facility. The latter resembles the composition of the sulfide-rich tailings from San Felipe de Jesús, indicating a link with the sulfide mineralization exploited in the region (*e.g.*, the inactive El Gachi mine; Del Rio-Salas *et al.*, 2024).

Studies of cattle exposed to mining areas yielded higher concentrations of Pb and Cd in the liver and kidneys (Yabe *et al.*, 2011), whereas in beef tissue, the concentrations were within acceptable ranges (*e.g.*, Cai *et al.*, 2009). Similar findings were observed in goats exposed to historical mining areas in southern Mexico (Salgado-Souto *et al.*, 2025), pointing to the effectiveness of Pb isotope signatures in tracing exposure to PTE. However, there is no clear influence of the environment impacted by mining activities (both active and inactive) in the Sonoran River basin. Rather, the Pb isotope composition of most edible food products falls within the area defined by rocks of the North American block, while some are positioned close to its margin. However, human involvement in the preparation process can affect the elemental content of edible products, particularly in shredded beef jerky, chorizo, ground beef, red chili, and farmer's cheese. During preparation, tools, condiments, and other items can alter the Pb isotope composition.

A more detailed comparison between the Pb isotope composition of edible products and the main potential sources of Pb in the region indicates that most samples do not overlap with the compositions defined by mine tailings, mineralization, or the 2014 mine spill and associated sediments. This suggests that these anthropogenic sources have not contributed to the Pb composition of regional food. Most of the edible products are plotted by the field defined by the regional lithologies, particularly those from the North American block, highlighting the geogenic nature of Pb.

Implications

The PTE concentrations in most measured food and food product samples are below the recommended limits set by the FAO/WHO and European Union guidelines, suggesting no contamination in regional products of the study area. A limited number of samples exceeded the recommended Pb values, suggesting local variability rather than a regional pattern. A previous study by Calmus *et al.* (2018) determined the natural geochemical background of the region, considering all the lithological units outcropping in the area; the findings were that some elements of environmental interest (*i.e.*, Pb, Cu, Zn, As, Ag, among others) were slightly enriched with respect to the UCC. These geochemical anomalies may influence the composition of soils and sediments and, ultimately, contribute to the composition of food and food products. The Pb isotope compositions of regional food products support this, as they are similar to the Pb isotope compositions of the lithological units, indicating their geogenic nature and excluding anthropogenic sources, with no clear evidence of mining-related impacts. Although this investigation does not provide a quantitative health risk assessment, the results highlight the importance of monitoring PTE contents in food and food products, particularly in regions where historical mining has been a major economic activity.

Limitations of the study

A limitation of this study is the relatively small number of samples analyzed, which may not fully represent the variability of PTE concentrations throughout the Sonora River basin. Future

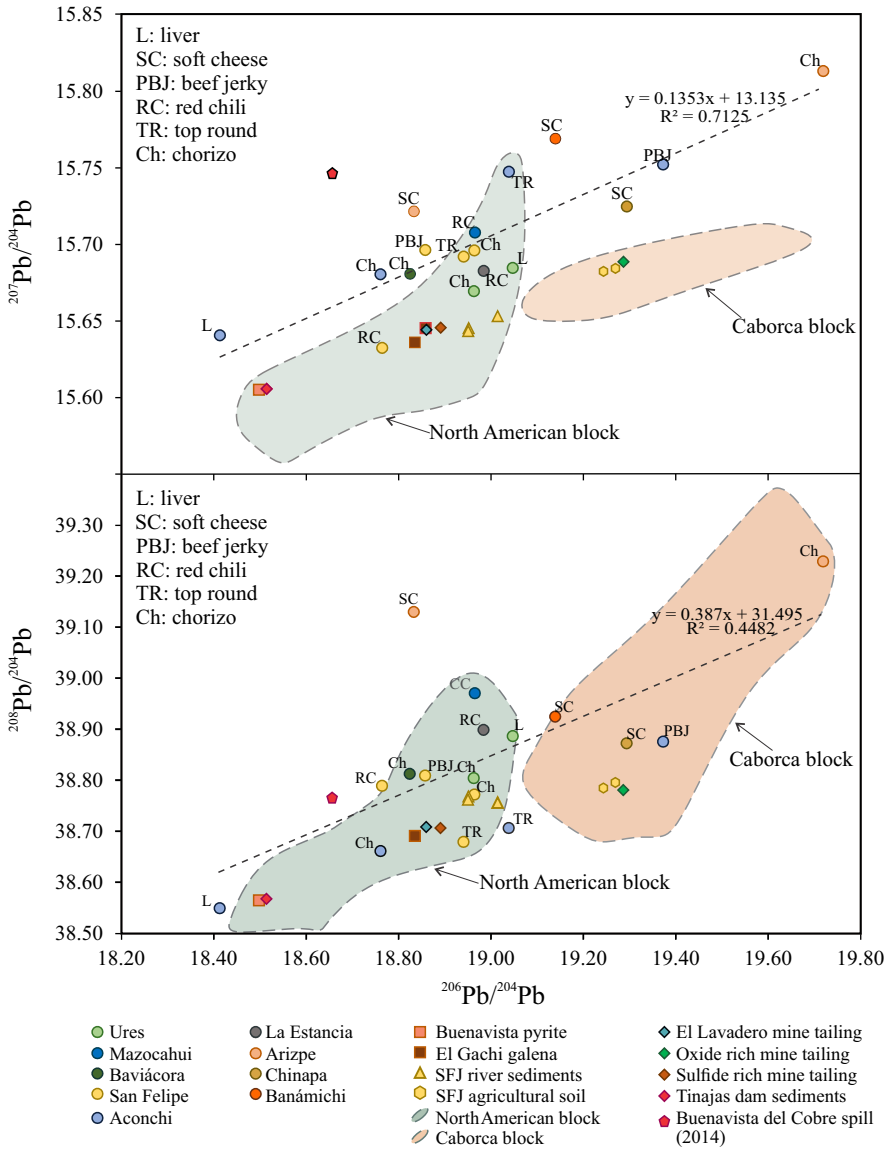


Figure 7. $^{206}Pb/^{204}Pb$ *vs.* $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ *vs.* $^{208}Pb/^{204}Pb$ diagrams for samples of edible products collected from localities in the upper Sonora River basin, and for minerals, river sediments, mining waste, and lithologies of the Caborca and North American blocks.

research should include a larger sample size and adopt a more systematic sampling approach to improve statistical data and spatial representativity. Moreover, this study lacks detailed data on food consumption patterns (frequency and amount) and dietary surveys. Future studies should include this information to provide a more complete context for the presence of PTE in food products, and ultimately, perform a risk assessment.

CONCLUSIONS

The concentrations of Al, As, Ba, Cd, Cr, Cu, Fe, Ni, Pb, and Zn found in regional foods, including chorizo, liver, top round, shredded beef jerky, farmer's cheese, and red chili, commonly consumed in the upper Sonoran River basin, showed variations among the different settlements. When using the Upper Continental Crust as a reference, some of these products exceeded the Cu, Zn, and Cd levels, which may be due to the region's natural geochemical anomaly. However, limited processed foods, such as chorizo and beef jerky, exceeded the Pb limits set by the FAO/WHO and the European Union, indicating isolated variability rather than a consistent regional contamination pattern. Most of the Pb isotope compositions of these regional edible products fall within the compositional field of North American block rocks, indicating that Pb is mainly derived from geogenic sources, with no clear evidence of significant influence from mining activities (both active and inactive). Variability in isotope composition may be related to the preparation process, where human involvement can influence elemental content, especially in shredded beef jerky, chorizo, ground beef, red chili, and farmer's cheese. These findings highlight the value of Pb isotope systematics as a tool for tracing contamination sources in food systems, even at low concentrations.

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Declaration of competing interests. The authors declare that they have no financial, academic, or personal relationships that could be perceived as influencing the research presented in this manuscript. The study was conducted independently of any organizations or individuals that could benefit from the results.

Data availability statement. All data utilized in this study are fully available and are provided in the accompanying tables.

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REFERENCES

Aguilar-Hinojosa, Y., Meza-Figueroa, D., Villalba-Atondo, A. I., Encinas-Romero, M. A., Valenzuela-García, J. L., & Gómez-Álvarez, A. (2016). Mobility and bioavailability of metals in stream sediments impacted by mining activities: the Jaralito and the Mexicana in Sonora, Mexico. *Water, Air, & Soil Pollution*, *227*(9), 345. https://doi.org/10.1007/s11270-016-3046-1

Anderson, T. H., & Silver, L. T. (1977). U-Pb isotope ages of granitic plutons near Cananea, Sonora. *Economic Geology, 72*(5), 827-836.

Anderson, T. H., Silver, L. T., Nourse, J. A., McKee, J. W., & Steiner, M. B. (2005). The Mojave-Sonora megashear-Field and analytical studies leading to the conception and evolution of the hypothesis. In T. H. Anderson, J. A. Nourse, J. W. McKee, M. B. Steiner (Eds.) *The Mojave-Sonora Megashear Hypothesis: Development, Assessment, and Alternatives* (pp. 1-50). Geological Society of America Special Paper 393. https://doi.org/10.1130/0-8137-2393-0.1

Anguebes-Franseschi, F., Abatal, M., Ucán, C. A., Ruiz Marín, A., Tamayo-Ordoñez, F., Canedo-López, Y., Pérez-Reda, L., & Damás-Damas, S. (2023). Determination of the Concentration of Heavy Metals in Artisanal Cheeses Produced in the Mexican States of Tabasco and Chiapas. *Molecules*, *28*(23), 7907. https://doi.org/10.3390/molecules28237907

Ali, M. U., Liu, G., Yousaf, B., Ullah, H., Abbas, Q., & Munir, M. A. M. (2019). A systematic review on global pollution status of particulate matter-associated potential toxic elements and health perspectives in urban environment. *Environmental Geochemistry and Health*, *41*(3), 1131–1162. https://doi.org.10.1007/s10653-018-0203-z

Alturiqi, A. S., & Albedair, L. A. (2012). Evaluation of some heavy metals in certain fish, meat and meat products in Saudi Arabian markets. *The Egyptian Journal of Aquatic Research*, *38*(1), 45–49. https://doi.org/10.1016/j.ejar.2012.08.003

Anawar, H. M. (2015). Sustainable rehabilitation of mining waste and acid mine drainage using geochemistry, mine type, mineralogy, texture, ore extraction and climate knowledge. *Journal of Environmental Management, 158*, 111–121. https://doi.org/10.1016/j.jenvman.2015.04.045

Bi, C., Zhou, Y., Chen, Z., Jia, J., & Bao, X. (2018). Heavy metals and lead isotopes in soils, road dust and leafy vegetables and health risks via vegetable consumption in the industrial areas of Shanghai, China. *Science of The Total Environment*, *619*, 1349–1357. https://doi.org/10.1016/j.scitotenv.2017.11.177

Boente, C., Martín-Méndez, I., Bel-Lan, A., & Gallego, J. R. (2020). A novel and synergistic geostatistical approach to identify sources and cores of Potentially Toxic Elements in soils: An application in the region of Cantabria (Northern Spain). *Journal of Geochemical Exploration*, *208*, 106397. https://doi.org/10.1016/j.gexplo.2019.106397

Bonanno, G., Borg, J. A., & Di Martino, V. (2017). Levels of heavy metals in wetland and marine vascular plants and their biomonitoring potential: A comparative assessment. *Science of the Total Environment*, *576*, 796–806. https://doi.org/10.1016/j.scitotenv.2016.10.171

Bouse, R. M., Ruiz, J., Titley, S. R., Tosdal, R. M., & Wooden, J. L. (1999). Lead isotope compositions of Late Cretaceous and early Tertiary igneous rocks and sulfide minerals in Arizona; implications for the sources of plutons and metals in porphyry copper deposits. *Economic Geology*, *94*(2), 211–244.

Brewer, P. A., Bird, G., & Macklin, M. G. (2016). Isotopic provenancing of Pb in Mitrovica, northern Kosovo: Source identification of chronic Pb enrichment in soils, house dust and scalp hair. *Applied Geochemistry*, *64*, 164–175. https://doi.org/10.1016/j.apgeochem.2015.08.003

Calmus, T., Valencia-Moreno, M., Río-Salas, D., Ochoa-Landín, L., & Mendivil-Quijada, H. (2018). A multi-elemental study to establish the natural background and geochemical anomalies in rocks from the Sonora river upper basin, NW Mexico. *Revista Mexicana de Ciencias Geológicas*, *35*(2), 158-167.

Cai, Q., Long, M. L., Zhu, M., Zhou, Q. Z., Zhang, L., & Liu, J. (2009). Food chain transfer of cadmium and lead to cattle in a lead–zinc smelter in Guizhou, China. *Environmental Pollution*, *157*(11), 3078–3082.

Cheng, H., & Hu, Y. (2010). Lead (Pb) isotopic fingerprinting and its applications in lead pollution studies in China: A review. *Environmental Pollution*, *158*(5), 1134–1146.

Coelho, P., Costa, S., Silva, S., Walter, A., Ranville, J., Sousa, A. C. A., Costa, C., Coelho, M., García-Lestón, J., Pastorinho, M. R., Laffon, B., Pásaro E., Harrington, C., Taylor, A., & Teixeira, J. P. (2012). Metal (loid) levels in biological matrices from human populations exposed to mining contamination—Panasqueira Mine (Portugal). *Journal of Toxicology and Environmental Health, Part A*, *75*(13–15), 893–908.

Del Rio-Salas, R., Ayala-Ramírez, Y., Loredo-Portales, R., Romero, F., Molina-Freaner, F., Minjarez-Osorio, C., Pi-Puig, T., Ochoa–Landín, L., & Moreno-Rodríguez, V. (2019). Mineralogy and geochemistry of rural road dust and nearby mine tailings: a case of ignored pollution hazard from an abandoned mining site in semi-arid zone. *Natural Resources Research*, *28*(4), 1485–1503.

Del Rio-Salas , R., Moreno-Rodríguez, V., Loredo-Portales, R., Salgado-Souto, S. A., Valencia-Moreno, M., Ochoa-Landín, L., & Romo-Morales, D. (2024). Traceability and dispersion of highly toxic soluble phases from historical mine tailings: insights from Pb isotope systematics. *Environmental Geochemistry and Health*, *46*(10), 395.

Del Rio-Salas, R., Moreno-Rodríguez, V., Loredo-Portales, R., Salgado-Souto, S., Rader, S., Valencia-Moreno, M., Romo-Morales, D., Aguirre-Noyola, J. L., & Ramos-Pérez, D. (2025). Do efflorescent salts from worn lead-acid automotive batteries represent potential non-exhaust emissions to urban pollution? A Pb isotope perspective. *Journal of Hazardous Materials*, 137366.

Deniel, C., & Pin, C. (2001). Single-stage method for the simultaneous isolation of lead and strontium from silicate samples for isotopic measurements. *Analytica Chimica Acta*, *426*(1), 95–103.

Díaz-Caravantes, R. E., Duarte-Tagles, H., & Durazo-Gálvez, F. M. (2016). Amenazas para la salud en el Río Sonora: análisis exploratorio de la calidad del agua reportada en la base de datos oficial de México. *Salud UIS*, *48*(1), 91–96.

Dickin, A. P. (2018). *Radiogenic isotope geology*. Cambridge University Press.

Dickinson, W. R., & Lawton, T. F. (2001). Carboniferous to Cretaceous assembly and fragmentation of Mexico. *Geological Society of America Bulletin*, *113*(9), 1142–1160.

Duan, X. C., Yu, H. H., Ye, T. R., Huang, Y., Li, J., Yuan, G. L., & Albanese, S. (2020). Geostatistical mapping and quantitative source apportionment of potentially toxic elements in top-and sub-soils: A case of suburban area in Beijing, China. *Ecological Indicators*, *112*, 106085.

Escobar-Quiroz, I. N., Villalobos-Peñalosa, M., Pi-Puig, T., Romero, F. M., & Aguilar-Carrillo de Albornoz, J. (2019). Identification of jarosite and other major mineral Fe phases in acidic environments affected by

mining-metallurgy using X-ray Absorption Spectroscopy: With special emphasis on the August 2014 Cananea acid spill. *Revista Mexicana de Ciencias Geológicas*, *36*(2), 229–241.

European Union [EU] (2023). *Commission Regulation (EU) 2023/915 of 25 April 2023 on Maximum Levels for Certain Contaminants in Food and Repealing Regulation (EC) No 1881/2006*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02023R0915-20251008.

Food and Agriculture Organization of the United Nations [FAO)], & World Health Organization [WHO], 2023, General standard for contaminants and toxins in food and feed (CXS 193-1995). *Codex Alimentarius; International Food Standards*.

Foreign Agriculture Service [FAS], 2022, *China Releases the Standard for Maximum Levels of Contaminants in Foods* (Report number CH2023-0040). United States Department of Agriculture.

Galeana-Pizaña, J. M., Verdeja-Vendrell, L., González-Gómez, R., & Tapia-McClung, R. (2023). Spatio-temporal patterns of the mortality of diseases associated with malnutrition and their relationship with food establishments in Mexico. *Spatial and Spatio-temporal Epidemiology*, *47*, 100619.

Galer, S. J. G., & Abouchami, W. (1998). Practical application of lead triple spiking for correction of instrumental mass discrimination. *Mineralogical Magazine*, *62*, 491–492. DOI:10.1180/MINMAG.1998.62A.1.260

Gans, P.B. (1997). Large-magnitude Oligo-Miocene extension in southern Sonora: Implications for the tectonic evolution of northwest Mexico: *Tectonics*, *16*(3), 388–408.

González-Becuar, E., Pérez-Segura, E., Vega-Granillo, R., Solari, L., González-León, C. M., Solé, J., & Martínez, M. L. (2017). Laramide to Miocene syn-extensional plutonism in the Puerta del Sol area, central Sonora, Mexico. *Revista Mexicana de Ciencias Geológicas*, *34*(1), 45–61.

González-León, C. M., Solari, L., Solé, J., Ducea, M. N., Lawton, T. F., Bernal, J. P., González Becuar, E., Gray, F., López Martínez, M., & Lozano Santacruz, R. (2011). Stratigraphy, geochronology, and geochemistry of the Laramide magmatic arc in north-central Sonora, Mexico. *Geosphere*, *7*(6), 1392–1418.

Grijalva-Noriega, F. J. & Roldán-Quintana, J. R., (1998). An overview of the Cenozoic tectonic and magmatic evolution of Sonora, northwestern Mexico. *Revista Mexicana de Ciencias Geológicas*, *15*(2), 145–156.

Han, J. L., Pan, X. D., & Chen, Q. (2022). Distribution and safety assessment of heavy metals in fresh meat from Zhejiang, China. *Scientific Reports*, *12*(1), 3241.

Ihedioha, J. N., Ukoha, P. O., & Ekere, N. R. (2017). Ecological and human health risk assessment of heavy metal contamination in soil of a municipal solid waste dump in Uyo, Nigeria. *Environmental Geochemistry and Health*, *39*(3), 497–515.

Iriondo, A., & Premo, W. R. (2011). Las rocas cristalinas proterozoicas de Sonora y su importancia para la reconstrucción del margen continental SW de Laurencia—La pieza mexicana del rompecabezas de Rodinia. In T. Calmus (Ed.) *Panorama de la Geología de Sonora, México*. Instituto de Geología. UNAM, Boletín 118, 25–55.

Jiang, Y., Chao, S., Liu, J., Yang, Y., Chen, Y., Zhang, A., & Cao, H. (2017). Source apportionment and health risk assessment of heavy metals in soil for a township in Jiangsu Province, China. *Chemosphere*, *168*, 1658–1668.

Kamunda, C., Mathuthu, M., & Madhuku, M. (2016). Health risk assessment of heavy metals in soils from Witwatersrand gold mining basin, South Africa. *International Journal of Environmental Research and Public Health*, *13*(7), 663. DOI: 10.3390/ijerph13070663

Khan, A., Khan, S., Lei, M., Alam, M., Khan, M. A., & Khan, A. (2020). Biochar characteristics, applications and importance in health risk reduction through metal immobilization. *Environmental Technology & Innovation*, *20*, 101121.

Komárek, M., Ettler, V., Chrastný, V., & Mihaljevič, M. (2008). Lead isotopes in environmental sciences: A review. *Environment international*, *34*(4), 562–577.

Lee, S., Shin, D., Han, C., Choi, K. S., Do Hur, S., Lee, J., Byun, D. S., Kim, Y. T, & Hong, S. (2019). Characteristic concentrations and isotopic composition of airborne lead at urban, rural and remote sites in western Korea. *Environmental Pollution*, *254*, 113050.

León-García, G. J., Gómez-Álvarez, A., Meza-Figueroa, D. M., Valenzuela-García, J. L., Encinas-Romero, M. A., Villalba-Atondo, A. I., Centeno-García, E. & Encinas-Soto, K. K. (2021). Assessment of heavy metal pollution in sediments of the Sonora River basin impacted by mining activities. *Environmental Progress & Sustainable Energy*, *41*(3), e13796.

Li, Z., Ma, Z., van der Kuijp, T. J., Yuan, Z., & Huang, L. (2014). A review of soil heavy metal pollution from mines in China: pollution and health risk assessment. *Science of the total environment*, *468*, 843–853.

Liu, C.-P., Luo, C.-L., Gao, Y., Li, F.-B., Lin, L.-W., Wu, C.-A., & Li, X.-D. (2010). Arsenic contamination and potential health risk implications at an abandoned tungsten mine, southern China. *Environmental Pollution*, *158*(3), 820–826.

Loredo, J., Ordóñez, A., Charlesworth, S., & De Miguel, E. (2003). Influence of industry on the geochemical urban environment of Mieres (Spain) and associated health risk. *Environmental Geochemistry and Health*, *25*(3), 307–323.

Loredo-Portales, R., Bustamante-Arce, J., González-Villa, H. N., Moreno-Rodríguez, V., Del Rio-Salas, R., Molina-Freaner, F., González-Méndez, B., & Archundia-Peralta, D. (2020). Mobility and Accessibility of Zn, Pb, and As in abandoned mine tailings of northwestern Mexico. *Environmental Science and Pollution Research*, 1–16.

Marrugo-Negrete, J., Pinedo-Hernández, J. & Díez, S. (2017). Assessment of heavy metal pollution, spatial distribution and origin in agricultural soils along the Sinú River Basin, Colombia. *Environmental Research*, *154*, 380–388.

Mauel, D. J., Lawton, T. F., González-León, C., Iriondo, A., & Amato, J. M. (2011). Stratigraphy and age of Upper Jurassic strata in north-central Sonora, Mexico: Southwestern Laurentian record of crustal extension and tectonic transition. *Geosphere*, *7*(2), 390–414.

Mihaljevič, M., Baieta, R., Ettler, V., Vaněk, A., Kříbek, B., Penížek, V., Drahota, P., Trubač, J., Sracek, O., Chrastný, V., & Mapani, B. S. (2019). Tracing the metal dynamics in semi-arid soils near mine tailings using stable Cu and Pb isotopes. *Chemical Geology*, *515*, 61–76.

More, S. J., Bampidis, V., Benford, D., Bragard, C., Halldorsson, T. I., Hernández-Jerez, A. F., Hougaard Bennekou, S., Koutsoumanis, K., Lambré, C., Machera, K., Mullins, E., Søren Saxmose, N., Schlatter, J. R., Schrenk, D., Turck, D., Younes, M., Boon, P., Ferns, G. A. A., Lindtner, O., ... Leblanc, J. C. (2023). Re-evaluation of the existing health-based guidance values for copper and exposure assessment from all sources. *EFSA Journal*, *21*(1). https://doi.org/10.2903/j.efsa.2023.7728.

Müller, A., Österlund, H., Marsalek, J., & Viklander, M. (2020). The pollution conveyed by urban runoff: A review of sources. *Science of the Total Environment*, *709*, 136125.

National Institutes of Health, Office of Dietary Supplements (2024). *Copper; Fact Sheet for Health Professionals*. U.S. Department of Health & Human Services. https://ods.od.nih.gov/factsheets/Copper-HealthProfessional/#h15

National Toxicology Program (2021). *Report on Carcinogens* (15th ed.). U.S. Department of Health and Human Services. https://ntp.niehs.nih.gov/go/roc15

Nerín, C., Aznar, M., & Carrizo, D. (2016). Food contamination during food process. *Trends in Food Science & Technology*, *48*, 63–68.

Niede, R., & Benbi, D. K. (2022). Integrated review of the nexus between toxic elements in the environment and human health. *AIMS Public Health*, *9*(4), 758–789.

Noguez-Alcántara, B. (2008). *Reconstrucción del modelo genético y evolución tectónica del yacimiento tipo pórfido cuprífero Milpillas, Distrito de Cananea, Sonora, Mexico* [Unpublished doctoral dissertation]. Universidad Nacional Autónoma de México.

Page, W. R., Gray, F., Iriondo, A., Miggins, D., Blodgett, R. B., Maldonado, F., & Miller, R. J. (2010). Stratigraphy and Mesozoic–Cenozoic tectonic history of northern Sierra Los Ajos and adjacent areas, Sonora, Mexico. *Journal of South American Earth Sciences*, *29*(3), 557–571.

Pakdel, M., Olsen, A., & Bar, E. M. S. (2023). A review of food contaminants and their pathways within food processing facilities using open food processing equipment. *Journal of Food Protection*, *86*(12), 100184.

Pan, L., Wang, Y., Ma, J., Hu, Y., Su, B., Fang, G., Wang, L., & Xiang, B. (2018). A review of heavy metal pollution levels and health risk assessment of urban soils in Chinese cities. *Environmental Science and Pollution Research*, *25*(2), 1055–1069.

Peña-Leal, J.L., Zamora-Tovar, R.E., Núñez-Othon, A., & Orantes-Contreras, V. (1999). *Carta geológica minera Hermosillo H12-8, 1: 250,000*. Servicio Geológico Mexicano.

Peña-Ortega, M., Del Rio-Salas, R., Valencia-Sauceda, J., Mendívil-Quijada, H., Minjarez-Osorio, C., Molina-Freaner, F., de la O-Villanueva, M., & Moreno-Rodríguez, V. (2019). Environmental assessment and historic erosion calculation of abandoned mine tailings from a semi-arid zone of northwestern Mexico: insights from geochemistry and unmanned aerial vehicles. *Environmental Science and Pollution Research*, *26*, 26203–26215.

Pérez-Quezadas, J., Adams, D., Sánchez-Murillo, R., Jiménez-Lagunes, A., & Rodríguez-Castañeda, J. L. (2021). Isotopic variability (δ18O, δ2H and d-excess) during rainfall events of the north American monsoon across the Sonora River Basin, Mexico. *Journal of South American Earth Sciences*, *105*, 102928. https://doi.org/10.1016/j.jsames.2020.102928

Reddy, Y. S., Sunitha, V., & Suvarna, B. (2022). Physical and Hydro Geochemical Impact Assessment of Inactive Mines in and Around Southwestern Part of Cuddapah Basin Using a Conceptual Site Model (CSM). In Dikshit, A.K., Narasimhan, B., Kumar, B., Patel, A.K. (Eds.) *Innovative Trends in Hydrological and Environmental Systems. Select Proceedings of ITHES 2021* (pp. 793-807). Springer. https://doi-org.pbidi.unam.mx:2443/10.1007/978-981-19-0304-5_55

Rehman, I., Ishaq, M., Muhammad, S., Din, I. U., Khan, S., & Yaseen, M. (2020). Evaluation of arsenic contamination and potential risks assessment through water, soil and rice consumption. *Environmental Technology & Innovation*, *20*, 101155.

Reyes-Pablo, A. E., Campa-Córdoba, B. B., Luna-Viramontes, N. I., Ontiveros-Torres, M. Á., Villanueva-Fierro, I., Bravo-Muñoz, M., Sáenz-Ibarra, B., Barbosa, O., Guadarrama-Ortíz, P., Garcés-Ramírez, L., de la Cruz, F., Harrington, C.R., Martínez-Robles, S., González-Ballesteros, E., Perry, G., Pacheco-Herrero, M., & Luna-Muñoz, J. (2020). National dementia BioBank: a strategy for the diagnosis and study of neurodegenerative diseases in Mexico. *Journal of Alzheimer's Disease*, *76*(3), 853–862.

Rivera-Uria, M. Y., Ziegler-Rivera, F. R. A., Díaz-Ortega, J., Prado-Pano, B. L., & Romero, F. M. (2018). Effect of an acid mine spill on soils in Sonora River Basin: Micromorphological indicators. *Spanish Journal of Soil Science*, *8*, 258 – 274.

Robles-Morua, A., Che, D., Mayer, A. S., & Vivoni, E. R. (2015). Hydrological assessment of proposed reservoirs in the Sonora River Basin, Mexico, under historical and future climate scenarios. *Hydrological Sciences Journal*, *60*(1), 50–66.

Rodríguez-Marín, N., Hardisson, A., Gutiérrez, Á. J., Luis-González, G., González-Weller, D., Rubio, C., Paz, S. (2019). Toxic (Al, Cd, and Pb) and trace metal (B, Ba, Cu, Fe, Mn, Sr, and Zn) level in tissues of slaughtered steers: risk assessment for the consumers. *Environmental Science and Pollution Research*, *26*(28), 28787–28795.

Roldán-Quintana, J. (1991). Geology and chemical composition of the Jaralito and Aconchi batholiths in east-central Sonora, Mexico. In E. Pérez-Segura, & C. Jacques-Ayala, *Studies of Sonoran Geology*,. Geological Society of America. https://doi.org/10.1130/SPE254-p69

Romero, F. M., Armienta, M. A., & González-Hernández, G. (2007). Solid-phase control on the mobility of potentially toxic elements in an abandoned lead/zinc mine tailings impoundment, Taxco, Mexico. *Applied Geochemistry*, *22*(1), 109–127.

Romero-Lázaro, E. M., Ramos-Pérez, D., Romero, F. M., & Sedov, S. (2019). Indicadores indirectos de contaminación residual en suelos y sedimentos de la cuenca del Río Sonora, México. *Revista Internacional de Contaminación Ambiental*, *35*(2), 371–386.

Romo-Morales, D., Moreno-Rodríguez, V., Molina-Freaner, F., Valencia-Moreno, M., Ruiz, J., Minjárez-Osorio, C., Hernández-Mendiola, E., & del Rio-Salas, R. (2020). Assessment of Geogenic and Anthropogenic Pollution Sources Using an Aquatic Plant Along the Sonora River Basin: Insights from Elemental Concentrations and Pb Isotope Signatures. *Natural Resources Research*, 1–14.

Rubinos, D. A., Jerez, Ó., Forghani, G., Edraki, M., & Kelm, U. (2021). Geochemical stability of potentially toxic elements in porphyry copper-mine tailings from Chili as linked to ecological and human health risks assessment. *Environmental Science and Pollution Research*, *28*(41), 57499–57529.

Rudnick, R. L., & Gao, S. (2003). Composition of the continental crust. In Holland, H. D., & Turekian, K. K. (Eds.), *Treatise of Geochemistry*, *v. 3 The Crust* (pp. 1-64). Elsevier.

Salgado-Souto, S. A., Escorcia-Reynoso, M. U., Del Rio-Salas, R., Talavera-Mendoza, O., Bottini-Luzardo, M. B., Núñez-Martínez, G., Aguirre-Noyola, J. L., & Hernández-Flores, G. (2025). Assessing bioaccumulation of Pb, Cd, and As in Goats: Impacts of exposure to mine tailings in a polymetallic mining region. *Journal of South American Earth Sciences*, 105372. https://doi.org/10.1016/j.jsames.2025.105372

Sandoval-Godoy, S. A., & Camarena-Gómez, D. M. (2012). Consumo de alimentos de la población sonorense: tradición versus internacionalización. *Estudios Sociales*, (2), 52–72.

Stegink, T. G., & Rader, S. T. (2024). Lead Translocation and Isotopic Fractionation after Uptake by Brassica juncea (Brown Mustard). *ACS Earth and Space Chemistry*, *8*(11), 2187–2197. https://doi.org/10.1021/acsearthspacechem.4c00174

Valencia-Moreno, M., López-Martínez, M., Orozco-Esquivel, T., Ferrari, L., Calmus, T., Noury, M., & Mendívil-Quijada, H. (2021). The Cretaceous-Eocene Mexican Magmatic Arc: Conceptual framework from geochemical and geochronological data of plutonic rocks. *Earth-Science Reviews*, *220*, 103721. https://doi.org/10.1016/j.earscirev.2021.103721

Valenzuela-Navarro, L. C., Valencia-Moreno, M., Thierry-Calmus, L. O. L., & González-León, C. (2005). Marco geológico del pórfido de molibdeno El Crestón, Sonora central, México. *Revista Mexicana de Ciencias Geológicas*, *22*(3), 345-357.

Villerías Alarcón, I., & Juárez Gutiérrez, M. C. (2021). México: Las enfermedades crónico degenerativas (diabetes mellitus e hipertensión) y la vulnerabilidad ante el COVID-19 a un año de la pandemia. *Posición. Revista del Instituto de Investigaciones Geográficas*, (5), 1–11.

Wang, X., Zhang, Y., Geng, Z., Liu, Y., Guo, L., & Xiao, G. (2019). Spatial analysis of heavy metals in meat products in China during 2015–2017. *Food Control*, *104*, 174–180. https://doi.org/10.1016/j.foodcont.2019.04.033

Yabe, J., Nakayama, S. M., Ikenaka, Y., Muzandu, K., Ishizuka, M., & Umemura, T. (2011). Uptake of lead, cadmium, and other metals in the liver and kidneys of cattle near a lead-zinc mine in Kabwe, Zambia. *Environmental Toxicology and Chemistry*, *30*(8), 1892–1897. https://doi.org/10.1002/etc.580

Yoo, E.-J., Lee, J.-A., Park, J.-S., Lee, K., Lee, W.-S., Han, J.-S., & Choi, J.-W. (2014). Tracing lead pollution sources in abandoned mine areas using stable Pb isotope ratios. *Environmental Monitoring and Assessment*, *186*, 781–789. https://doi.org/10.1007/s10661-013-3416-8

Yu, A., Yang, Q., Xu, B., Yang, Y., Ren, Z., & Li, K. (2024). Analysis of lead contamination sources in roadside soil via the isotope tracing method. *Journal of Environmental Chemical Engineering*, *12*(6), 114205. https://doi.org/10.1016/j.jece.2024.114205

Zhao, R., Yan, S., Liu, M., Wang, B., Hu, D., Guo, D., Wang, J., Xu, W., & Fan, C. (2016). Seafood consumption among Chinese coastal residents and health risk assessment of heavy metals in seafood. *Environmental Science and Pollution Research*, *23*(16), 16834–16844. https://doi.org/10.1007/s11356-016-6817-8

Zhou, L. Q., & Liu, W. Z. (2024). Pollution of four heavy metal elements in dried chili peppers in Guizhou Province and its health risk assessment. *Scientific Reports*, *14*(1), 17759. https://doi.org/10.1038/s41598-024-68564-8

Zhou, Y., Wang, L., Xiao, T., Chen, Y., Beiyuan, J., She, J., Zhou, Y., Yin, M., Liu, J., Liu, Y., Wang, Y., & Wang, Y. (2020). Legacy of multiple heavy metal (loid)s contamination and ecological risks in farmland soils from a historical artisanal zinc smelting area. *Science of The Total Environment*, *720*. https://doi.org/10.1016/j.scitotenv.2020.137541