







Arsenic levels in humans and water sources for human consumption in Peru: A systematic review

Niveles de arsénico en humanos y fuentes de agua para consumo humano en el Perú: Una revisión sistemática

Rocío Lorena Adama Victorio¹ , Katherine Shirley Arango Chumpitazi¹ , Rodrigo Vargas-Fernández² , Fabriccio J. Visconti-Lopez¹ , Daniel Comandé³ , Akram Hernández-Vásquez⁴ 

- 1 Universidad Científica del Sur. Lima, Peru.
- 2 Epidemiology and Health Economics Research (EHER), Universidad Científica del Sur. Lima, Peru.
- 3 Institute for Clinical Effectiveness and Health Policy (IECS-CONICET). Buenos Aires, Argentina.
- 4 Centro de Excelencia en Investigaciones Económicas y Sociales en Salud, Vicerrectorado de Investigación, Universidad San Ignacio de Loyola. Lima, Peru.



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*Corresponding author:
ahernandez@usil.edu.pe

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ABSTRACT

In Peru, the high toxicity of arsenic constitutes a public health issue; however, data on its presence in water and human biomarkers is limited. The aim of this systematic review was to synthesize the evidence regarding reported arsenic levels in humans and drinking water in Peru. A systematic search was conducted on July 19, 2024, across eight databases (PubMed, WOS Core Collection, Scopus, Embase, CINAHL, CABI, LILACS and SciELO) using the search terms "Arsenic poisoning", "Arsenicals", "Arsenic" and "Peru". We included studies that contained data on reported arsenic levels in humans and drinking water. Our search identified 967 records, of which 21 were studies: 11 focused on human biomarkers (urine, blood, hair, nails and breast milk); 8 on water samples (groundwater, surface water and potable water), and; 2 studies addressed both scenarios. The highest concentrations of arsenic in humans were reported in Tacna, Junín and Apurímac, whereas the highest concentrations in water samples were observed in Puno, Junín, Lima, Ucayali and Tacna. Human studies reported arsenic concentrations ranging from 5.27 µg/L in urine to levels exceeding 424 µg/L; in blood, values ranged from 0.64 µg/L to 1.43 µg/dL. In water samples, average arsenic concentrations ranged from 12.2 µg/L to 54.5 µg/L, surpassing the established reference limits. These findings indicate high arsenic levels, underscoring the need to strengthen surveillance systems and implement mitigation strategies tailored to the specific conditions of each region. Our systematic review was registered in PROSPERO (CRD42022375707).

Keywords: Arsenic poisoning, arsenicals, arsenic, Peru

RESUMEN

En el Perú, el arsénico representa un problema de salud pública debido a su alta toxicidad; sin embargo, los datos sobre su presencia en el agua y en biomarcadores humanos son limitados. Esta revisión sistemática tuvo como objetivo sintetizar la evidencia relacionada con los niveles de arsénico reportados en humanos y en el agua potable en el Perú. El 19 de julio de 2024 se realizó una búsqueda sistemática en ocho bases de datos (PubMed, WOS Core Collection, Scopus, Embase, CINAHL, CABI, LILACS y SciELO) utilizando los términos de búsqueda "Arsenic Poisoning", "Arsenicals", "Arsenic" y "Peru". Se incluyeron estudios que proporcionaban datos sobre los niveles de arsénico notificados en seres humanos y en el agua potable. La búsqueda identificó 967 registros, de los cuales se incluyeron 21 estudios: 11 se centraron en biomarcadores humanos (orina, sangre, cabello, uñas y leche materna), 8 en muestras de agua (aguas subterráneas, aguas superficiales y agua potable) y 2 estudios abarcaron ambos escenarios. Las concentraciones más altas de arsénico en humanos se registraron en Tacna, Junín y Apurímac, mientras que las concentraciones más altas en muestras de agua se observaron en Puno, Junín, Lima, Ucayali y Tacna. Los estudios en humanos informaron concentraciones de arsénico que oscilaban entre 5,27 µg/L en la orina y niveles superiores a 424 µg/L; en la sangre, los valores variaban entre 0,64 µg/L y 1,43 µg/dL. En las muestras de agua, las concentraciones medias de arsénico oscilaron entre 12,2 µg/L y 54,5 µg/L, cifras que superaron los límites de referencia establecidos. Estos hallazgos indican niveles elevados de arsénico, lo que subraya la necesidad de reforzar los sistemas de vigilancia y aplicar estrategias de mitigación adaptadas a las condiciones específicas de cada región. La revisión sistemática se registró en PROSPERO (CRD42022375707).

Palabras clave: intoxicación por arsénico, compuestos arsenicales, arsénico, Perú



Introduction

The presence of arsenic in drinking water supplies exceeding the 10 µg/L limit established by the World Health Organization (WHO, 2022a) constitutes a public health issue. While the United Nations' Sustainable Development Goal 6.3 calls for the improvement of water quality by 2030, by reducing pollution, eliminating discharges and minimizing the release of hazardous chemicals and materials (Sachs *et al.*, 2022), in 2013, more than 200 million people were exposed to arsenic (Rahaman *et al.*, 2021). The highest figures were reported in Asian countries such as Bangladesh and South American countries such as Chile and Argentina (Naujokas *et al.*, 2013). Worldwide, in 2021, more than 290,000 disability-adjusted life years and over 10,000 deaths were attributed to arsenic exposure (Institute for Health Metrics and Evaluation, 2021). Measures to counteract this global problem include regular monitoring and surveillance in order to maintain arsenic concentrations below the recommended limit. The WHO emphasizes the need for the implementation of water safety plans in order to identify, evaluate and manage risks throughout the entire water cycle, from source to final consumption (Luo *et al.*, 2025; WHO, 2022b).

Across Latin America and the Caribbean, in 2009, approximately 4.5 million people were reported as being exposed to drinking water with concentrations of arsenic exceeding 50 µg/L. This problem is attributed in large part to the natural mobilization of arsenic from volcanic rocks and sulfide mineral oxidation processes, compounded by anthropogenic activities such as mining (Bundschuh *et al.*, 2012). In fact, based on the 10 µg/L limit, the estimated figure is closer to 14 million people in at least 14 different countries, with Argentina, Chile and Mexico being the most seriously affected (Bundschuh *et al.*, 2012). According to the WHO, in Peru, the arsenic limit in drinking water is 0.01 mg/L (10 µg/L) (WHO, 2022a). This figure was adopted by the Peruvian state in 2010 with the approval of the Drinking Water Quality regulatory framework, replacing the previous limit of 0.05 mg/L (Ticona Castro *et al.*, 2019). Despite this increase in the cutoff point, it has been reported that around 35% of residents in the regions of Puno, Moquegua and Tacna are exposed to high arsenic concentrations, ranging from 25 µg/L to ≥50 µg/L (Fano-Sizgorich *et al.*, 2021; Medina-Pizzali *et al.*, 2018). This figure may be attributable to lack of access to reliable and safe water for household consumption, as well as to human activities such as artisanal mining, and natural factors such as volcanic ash emissions resulting from tectonic movement (Abebe *et al.*, 2023).

Despite growing concern regarding arsenic exposure in Peru, actual knowledge related to specific levels of this metalloid, both in the population and in drinking water, remains insufficient and fragmented. Resulting in

both acute and chronic health effects, arsenic exposure, particularly in its inorganic form, constitutes a public health problem. The symptoms of acute arsenic poisoning can include nausea, vomiting, abdominal pain and diarrhea, and in severe cases may progress to neurological manifestations, renal injury, cardiovascular collapse and death (Kuivenhoven and Mason, 2026). Long-term exposure has been associated with carcinogenic and non-carcinogenic outcomes, including skin pigmentation changes, hyperkeratosis, cardiovascular disease, diabetes, respiratory disease, renal impairment, peripheral neuropathy, adverse pregnancy outcomes and cognitive development deficits (Rodríguez Padilla, 2021; Swedish Council on Health Technology Assessment, 2017). In particular, inorganic arsenic, the most toxic form, has been associated with an increased risk of hypertension and coronary heart disease, peripheral neuropathy and neurobehavioral alterations, even contributing to Type 2 diabetes, through the dysfunction of pancreatic β-cells and insulin resistance (Baker *et al.*, 2018; Rahaman *et al.*, 2021).

It is in this context that our aim in this study was to synthesize and analyze the available scientific evidence evaluating the presence of arsenic in humans and drinking water in Peru. By organizing the existing evidence, the aim of our research was to provide an overview of arsenic exposure throughout Peru. Through our findings, we hope to provide support for the formulating of public policy, mitigation strategies and measures aimed at improving water quality and reducing the risks associated with chronic arsenic exposure.

Materials and methods

Study type

For our study, we adopted the methodology of a systematic review, without meta-analysis of the biomedical literature. In order to ensure a rigorous and transparent presentation of our methods and findings, we followed, as applicable, the PRISMA and SWiM recommendations (Campbell *et al.*, 2020; Page *et al.*, 2021). Initial search was conducted in PROSPERO, in order to determine whether or not any recent or ongoing systematic review on the subject existed. Following this search, we registered our study in PROSPERO, with registration number CRD42022375707.

Formulation of the research question

The research question for this study was as follows: What levels of arsenic in humans and in drinking water in Peru are reported in the available biomedical literature?

In the structuring of this human-oriented question, the PEO (Population, Exposure and Outcomes) format was used:

Population: The general population residing in Peru.

Exposure: Exposure to arsenic from any source.

Outcomes: Arsenic levels in biological samples.

Sources of information and search strategy

The literature search was conducted across the following electronic databases: PubMed, Embase, Web of Science Core Collection, Scopus, CINAHL (Cumulative Index to Nursing and Allied Health Literature), CABI (Commonwealth Agricultural Bureaux International), LILACS (Latin American and Caribbean Literature in Health Sciences) and SciELO (Scientific Electronic Library Online) on July 19, 2024.

The search terms used included "Arsenic poisoning", "Arsenicals", "Arsenic" and "Peru". These terms were combined using Boolean operators (AND/OR) to focus on studies related to arsenic exposure or contamination in the Peruvian context, with "Peru" as a mandatory term, combined with any of the arsenic-related terms. The search strategy was conducted in English, with additional searches using Spanish equivalents in Latin American databases (LILACS and SciELO). The preliminary search strategy was conducted in PubMed and later adapted to the other databases. The design and validation of the strategy were carried out using the PRESS checklist, in order to identify and correct possible typographical errors or omissions (McGowan *et al.*, 2016). No restrictions were applied with regard to language, study type or publication period. The full electronic search strategy for all the databases is provided in the Supplementary Material.

Grey literature sources, such as theses, government reports or technical reports, were not included, in order to limit the analysis to studies published in peer-reviewed journals.

Eligibility criteria

The following inclusion and exclusion criteria were established:

- Inclusion: Peer-reviewed articles reporting arsenic measurements in human biological samples or water samples, including potable water and natural sources used for human consumption (surface and groundwater). Studies conducted in Peru, published in English, Spanish or Portuguese, available in full text, with no publication year restrictions, and with sufficient data to assess reported arsenic levels (either in quantitative form or as percentages above the limits).
- Exclusion: Editorials, letters to the editor, conference abstracts, reports and case series, multi-centric or multinational studies without Peru-specific data, and publications that did not undergo peer review.

Study selection

The records identified were exported to EndNote X9 for duplicate removal by one of the authors

(DC). Subsequently, an initial screening of titles and abstracts was performed using Rayyan, followed by a full-text evaluation. These processes were carried out independently and blindly by two authors (AVRL and ACKS). Discrepancies were resolved by consensus or by the intervention of a third researcher (AHV).

Data extraction and synthesis

Relevant data were extracted independently and blindly using a template created in Google Sheets, which included variables such as author, journal, study design, geographic area, population characteristics and reported arsenic levels. In cases of missing data, the corresponding authors were contacted for additional information. The extracted data were verified and validated by a team member (FJVL). A narrative synthesis was used to describe the characteristics and findings of the included studies.

Quality assessment of the included studies

For the evaluation of human studies only, the National Heart, Lung and Blood Institute (NHLBI) tool, containing 14 assessment criteria, was used (National Heart Lung and Blood Institute, 2021). These criteria allow for assessment of the validity and reliability of observational cohort and cross-sectional studies, to identify potential flaws in design and implementation. The quality assessment was performed independently and blindly by two authors (AVRL and ACKS). Discrepancies were resolved by consensus or with the intervention of a third researcher (AHV).

Ethical considerations

Given that this systematic review was based on articles published in scientific journals, ethical committee approval was not required. It should be noted that no primary data were collected, nor were any interventions performed on human subjects.

Results

Study selection process

The electronic search identified 967 records. After removing 552 duplicates, 415 records were screened by title and abstract, leading to 29 full-text articles for eligibility assessment. Applying the predefined inclusion and exclusion criteria during full-text assessment, 8 studies were excluded for the following reasons: inappropriate study design ($n = 4$) (Delahoy, M. J. *et al.*, 2018; Fano *et al.*, 2021; Garavito Rentería *et al.*, 2012; O'Callaghan-Gordo *et al.*, 2023), absence of arsenic measurements ($n = 3$) (Barenys *et al.*, 2014; de Meyer, C. *et al.*, 2019; Ramos *et al.*, 2008), and a study on non-potable water ($n = 1$) (Condori Apaza *et al.*, 2023). A list of excluded studies is provided in the Supplementary Material. Finally, 21 studies that met all the eligibility criteria were included in the review (Ale-Mauricio *et al.*, 2018; Astete *et al.*, 2014, 2010; Berky *et al.*,



2023; Bolisetty *et al.*, 2021; Choque-Quispe *et al.*, 2021; Custodio *et al.*, 2020; de Meyer *et al.*, 2017; Delahoy *et al.*, 2022; Fandiño Piñeiro *et al.*, 2021; Fano *et al.*, 2020; Fano-Sizgorich *et al.*, 2021; Fernández Jerí *et al.*, 2022; Ferro *et al.*, 2023; George *et al.*, 2014; Linares *et al.*, 2024, 2021; Málaga Apaza, 2023; O’Callaghan-Gordo *et al.*, 2018; Pettigrew *et al.*, 2022; Ramírez *et al.*, 1997).

The study selection process, along with the number of studies evaluated and the reasons for exclusion at each stage, is detailed in the PRISMA flow diagram (Figure 1).

General characteristics of the studies

The main characteristics of the included studies are summarized in Table 1, which details the author, study design, type of sample source (human or water), study areas and exposure sources. Of the 21 included studies, 11 reported arsenic levels in humans exclusively through biological biomarkers such as urine, hair, nails, breast milk and blood (Ale-Mauricio *et al.*, 2018; Astete *et al.*, 2010; Berky *et al.*, 2023; Bolisetty *et al.*, 2021; Fandiño Piñeiro *et al.*, 2021; Fano-Sizgorich *et al.*, 2021; Linares *et al.*, 2024, 2021; O’Callaghan-Gordo *et al.*, 2018; Pettigrew *et al.*, 2022; Ramírez *et al.*, 1997), while 8 studies reported arsenic levels solely in water samples (Choque-Quispe *et al.*, 2021; Custodio *et al.*, 2020; de Meyer *et al.*, 2017; Delahoy *et al.*, 2022; Fano *et al.*, 2020; Ferro *et al.*, 2023; George *et al.*, 2014; Málaga Apaza, 2023). Additionally, 2 studies reported arsenic levels in both humans and water sources (Astete *et al.*, 2014; Fernández Jerí *et al.*, 2022).

Human studies were conducted in various departments of Peru (Junín, Apurímac, Tacna, Ica, Pasco, Loreto and Madre de Dios), with predominantly cross-sectional designs and published between 1997 and 2024 (Table 1). The main exposure sources identified for humans were environmental (n = 12) (Ale-Mauricio *et al.*, 2018; Astete *et al.*, 2014, 2010; Berky *et al.*, 2023; Bolisetty *et al.*, 2021; Fandiño Piñeiro *et al.*, 2021; Fano-Sizgorich *et al.*, 2021; Fernández Jerí *et al.*, 2022; Linares *et al.*, 2024, 2021; O’Callaghan-Gordo *et al.*, 2018; Pettigrew *et al.*, 2022) and occupational (n = 1) (Ramírez *et al.*, 1997). The studies focused on drinking water quality were carried out in the departments of Tacna, Lima, Puno, Loreto, Ucayali, Junín, Apurímac and Piura. Mostly cross-sectional and published between 2014 and 2023, these studies evaluated the presence of arsenic in drinking water, groundwater and surface water in localities such as Azángaro, San Antonio de Putina, and San Román in Puno, as well as Andahuaylas in Apurímac (Choque-Quispe *et al.*, 2021; Fernández Jerí *et al.*, 2022; George *et al.*, 2014).

Arsenic levels in humans

A total of 13 studies analyzed human biomarkers of arsenic, primarily using urine samples (n = 7) (Astete *et al.*, 2010; Fernández Jerí *et al.*, 2022; Ramírez *et al.*, 1997; Astete *et al.*, 2014; O’Callaghan-Gordo *et al.*, 2018; Fano-Sizgorich *et al.*, 2021; Ale-Mauricio *et al.*, 2018), blood (n = 2) (Berky *et al.*, 2023; Linares *et al.*, 2021), hair (n = 1) (Fandiño Piñeiro *et al.*, 2021) and nails (n = 1) (Pettigrew *et al.*, 2022). Additionally, 2 studies evaluated arsenic levels in both blood and breast milk, as well as in nails and hair (Bolisetty *et al.*, 2021; Linares *et al.*, 2024). Average arsenic concentrations in urine ranged from 5.27 µg/L, reported in Tacna (Fano-Sizgorich *et al.*, 2021), to values exceeding 424 µg/L in Junín (Ramírez *et al.*, 1997). In blood, results showed broad variability in arsenic concentrations; in Madre de Dios, the average concentration was 0.64 µg/L (Berky *et al.*, 2023), while in a recent study in Ica it was 1.43 µg/dL (Linares *et al.*, 2024). In hair, average concentrations ranged from 0.14 mg/kg to 0.47 mg/kg, reported in studies conducted in Junín and Pasco (Fandiño Piñeiro *et al.*, 2021). In Madre de Dios, the median value in nails was 177 ng/g, with levels reaching up to 1260 ng/g (Pettigrew *et al.*, 2022), while in Ica the median concentration in breast milk was 0.73 µg/L (Linares *et al.*, 2024). The average duration of residence in the study areas ranged from 6 months to over 5 years. The analytical methods employed included inductively coupled plasma mass spectrometry (ICP-MS) (n=6) (Berky *et al.*, 2023; Fandiño Piñeiro *et al.*, 2021; Fano-Sizgorich *et al.*, 2021; Linares *et al.*, 2024, 2021; Pettigrew *et al.*, 2022), atomic absorption spectrophotometry (AAS) (n=4) (Ale-Mauricio *et al.*, 2018; Bolisetty *et al.*, 2021; Fernández Jerí *et al.*, 2022; O’Callaghan-Gordo *et al.*, 2018), ultraviolet-visible spectrophotometry (n=1) (Ramírez *et al.*, 1997), while 2 studies did not report the analytical method used (NR) (Astete *et al.*, 2010, 2014).

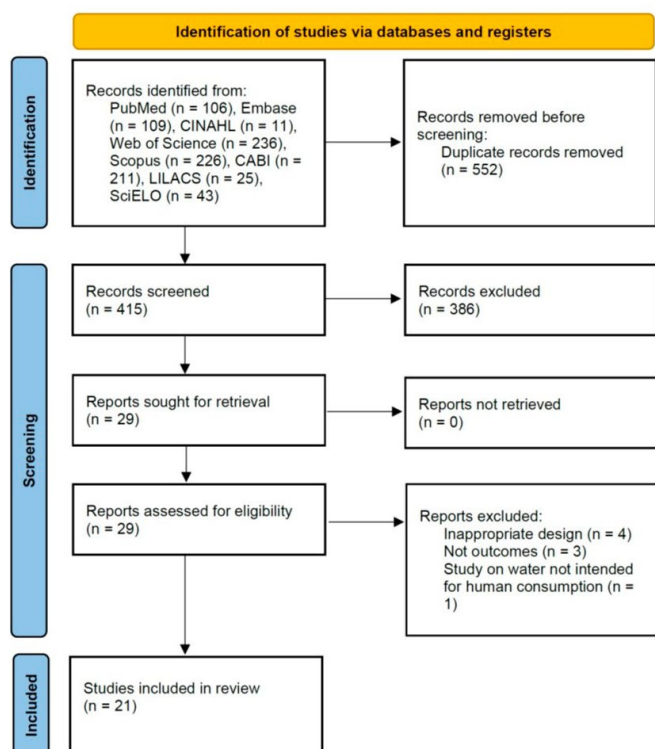


Figure 1. Summary of selection of studies included

Table 1. Characteristics of the studies included

Authors (year)	Study design	Sample source	Place			Human exposure	
			Department	Province	District		
Ramírez <i>et al.</i> (1997)	Cross-sectional study	Humans	Junín	Yauli	La Oroya	Occupational	
Astete <i>et al.</i> (2010)	Cross-sectional study	Humans	Apurímac	Cotabambas	Haqaira	Environmental	
				Graú	Chalhuahuacho		Progreso
Ale-Mauricio <i>et al.</i> (2018)	Cross-sectional study	Humans	Tacna	Candarave	Cairani	Environmental	
					Camilaca		
O'Callaghan <i>et al.</i> (2018)	Cross-sectional study	Humans	Loreto	NS	Cuninico	Environmental	
					San Pedro		
Bolisetty <i>et al.</i> (2021)	Cross-sectional study	Humans	Tacna	Tacna	Tacna	Environmental	
				Jorge Basadre	Inclán		Ticapampa
Fano <i>et al.</i> (2021)	Cross-sectional study	Humans	Tacna	Tacna	NS	Environmental	
Linares <i>et al.</i> (2021)	Cross-sectional study	Humans	Ica	NS	NS	Environmental	
Fandiño <i>et al.</i> (2021)	Cross-sectional study	Humans	Junín	Junín	Carhuamayo	Environmental	
			Pasco	Cerro de Pasco	Paragsha		
Pettigrew <i>et al.</i> (2022)	Cross-sectional study	Humans	Madre de Dios	Tambopata	Manu	Huepetuhe	Environmental
					Inambari		
					Laberinto		
				Tahuamanu	Tambopata	Las Piedras	
					Tahuamanu	Tahuamanu	
					Ibérica		
Berky <i>et al.</i> (2023)	Cross-sectional study	Humans	Madre de Dios	NS	NS	Environmental	
					NS		
Linares <i>et al.</i> (2024)	Cross-sectional study	Humans	Ica	NS	NS	Environmental	
George <i>et al.</i> (2014)	Cross-sectional study	Water	Puno	Azángaro	Achaya	NA	
					San Antón		
				San Antonio de Putina	Ananea		
				San Román	Caracoto		
					Juliaca		
				Puno	Platería		
					Puno		
				Chucuito			
				Carabaya	Crucero		
				Huancane	Taraco		
Junín	Yauli	La Oroya					
Lima	Lima	Lima					
de Meyer <i>et al.</i> (2017)	Cross-sectional study	Water	Loreto	Iquitos	NS	NA	
			Ucayali	Pucallpa			



Fano <i>et al.</i> (2020)	Cross-sectional study	Water	Tacna	Tacna	La Yarada	NA	
					Gregorio Albarracín Lanchipa		
					Tacna		
					Alto de la Alianza		
					Ciudad Nueva		
Pocollay							
Custodio <i>et al.</i> (2020)	Cross-sectional study	Water	Junín	NS	NS	NA	
Choque-Quispe <i>et al.</i> (2021)	Cross-sectional study	Water	Apurímac	Andahuaylas	Andahuaylas	NA	
					San Jerónimo		
					Talavera		
					Chiara		
Delahoy <i>et al.</i> (2022)	Cross-sectional study	Water	Piura	Piura	NS	NA	
				Morropón			
				Paita			
				Sechura			
				Sullana			
Ferro <i>et al.</i> (2023)	Cross-sectional study	Water	Puno	Puno	Capachica	NA	
					San Antonio de Esquilache		
					Vilque		
					Pichanaqui		
					Acora		
					Paucarcolla		
					Mañazo		
					Capachica		
Coata							
Málaga (2023)	Cross-sectional study	Water	Puno	San Román	Juliaca	NA	
Astete <i>et al.</i> (2014)	Cross-sectional study	Humans / Water	Apurímac	Cotabambas	Chalhuahuacho	Environmental	
					Haqira		
				Grau	Progreso		
Fernández <i>et al.</i> (2022)	Cross-sectional study	Humans / Water	Junín	Jauja	Apata	Environmental	
							Molinos

Note. NA: Not applicable. NS: Not specified.

Table 2. Arsenic levels in humans

Authors (year)	Analyzed samples (n)	Place	Biological sample	Arsenic level	Reference values	Time of residence	Analysis method
Ramírez <i>et al.</i> (1997)	166	La Oroya*	Urine	Mean: 424 µg/L; SD: 49.2 µg/L	NR	NR	Ultraviolet and visible light (UV-Vis) spectrophotometer
Astete <i>et al.</i> (2010)	154	Haquira*	Urine	Mean: 36.7 µg/L; SD: NR	≤100 µg/L	≥6 months	NR
	214	Chalhuahuacho*		Mean: 58.6 µg/L; SD: NR			
	85	Progreso*		Mean: 55.7 µg/L; SD: NR			
Astete <i>et al.</i> (2014)	304	Chalhuahuacho*	Urine	Mean: 26.1 µg/L; SD: NR	<100 µg/L	≥6 months	NR
		Haquira*		Mean: 24.2 µg/L; SD: NR			
		Progreso*		Mean: 14.6 µg/L; SD: NR			
Ale-Mauricio <i>et al.</i> (2018)	103	Cairani*	Urine	M: 601.6 µg/g (IQR: 407.3 µg/g - 847.1 µg/g) Cr	NR	≥1 year	Atomic absorption spectroscopy (AAS)
	71	Camilaca*		M: 30.2 µg/g (IQR: 21.4 µg/g - 39.7 µg/g) Cr			
O'Callaghan <i>et al.</i> (2018)	113	Cuninico ^a	Urine	M: 2.91 µg/g (IQR: 2.91 µg/g - 3.17 µg/g) Cr	20 µg/g Cr	≥6 months	Atomic absorption spectrophotometry (ASS)
		San Pedro ^a		M: 3.55 µg/g (IQR: 3.55 µg/g - 2.34 µg/g) Cr			
Bolisetty <i>et al.</i> (2021)	NS	Tacna*	Hair / Nail	Mean: 0.27 µg/g(-1) (Hair Sample)	NR	NR	Atomic absorption spectroscopy (AAS)
				Mean: 0.46 µg/g(-1) (First Nail Sample)			
				Mean: 0.84 µg/g(-1) (Second Nail Sample)			
				Mean: 0.57 µg/g(-1) (Third Nail Sample)			
				Mean: 0.11 µg/g(-1) (Hair Sample)			
		Inclán*		Mean: 1.12 µg/g(-1) (First Nail Sample)			
				Mean: 1.36 µg/g(-1) (Second Nail Sample)			
		Ticapampa*		Mean: 1.34 µg/g(-1) (First Hair Sample)			
				Mean: 2.68 µg/g(-1) (Second Hair Sample)			
				Mean: 0.12 µg/g(-1) (First Nail Sample)			
		Mean: 2.46 µg/g(-1) (Second Nail Sample)					
Fano <i>et al.</i> (2021)	147	Tacna**	Urine	GM±SD: 52.65 µg/L ± 33.1 µg/L (U-tAs) GM±SD: 5.27 µg/L ± 2.91 µg/L (U-iAs)	NR	≥5 years	Inductively coupled plasma - mass spectrometry (ICP-MS)
Linares <i>et al.</i> (2021)	42	Ica***	Blood	M: 1.36 µg/L (IQR: 0.71 µg/L)	NR	NR	Inductively coupled plasma - mass spectrometry (ICP-MS)
Fandiño <i>et al.</i> (2021)	16	Carhuamayo*	Hair	Mean: 0.18 mg/kg (Hair root); Mean: 0.14 mg/kg (Hair tip)	<0.20 mg/kg	NR	Inductively coupled plasma - mass spectrometry (ICP-MS)
	76	Paragsha*		Mean: 0.47 mg/kg (Hair root); Mean: 0.42 mg/kg (Hair tip)			
Pettigrew <i>et al.</i> (2022)	417	Madre de Dios***	Nail	M: 177 ng/g (Min/Max: 8 ng/g - 1260 ng/g)	NR	≥6 months	Inductively coupled plasma - mass spectrometry (ICP-MS)
Fernández <i>et al.</i> (2022)	31	Apata*	Urine	M: 4.4 µg/L (IQR: 3.4 µg/L - 7.5 µg/L) (U-tAs) M: 6.2 µg/g Cr (IQR: 5.0 µg/g - 8.9 µg/g) (U-tAs)	NR	≥5 years	Atomic absorption spectroscopy (AAS)
	81	Molinos*		M: 28.5 µg/L (IQR: 22.4 µg/L - 41.4 µg/L) (U-tAs) M: 32.4 µg/L Cr (IQR: 24.8 µg/g - 41.8 µg/g) (U-tAs)			
Berký <i>et al.</i> (2023)	198	Madre de Dios***	Venous Blood (Mother)	GM±SD: 0.64 µg/L ± 1.7 µg/L	NR	NR	Inductively coupled plasma - mass spectrometry (ICP-MS)
	198		Cord blood	GM±SD: 0.61 µg/L ± 1.7 µg/L			
Linares <i>et al.</i> (2024)	40	Ica***	Blood	GM±SD: 1.43 µg/L ± 1.39 µg/dL	<1.3 µg/dL	NR	Inductively coupled plasma - mass spectrometry (ICP-MS)
		Breast milk	M: 0.73 µg/L (Min/Max: 0.63 µg/L - 0.91 µg/L)	0.2 µg/L - 0.6 µg/L			

Notes. ^a: Native communities; Cr: Creatinine; M: Median; IQR: Interquartil range; U-tAs: Total arsenic urinary; Min/Max: Minimum / Maximum range; SD: Standard deviation; GM±SD: Geometric mean ± Standard deviation; U-iAs: Inorganic arsenic urinary; NS: Not specified; NR: Not reported.

*District.
** Province.
***Department.



Table 3. Arsenic levels reported in water samples

Authors (year)	Sample province	Analyzed samples (n)	Place	Arsenic level	Reference values	% of water samples out of range	Analytical method
Astete <i>et al.</i> (2014)	Not specified	6	Chalhuahuacho*				
		6	Haqaira*	NR	10 µg/L	0%	NR ^a
		10	Progreso*				
George <i>et al.</i> (2014)	Groundwater	111	Puno***	Mean: 54.5 µg/L; SD: 36.2 µg/L	10 µg/L	> 10 µg/L: 86%; > 50 µg/L: 56%	Inductively coupled plasma - mass spectrometry (ICP-MS)
	Surface Water	40	Junín***	Mean: 12.2 µg/L; SD: 11.1 µg/L		> 10µg/L: 50%	
			Lima***				
de Meyer <i>et al.</i> (2017)	Groundwater	26	Ucayali***	M: 27µg/L (Min/Max: 3 µg/L - 715 µg/L) (Aquifer Type 1)	10 µg/L	NR	Inductively coupled plasma - mass spectrometry (ICP-MS)
				M: 2 µg/L (Min/Max: 0.5 µg/L - 35µg/L) (Aquifer typer 2)			
		31	Loreto***	M: <0.5 µg/L (Min/Max : 0.5 µg/L - 2 µg/L) (Aquifer Typer 3)			
				M: 1 µg/L (Min/Max: 0.5 µg/L - 10 µg/L) (Aquifer Typer 4)			
Fano <i>et al.</i> (2020)	Drinking water	158	Tacna***	NR	10 µg/L	≥ 25 µg/L: 70.25% (35.44% with 25 µg/L and 34.81% with >25 µg/L)	Qualitative colorimetric analysis
Custodio <i>et al.</i> (2020)	Surface water	NS	Junín***	Mean: 0.0837 mg/L; SD: 0.0787 mg/L (CIMIRM Canal)	0.01 mg/L	85.71%	Atomic absorption spectroscopy (AAS)
				Mean: 0.0689 mg/L; SD: 0.0565 mg/L (Meris Canal)			
				Mean: 0.0143 mg/L; SD: 0.0017 mg/L (Chanchas River)			
				Mean: 0.0116 mg/L; SD: 0.0027 mg/L (Chia River)			
				Mean: 0.0107 mg/L; SD: 0.0012 mg/L (Cunas River)			
				Mean: 0.00685 mg/L; SD: 0.0037 mg/L (Shullcas River)			
				Mean: 0.0341 mg/L; SD: 0.0213 mg/L (Junin Lake)			
Choque-Quispe <i>et al.</i> (2021)	Groundwater	5	Andahuaylas*		0.01 mg/L	100%	Inductively coupled plasma - optical emission spectrometry (ICP-OES)
		4	San Jerónimo*	NR			
		4	Talavera*				
		4	Chiara*				
Delahoy <i>et al.</i> (2022)	Not specified	96	Piura***	NR	10 µg/L	25.0%	Inductively coupled plasma - mass spectrometry (ICP-MS)
Fernández <i>et al.</i> (2022)	Groundwater	NS	Apata*	M: 5.0 µg/L (IQR: 2.0 µg/L - 6.0 µg/L)	10 µg/L	NR	Atomic absorption spectrophotometry (AAS)
	Surface water		Molinos*	M: 47.0 µg/L (IQR: 42.0 µg/L - 53.5 µg/L)			
Ferro <i>et al.</i> (2023)	Groundwater	NS	Puno***	NR	0.01 mg/L	NS (2018) 0% (2019)	Inductively coupled plasma - atomic emission spectrometry (ICP-AES)
	Surface water						
Málaga (2023)	Groundwater	96	Juliaca*	Mean: 0.031 mg/L; SD: 0.01 mg/L	0.01 mg/L	NR	Atomic absorption spectrophotometry (AAS)

Notes. M: Median; IQR: Interquantil range; NS: Not specified; NR: Not reported; SD: Standard deviation.

*District.

**Province.

***Department.

^a The article only specifies the analysis of lead, cadmium and zinc by atomic absorption spectrometry (AAS).

Table 4. Quality assessment according to the NHLBI tool for observational cohort and cross-sectional studies

N	Author	Year	Study design	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
1	Ramírez <i>et al.</i>	1997	Cross-sectional study	Yes	Yes	Yes	Yes	NR	No	No	NA	NA	NA	Yes	NA	NA	NA
2	Astete <i>et al.</i>	2010	Cross-sectional study	Yes	Yes	Yes	Yes	Yes	No	No	NA	NA	NA	Yes	NA	NA	NA
3	Astete <i>et al.</i>	2014	Cross-sectional study	Yes	Yes	Yes	Yes	Yes	No	No	NA	NA	NA	Yes	NA	NA	NA
4	O'Callaghan <i>et al.</i>	2018	Cross-sectional study	Yes	Yes	Yes	Yes	NR	No	No	NA	NA	NA	Yes	NA	NA	NA
5	Ale Mauricio <i>et al.</i>	2018	Cross-sectional study	Yes	Yes	Yes	Yes	Yes	No	No	NA	NA	NA	Yes	NA	NA	NA
6	Fano <i>et al.</i>	2021	Cross-sectional study	Yes	Yes	Yes	Yes	NR	No	No	NA	NA	NA	Yes	NA	NA	NA
7	Bolisetty <i>et al.</i>	2021	Cross-sectional study	Yes	Yes	Yes	No	NR	No	No	NA	NA	NA	Yes	NA	NA	NA
8	Linares <i>et al.</i>	2021	Cross-sectional study	Yes	Yes	Yes	Yes	No	No	No	NA	NA	NA	Yes	NA	NA	NA
9	Fandiño <i>et al.</i>	2021	Cross-sectional study	Yes	Yes	Yes	Yes	No	No	No	NA	NA	NA	Yes	NA	NA	NA
10	Pettigrew <i>et al.</i>	2022	Cross-sectional study	Yes	Yes	Yes	Yes	NR	No	No	NA	NA	NA	Yes	NA	NA	NA
11	Fernández <i>et al.</i>	2022	Cross-sectional study	Yes	Yes	Yes	Yes	No	No	No	NA	NA	NA	Yes	NA	NA	NA
12	Berky <i>et al.</i>	2023	Cross-sectional study	Yes	Yes	Yes	Yes	NR	No	No	NA	NA	NA	Yes	NA	NA	NA
13	Linares <i>et al.</i>	2024	Cross-sectional study	Yes	Yes	Yes	Yes	NR	No	No	NA	NA	NA	Yes	NA	NA	NA

Note. Quality assessment tool for observational cohort and cross-sectional studies. CD: Cannot determine; NA: Not applicable; NR: Not reported. Q: Question of the study assessment tools.

Arsenic levels in water samples

Ten studies evaluated arsenic concentrations in water sources intended for human consumption (Table 3), mostly using groundwater samples ($n = 3$) (Choque-Quispe *et al.*, 2021; de Meyer *et al.*, 2017; Málaga Apaza, 2023), potable water ($n = 1$) (Fano *et al.*, 2020), surface water ($n = 1$) (Custodio *et al.*, 2020) and unspecified sources ($n = 2$) (Astete *et al.*, 2014; Delahoy *et al.*, 2022). Additionally, three studies analyzed arsenic levels in more than one category of water sample, specifically groundwater and surface water (Fernández Jerí *et al.*, 2022; Ferro *et al.*, 2023; George *et al.*, 2014). In the study by George *et al.* (2014), the reported average arsenic concentrations ranged from 12.2 µg/L in surface water samples from Junín and Lima to 54.5 µg/L in groundwater samples from Puno (George *et al.*, 2014). Furthermore, in 100% and 85.71% of the analyzed samples in Apurímac and Junín, respectively, the values exceeded the reference levels of 0.01 µg/L (Choque-Quispe *et al.*, 2021; Custodio *et al.*, 2020). The highest arsenic levels were found in groundwater and surface water sources. The most affected departments included Junín (Lake Junín, major rivers and irrigation channels) (Custodio *et al.*, 2020), Puno (wells in Juliaca and Caracoto) (George *et al.*, 2014) and Apurímac (springs in Andahuaylas) (Choque-Quispe *et al.*, 2021). The analytical methods used included atomic absorption spectrometry (AAS) ($n = 3$) (Custodio *et al.*, 2020; Fernández Jerí *et al.*, 2022; Málaga Apaza, 2023), followed by ICP-MS ($n = 3$) (de Meyer *et al.*, 2017; Delahoy *et al.*, 2022; George *et al.*, 2014), inductively coupled plasma optical emission spectrometry (ICP-OES) ($n = 1$) (Choque-Quispe *et al.*, 2021) and inductively coupled plasma atomic emission spectrometry (ICP-AES) ($n = 1$) (Ferro *et al.*, 2023), and a

qualitative colorimetric method ($n = 1$) (Fano *et al.*, 2020). One additional study did not report the analytical method used (Astete *et al.*, 2010, 2014).

Quality assessment

Thirteen studies reporting arsenic levels in humans were analyzed. The evaluated studies exhibited strengths in the clarity of the research questions and the specification of the study populations, receiving a «Yes» rating in these aspects. Only three studies reported a justification of sample size, power analysis or effect size estimations. Details of the quality assessment are provided in Table 4.

Discussion

In this systematic review, we summarize the evidence regarding the presence of arsenic in humans and drinking water across 11 political-administrative regions of Peru. Overall, variations in arsenic levels in humans and drinking water were dependent upon factors such as sample type, analytical technique and the political-administrative region in question. The highest arsenic levels in humans were reported in Tacna, Junín and Apurímac, while for water samples the highest concentrations were observed in Puno, Junín, Lima, Ucayali and Tacna. These findings contribute to strengthening knowledge regarding the presence of this metalloid in Peru and highlight the need for implementation of control measures, in order to achieve the goal of Sustainable Development Goal 6.3, the aim of which is to improve water quality through the reduction of pollution, the elimination of discharges, and the minimization of the release of hazardous chemicals and materials by 2030 (United Nations, 2026).



High arsenic exposure is a problem in several Latin American countries, including Peru. For example, a study in Mexico reported median urine arsenic levels ranging from 4.8 $\mu\text{g/L}$ to 18.1 $\mu\text{g/L}$ (Sánchez-Rodríguez *et al.*, 2023), while in Ecuador the average urine arsenic level was 24.38 $\mu\text{g/L}$, with a maximum of up to 50.32 $\mu\text{g/L}$ (Lam-Vivanco *et al.*, 2022). In Chile, arsenic levels in urine were found to be as high as 239 $\mu\text{g/L}$, substantially exceeding the reference value of 35 $\mu\text{g/L}$ (Medel-Jara *et al.*, 2023). In Brazil, arsenic levels have been measured in both blood and urine, with average urine levels of 31.5 $\mu\text{g/L}$ exceeding the reference value of 9.210 $\mu\text{g/L}$. Meanwhile, reported arsenic levels in blood increased over the years from 3.2 $\mu\text{g/L}$ to 7.2 $\mu\text{g/L}$, exceeding the reference range of 0.1 to 3.2 $\mu\text{g/L}$ (Vormittag *et al.*, 2021). Similarly, Argentina has reported blood concentrations in two cities (Ushuaia and Salta) with geometric means of 0.63 $\mu\text{g/L}$ and 0.55 $\mu\text{g/L}$, respectively (Xu *et al.*, 2022). The main source of arsenic exposure in these countries is the consumption of water in areas with high levels of arsenic and mining activities (Lam-Vivanco *et al.*, 2022; Medel-Jara *et al.*, 2023; Sánchez-Rodríguez *et al.*, 2023; Vormittag *et al.*, 2021; Xu *et al.*, 2022).

Arsenic levels in humans in Peru

Our results indicated that arsenic levels in humans in Peru varied according to the type of biological sample, analytical technique and political-administrative region. Urinary arsenic measurements should be interpreted with caution, since the included studies did not systematically report whether the values corresponded to total arsenic or to specific urinary species or metabolites. This is relevant because inorganic arsenic is the most toxic form, and urinary measurements without chemical speciation provide a less precise estimate of toxicologically relevant exposure (Kuivenhoven and Mason, 2026). In addition, the included studies did not consistently report clinical diagnoses or symptoms compatible with arsenic intoxication, which limits the interpretation of elevated urinary arsenic levels in clinical terms. The highest average arsenic levels were found in urine samples compared to studies focused on blood, hair, nails or breast milk. This difference may be attributed to the metabolism of arsenic in humans. Generally, both organic forms of arsenic (e.g., monomethylarsonic acid and dimethylarsinic acid) and inorganic forms (arsenite and arsenate) are excreted through the kidneys, and their detection in urine is an indicator of recent exposure (Lindberg *et al.*, 2007). Moreover, urine sampling is one of the most common practices in epidemiological studies to detect the health effects of arsenic exposure (Rivera *et al.*, 2010), as evidenced by the fact that seven of the 13 included human studies employed this biological sample (Ale-Mauricio *et al.*, 2018; Astete *et al.*, 2014, 2010; Fano-Sizgorich *et al.*, 2021; Fernández Jerí *et al.*, 2022; O'Callaghan-Gordo *et al.*, 2018; Ramírez *et al.*, 1997). In contrast, arsenic has a short

half-life in blood, making this study method most suitable for identifying very recent exposure. In the case of nails and hair, arsenic is incorporated into keratin and remains for prolonged periods, which allows for the assessment of long-term exposure (US National Research Council, 1999); however, these samples may be susceptible to environmental contamination, potentially compromising their diagnostic validity (Katz, 2019).

Another aspect influencing arsenic levels was the analytical technique used. Most of the studies processed samples using ICP-MS (Berky *et al.*, 2023; Fandiño Piñeiro *et al.*, 2021; Fano-Sizgorich *et al.*, 2021; Linares *et al.*, 2024, 2021; Pettigrew *et al.*, 2022). Notably, the highest arsenic levels were reported in studies employing other analytical techniques, such as ultraviolet-visible spectrophotometry (UV-Vis) and atomic absorption spectrophotometry (AAS) (Ale-Mauricio *et al.*, 2018; Ramírez *et al.*, 1997). The choice of technique is dependent upon detection limits and the economic resources of the laboratories involved. Although ICP-MS is expensive, its low detection limits compared to AAS and UV-Vis make it one of the most sensitive techniques available (Valskys *et al.*, 2022). According to Bhat *et al.*, the detection limit of ICP-MS is lower (0.0003–1 parts per billion [ppb]) and requires a smaller sample size (2–200 μL) compared to AAS, which has a higher detection limit (0.0009–1 ppb) and requires a larger sample (>1000 μL) (Bhat *et al.*, 2023). This means that ICP-MS is preferable for detecting ultra-low arsenic concentrations, allowing for more precise detection compared to other methods. Based on our findings, the presence of high arsenic levels using techniques such as AAS and UV-Vis might be subject to misclassification bias or misinterpretation, due to lower sensitivity and the difficulty in obtaining the required sample volume.

Across the different political-administrative regions of Peru, the highest urinary arsenic levels were observed in districts of Tacna (601.6 $\mu\text{g/g}$) (Ale-Mauricio *et al.*, 2018), Junín (424 $\mu\text{g/L}$) (Ramírez *et al.*, 1997), and Apurímac (ranging from 36.7 $\mu\text{g/L}$ to 58.6 $\mu\text{g/L}$) (Astete *et al.*, 2010). In Ica, arsenic levels in blood of 1.36 $\mu\text{g/L}$ were reported (Linares *et al.*, 2021). In Madre de Dios, the median arsenic concentration in nails was 177 ng/g , reaching maximum values of up to 1260 ng/g (Pettigrew *et al.*, 2022). Additionally, a study conducted on women and newborns in Madre de Dios reported mean arsenic levels of 0.64 $\mu\text{g/L}$ in maternal blood and 0.61 $\mu\text{g/L}$ in umbilical cord blood (Berky *et al.*, 2023), while a study of lactating women in Ica reported an arsenic level of 0.73 $\mu\text{g/L}$ (Linares *et al.*, 2024). Moreover, a study in Pasco reported arsenic levels of 0.47 mg/kg in hair, exceeding the reference value of 0.20 mg/kg (Fandiño Piñeiro *et al.*, 2021). While arsenic levels were found to vary according to the study population and sample type, this may be dependent upon the exposure source. In Apurímac, Pasco and Madre de Dios, the main exposure source is artisanal mining, which produces both environmental contamination and the contamination of

groundwater used for human consumption (Gerson *et al.*, 2022). This is relevant, since arsenic absorption occurs mainly through gastrointestinal and respiratory routes, as well as dermal absorption (Mohammed Abdul *et al.*, 2015). In Tacna, elevated arsenic levels in drinking water are attributed to the dissolution of arsenic in volcanic soils and agricultural activities (Mori Sosa *et al.*, 2025), while in Junín occupational exposure, such as in metallurgy, is the main source of arsenic exposure (Castillo Ungaro & Pulido Capurro, 2024).

In addition to exposure sources, arsenic metabolism and susceptibility may also be influenced by host-related factors such as genetics, age, nutritional status and underlying health conditions. Children may be particularly vulnerable, because arsenic metabolism can differ from that in adults and exposure during early life occurs during critical developmental periods. Also, inadequate nutritional status, including deficiencies in nutrients involved in one-carbon metabolism and essential trace elements, may impair arsenic methylation and increase toxicity (Skröder Löveborn *et al.*, 2016). For example, an earlier systematic review reported the presence of polymorphisms in arsenic methyltransferase (AS3MT), glutathione S-transferase (GST) and carbon metabolism genes in Latin American populations that may modulate arsenic metabolism (McClintock *et al.*, 2012). However, the presence of this characteristic in Peru remains uncertain. Clinically, exposure to elevated arsenic levels in humans (from 20 µg/L onward) is associated with increased mortality and cardiovascular disease incidence, exhibiting a dose-response relationship (Moon *et al.*, 2017). Given the values reported in our systematic review, it is imperative that more rigorous control measures be implemented in order to reduce elevated arsenic levels and prevent potential health consequences. It should also be noted that international evidence has identified foods such as rice and crops irrigated or prepared with contaminated water as potential complementary sources of exposure (Harine *et al.*, 2021).

The issue of elevated arsenic concentrations in water in Latin American countries, such as Argentina, Chile, Colombia and Mexico, constitutes a significant public health concern. In Colombia, in surface water sources in the Magdalena-Cauca basin, arsenic concentrations exceeding 10 µg/L have been reported (Pedraza and Espinosa Ramírez, 2021). In Argentina, groundwater arsenic concentrations of up to 4.5 mg/L (Marchetti *et al.*, 2021) have been recorded, while in potable water concentrations as high as 200 µg/L have been reported (Navoni *et al.*, 2012). In two municipalities in Mexico (San Pedro and Lerdo) with high arsenic exposure, the median concentrations were found to be 21.0 µg/L⁻¹ and 67.2 µg/L⁻¹ in groundwater, and 16.8 µg/L⁻¹ and 42.2 µg/L⁻¹ in potable water (Sánchez-Rodríguez *et al.*, 2023). In Chile, arsenic levels in surface water were found to be as high as 0.860 mg/L, although these were reduced to 0.005

mg/L through the work of treatment plants (Ruffino *et al.*, 2022). In some settings, elevated arsenic concentrations in groundwater may also be influenced by hydrogeochemical changes associated with intensive groundwater extraction, which can favor arsenic mobilization from aquifer materials (Rahaman *et al.*, 2021).

Arsenic levels in drinking water samples in Peru

According to our results, in the Peruvian context arsenic levels in drinking water vary according to water source, analytical technique and political-administrative region. In the case of water source, most studies (i.e., six of the ten studies included in this review) used groundwater samples to determine arsenic levels (Choque-Quispe *et al.*, 2021; de Meyer *et al.*, 2017; Fernández Jerí *et al.*, 2022; Ferro *et al.*, 2023; George *et al.*, 2014; Málaga Apaza, 2023). Notably, the highest arsenic concentrations were found in these samples, followed by surface water samples (George *et al.*, 2014; Málaga Apaza, 2023). Natural geogenic conditions and anthropogenic activities such as mining and agriculture may promote the mobilization of arsenic from soils, sediments and mineralized materials into groundwater and surface water. In this context, contamination of water sources intended for human consumption constitutes a relevant pathway of exposure for the population (Pal *et al.*, 2009a; Rahaman *et al.*, 2021). Groundwater is one of the main sources of water for human consumption, and arsenic mobilization in these systems may be influenced by hydrogeochemical conditions such as pH, redox status and groundwater flow dynamics. In addition, in some settings, water table decline and other hydrologic changes associated with groundwater extraction may favor the release into groundwater of arsenic retained in aquifer sediments (Pal *et al.*, 2009b).

Exposure to arsenic-contaminated groundwater has been linked to various chronic diseases (Fatoki and Badmus, 2022). Given the importance of groundwater to human health, the WHO promotes strategies to improve its quality (Schmoll *et al.*, 2006); however, regions including South America continue to report elevated groundwater arsenic levels (>10 µg/L), consistent with the findings of this systematic review (Yadav *et al.*, 2021). In the case of surface water, samples originate from rivers, lakes or channels that may be exposed to anthropogenic activities such as artisanal gold mining (Custodio *et al.*, 2020; Fernández Jerí *et al.*, 2022; Ferro *et al.*, 2023; George *et al.*, 2014).

Analytical techniques also affect arsenic level results in water samples. In general, most studies employed ICP-MS and AAS (Custodio *et al.*, 2020; de Meyer *et al.*, 2017; Delahoy *et al.*, 2022; Fernández Jerí *et al.*, 2022; George *et al.*, 2014; Málaga Apaza, 2023), while some used methods such as qualitative colorimetry (Fano *et al.*, 2020), ICP-OES (Choque-Quispe *et al.*, 2021), and ICP-AES (Ferro *et al.*, 2023). The highest arsenic levels were reported in

studies using ICP-MS and AAS techniques (Custodio *et al.*, 2020; Fernández Jerí *et al.*, 2022; George *et al.*, 2014; Málaga Apaza, 2023). According to Bhat *et al.*, ICP-MS is the technique of choice for water sample analysis, due to its low detection limits. But, although ICP-MS is the preferred method, AAS is often used, by virtue of its cost-benefit relationship compared to ICP-MS (Bhat *et al.*, 2023). As in the analysis of human samples, the use of ICP-MS for detecting arsenic levels in water in most studies contributes to a reduction in misclassification bias and misinterpretation, thereby increasing the internal validity of the findings.

Across the different political-administrative regions of Peru, the highest arsenic levels were observed in Puno, Junín, Lima, Ucayali and Tacna. In this context, it was reported that 86% and 56% of samples in Puno exceeded the reference limit, while 50% of samples in regions such as Junín and Lima had values above the reference level (George *et al.*, 2014). Another study that analyzed surface water samples in Junín showed that 85.7% of river, lake and canal samples had arsenic levels above the reference value (Custodio *et al.*, 2020). In Tacna, in 70% of drinking water samples levels above 25 µg/L were recorded (Fano *et al.*, 2020), while in Apurímac, 100% of the samples were found to exceed 0.010 mg/L (Choque-Quispe *et al.*, 2021). Similarly, in Tacna, 70% of samples surpassed the permissible limits for arsenic (Fano *et al.*, 2020). While arsenic levels vary between different political-administrative regions, most exceed WHO reference values (WHO, 2022b). A possible explanation for these findings is that these regions are consistently exposed to arsenic-generating activities such as artisanal mining, lack of access to quality water supplies, and volcanic ash emissions resulting from tectonic movements (George *et al.*, 2014).

In Peru, water quality control is an essential measure for the surveillance and verification of arsenic contamination, but it does not by itself reduce population exposure. For example, Peru's Drinking Water Quality Regulations include maximum permissible arsenic limits (Ministry of the Environment, 2017), which are aligned with WHO recommendations (United Nations Children's Fund and WHO, 2018). However, the effectiveness of reduction of exposure is dependent upon the implementation of treatment, remediation and safe water supply measures, in addition to water safety and monitoring plans (Autoridad Nacional del Agua, 2015). In a recent study in the province of Pisco, Peru, in water passed through activated carbon filters impregnated with iron (AC-Fe), arsenic levels were reduced from 14 µg/L to levels recommended by the WHO (i.e., below 10 µg/L) (Chávez and Ruffner, 2024). In order to ensure access to good quality drinking water for all affected populations, it will be necessary to strengthen infrastructure and improve oversight throughout the

country. Collaboration between government, non-governmental organizations and academia will be crucial, if this problem is to be effectively addressed.

Several possible limitations in this systematic review could potentially influence interpretation of the results. The selected studies may be subject to selection bias, which could affect the representativeness of their findings. The included studies might not have covered all the regions or populations exposed to arsenic, in both humans and in drinking water. This is due principally to a lack of available data and studies in geographically hard-to-reach areas, possibly resulting in an incomplete picture of the scope of the problem throughout Peru. Although an exhaustive search was conducted across multiple databases, analysis of a total of 21 studies may limit the generalizability of the results. Another significant limiting factor is the lack of data available for some Peruvian departments, which could mean that the true magnitude of the problem is being underestimated, particularly in the case of rural or remote areas where research and monitoring resources are severely limited. Additionally, variations in the analytical methods used among the reviewed studies, such as sampling procedures and arsenic measurement techniques, may also have influenced the results, hindering a homogeneous comparative analysis of the data. For instance, in different studies ICP-MS, ICP-AES and, AAS methods were selected for use, making standardization of data analysis difficult. These limitations should be considered when evaluating the findings of this review, and they also highlight the need for future research incorporating a broader and more representative approach.

Conclusion

Our study highlights the critical importance of addressing arsenic exposure in Peru. Elevated arsenic concentrations in water sources for human consumption, together with evidence of increased arsenic levels in human biomarkers, constitute a significant public health concern in Peru. This concern is of particular relevance in regions where elevated levels have been documented, including Tacna, Ucayali, Puno, Junín, Apurímac, Madre de Dios and Pasco, and may be associated with a combination of geogenic conditions and anthropogenic activities such as mining, metallurgy and agriculture. It is essential that effective mitigation and control strategies for arsenic in both humans and drinking water be established, as these are crucial for the preservation of public health. Furthermore, it is imperative that government policies ensure the implementation and strict enforcement of rigorous regulatory frameworks, alongside continuous monitoring of arsenic levels in water, in order to ensure that they remain within the limits established by health authorities.

Author contributions

Conceptualization: AHV; methodology: AHV and RVF; validation: AHV, RVF, FJVL; formal analysis: AVRL, ACKS, DC, AHV; investigation: AVRL, ACKS, RVF, FJVL, DC, AHV; data curation: AVRL, ACKS, DC, AHV; supervision: AHV, RVF, FJVL; project administration: AHV, DC; writing, original draft preparation: AVRL, ACKS, RVF, FJVL, AHV; writing, revising and editing: AVRL, ACKS, RVF, FJVL, DC, AHV. All the authors have accepted responsibility for the entire content of the manuscript and approved its submission.

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Conflicts of interest

The authors declare no conflict of interest.

Generative Artificial Intelligence (AI) use statement

The authors declare that no artificial intelligence tools were used in any part of the manuscript preparation process.



Bibliographic references

- Abebe, Y., Whitehead, P., Alamirew, T., Jin, L., and Alemayehu, E. (2023).** «Evaluating the effects of geochemical and anthropogenic factors on the concentration and treatability of heavy metals in Awash River and Lake Beseka, Ethiopia: arsenic and molybdenum issues». *Environmental Monitoring and Assessment*, 195, 1188. Available at: <https://doi.org/10.1007/s10661-023-11674-z>
- Ale-Mauricio, D. A., Villa, G., and Gastañaga, M. D. C. (2018).** «Concentraciones de arsénico urinario en pobladores de dos distritos de la región Tacna, Perú, 2017». *Revista Peruana de Medicina Experimental y Salud Pública*, 35(2), pp. 183-189. Available at: <https://doi.org/10.17843/rpmpesp.2018.352.3693>
- Astete, J., Gastañaga, M. del C., Fiestas, V., Oblitas, T., Sabastizagal, I., Lucero, M., Abadía, J. del M., Muñoz, M. E., Valverde, and A., Suárez, M. (2010).** «Enfermedades transmisibles, salud mental y exposición a contaminantes ambientales en población aledaña al proyecto minero Las Bambas antes de la fase de explotación, Perú 2006». *Revista Peruana de Medicina Experimental y Salud Pública*, 27(4), pp. 512-519. Available at: <http://www.scielo.org.pe/pdf/rins/v27n4/a04v27n4.pdf>
- Astete, J., Gastañaga, M. D. C., and Pérez, D. (2014).** «Niveles de metales pesados en el ambiente y su exposición en la población luego de cinco años de exploración minera en Las Bambas, Perú 2010». *Revista Peruana de Medicina Experimental y Salud Pública*, 31(4). Available at: <https://doi.org/10.17843/rpmpesp.2014.314.120>
- Autoridad Nacional del Agua. (2015).** «Política y estrategia nacional de recursos hídricos». Available at: https://www.ana.gob.pe/sites/default/files/default_images/politica_y_estrategia_nacional_de_recursos_hidricos_ana.pdf
- Baker, B.A., Cassano, V.A., Murray, C. (2018).** «Arsenic exposure, assessment, toxicity, diagnosis, and management: Guidance for occupational and environmental physicians». *Journal of Occupational & Environmental Medicine*, 60, e634-e639. Available at: <https://doi.org/10.1097/JOM.0000000000001485>
- Barenys, M., Boix, N., Farran-Codina, A., Palma-Linares, I., Montserrat, R., Curto, A., Gomez-Catalan, J., Ortiz, P., Deza, N., and Llobet, J. M. (2014).** «Heavy metal and metalloids intake risk assessment in the diet of a rural population living near a gold mine in the Peruvian Andes (Cajamarca)». *Food and Chemical Toxicology*, 71, pp. 254-263. Available at: <https://doi.org/10.1016/j.fct.2014.06.018>
- Berky, A. J., Weinhouse, C., Vissoci, J., Rivera, N., Ortiz, E. J., Navio, S., Miranda, J. J., Mallipudi, A., Fixen, E., Hsu-Kim, H., and Pan, W. K. (2023).** «In utero exposure to metals and birth outcomes in an artisanal and small-scale gold mining birth cohort in Madre de Dios, Peru». *Environmental Health Perspectives*, 131, 097008. Available at: <https://pubmed.ncbi.nlm.nih.gov/37747404/>
- Bhat, A., Hara, T. O., Tian, F., and Singh, B. (2023).** «Review of analytical techniques for arsenic detection and determination in drinking water». *Environmental Science: Advances*, 2, pp. 171-195. Available at: <https://doi.org/10.1039/D2VA00218C>
- Bolisetty, S., Rahimi, A., and Mezzenga, R. (2021).** «Arsenic removal from Peruvian drinking water using milk protein nanofibril-carbon filters: A field study». *Environmental Science: Water Research & Technology*, 7, 22232230. Available at: <https://doi.org/10.1039/D1EW00456E>
- Bundschuh, J., Litter, M. I., Parvez, F., Román-Ross, G., Nicolli, H. B., Jean, J.-S., Liu, C.-W., López, D., Armienta, M. A., Guilherme, L. R. G., Cuevas, A. G., Cornejo, L., Cumbal, L., and Toujaguez, R. (2012).** «One century of arsenic exposure in Latin America: A review of history and occurrence from 14 countries». *Science of the Total Environment*, 429, pp. 2-35. Available at: <https://doi.org/10.1016/j.scitotenv.2011.06.024>
- Campbell, M., McKenzie, J. E., Sowden, A., Katikireddi, S. V., Brennan, S. E., Ellis, S., Hartmann-Boyce, J., Ryan, R., Shepperd, S., Thomas, J., Welch, V., and Thomson, H. (2020).** «Synthesis without meta-analysis (SWiM) in systematic reviews: Reporting guideline». *BMJ*, 368, l6890. Available at: <https://doi.org/10.1136/bmj.l6890>
- Castillo Ungaro, R., and Pulido Capurro, V. (2024).** «Remoción de los contenidos metálicos procedentes de las aguas del depósito de relaves de la planta concentradora Mahr Túnel - Yauli, Junín, Perú». *Revista de Investigaciones Altoandinas*, 26(3), pp. 138-146. Available at: <https://doi.org/10.18271/ria.2024.616>
- Chávez, M., and Ruffner, B. A. (2024).** «Field study of an arsenic removal plant for drinking water using activated carbon and iron in a rural community in the province of Pisco, Peru». *Journal of Water and Health*, 22(2), pp. 329-336. Available at: <https://doi.org/10.2166/wh.2024.273>
- Choque-Quispe, D., Froehner, S., Ligarda-Samanez, C. A., Ramos-Pacheco, B. S., Peralta-Guevara, D. E., Palomino-Rincón, H., Choque-Quispe, Y., Solano-Reynoso, A. M., Barboza-Palomino, G. I., Taípe-Pardo, F., and Zamalloa-Puma, L. M. (2021).** «Insights from water quality of high Andean springs for human consumption in Peru». *Water*, 13(19), 2650. Available at: <https://doi.org/10.3390/w13192650>
- Condori Apaza, R. M., Alviz Gonzáles, L. F., and Méndez Ancca, S. (2023).** «Niveles de concentración de metales pesados en sedimentos de zona alta del río Locumba, Perú». *Producción + Limpia*, 18(2), pp. 103-115. Available at: <https://doi.org/10.22507/pml.v18n2a6>
- Custodio, M., Álvarez, D., Cuadrado, W., Montalvo, R., and Ochoa, S. (2020).** «Potentially toxic metals and metalloids in surface water intended for human consumption and other uses in the Mantaro River watershed, Peru». *Soil and Water Research*, 15(4), pp. 237-245. Available at: <https://doi.org/10.17221/152/2019-SWR>
- de Meyer, C. M. C., Rodríguez, J. M., Carpio, E. A., García, P. A., Stengel, C., and Berg, M. (2017).** «Arsenic, manganese and aluminum contamination in groundwater resources of Western Amazonia (Peru)». *Science of the Total Environment*, 607-608, pp. 1437-1450. Available at: <https://doi.org/10.1016/j.scitotenv.2017.07.059>
- Delahoy, M. J., Mattioli, and M., Knee, J. (2018).** «Chemical and microbiological contamination of drinking water in Peruvian households with infants». *The American Journal of Tropical Medicine and Hygiene*, 99(4), pp. 419. Available at: <https://www.webofscience.com/wos/woscc/full-record/WOS:000461386604032>
- Delahoy, M. J., Hubbard, S., Mattioli, M., Culquichicón, C., Knee, J., Brown, J., Cabrera, L., Barr, D. B., Ryan, P. B., Lescano, A. G., Gilman, R. H., and Levy, K. (2022).** «High prevalence of chemical and microbiological drinking water contaminants in households with infants enrolled in a birth cohort—Piura, Peru, 2016». *The American Journal of Tropical Medicine and Hygiene*, 107(4), pp. 881-892. Available at: <https://doi.org/10.4269/ajtmh.22-0098>
- Fandiño Piñero, X., Ave, M. T., Mallah, N., Caamaño-Isorna, F., Jiménez, A. N. G., Vieira, D. N., Bianchini, F., and Muñoz-Barús, J. I. (2021).** «Heavy metal contamination in Peru: Implications on children's health». *Scientific Reports*, 11, 22729. Available at: <https://doi.org/10.1038/s41598-021-02163-9>
- Fano, D., Vásquez-Velásquez, C., Aguilar, J., Gribble, M. O., Wickliffe, J. K., Lichtveld, M. Y., Steenland, K., and Gonzales, G. F. (2020).** «Arsenic concentrations in household drinking water: A cross-sectional survey of pregnant women in Tacna, Peru, 2019». *Exposure & Health*, 12, pp. 555-560. Available at: <https://doi.org/10.1007/s12403-019-00337-5>

- Fano, D., Vásquez-Velásquez, C., Ramírez-Atencio, C., Yucra, S., and Gonzáles, G. F. (2021). «Reproductive outcomes in pregnant women and its association with arsenic contamination in drinking water, in a region characterized by high birth weight rates in Peru». *The Journal of Maternal-Fetal & Neonatal Medicine*, 34, pp. 3997-3999. Available at: <https://doi.org/10.1080/14767058.2019.1702946>
- Fano-Sizgorich, D., Vásquez-Velásquez, C., Yucra, S., Vásquez, V., Tokeshi, P., Aguilar, J., Ramírez-Atencio, C., Barr, D. B., and Gonzáles, G. F. (2021). «Total urinary arsenic and inorganic arsenic concentrations and birth outcomes in pregnant women of Tacna, Peru: A cross-sectional study». *Exposure & Health*, 13, pp. 133-140. Available at: <https://doi.org/10.1007/s12403-020-00377-2>
- Fatoki, J. O., and Badmus, J. A. (2022). «Arsenic as an environmental and human health antagonist: A review of its toxicity and disease initiation». *Journal of Hazardous Materials Advances*, 5, 100052. Available at: <https://doi.org/10.1016/j.hazadv.2022.100052>
- Fernández Jerí, Y., Benavides Rivera, E. R., Dávila Espinoza, C. E., Gonsebatt, M. E., and Del Razo, L. M. (2022). «Evaluación de la exposición a arsénico y factores de riesgo de aterogénesis en una población altoandina en Perú». *Revista Internacional de Contaminación Ambiental*, 38, pp. 399-410. Available at: <https://doi.org/10.20937/RICA.54436>
- Ferro, P., Farfán-Solís, R., Blanco-Shocosh, D., Ferró-González, A. L., and Ferro-González, P. F. (2023). «Determination of inorganic chemical parameters in drinking water in districts of the province of Puno in the region Puno-Peru». *Heliyon*, 9, e15624. Available at: <https://doi.org/10.1016/j.heliyon.2023.e15624>
- Garavito Rentería, J., Araujo Banchón, W. J., Quesada Ríos, M. P., and Ponce de León, D. (2012). «Linfoma no Hodgkin gástrico asociado a intoxicación por metales pesados». *Revista de Gastroenterología del Perú*, 32(4), pp. 418-422. <https://revistagastroperu.com/index.php/rgp/article/view/311/304>
- George, C. M., Sima, L., Arias, M. H. J., Mihalic, J., Cabrera, L. Z., Danz, D., Checkley, W., and Gilman, R. H. (2014). «Arsenic exposure in drinking water: An unrecognized health threat in Peru». *Bulletin of the World Health Organization*, 92, pp. 565-572. Available at: <https://doi.org/10.2471/BLT.13.128496>
- Gerson, J. R., Szponar, N., Zambrano, A. A., Bergquist, B., Broadbent, E., Driscoll, C. T., Erkenwick, G., Evers, D. C., Fernández, L. E., Hsu-Kim, H., Inga, G., Lansdale, K. N., Marchese, M. J., Martínez, A., Moore, C., Pan, W. K., Purizaca, R. P., Sánchez, V., Silman, M., Ury, E. A., Vega, C., Watsa, M., and Bernhardt, E. S. (2022). «Amazon forests capture high levels of atmospheric mercury pollution from artisanal gold mining». *Nature Communications*, 13, 559. Available at: <https://doi.org/10.1038/s41467-022-27997-3>
- Harine, I. J., Islam, M. R., Hossain, M., Afroz, H., Jahan, R., Siddique, A. B., Uddin, S., Hossain, M. A., Alamri, S., Siddiqui, M. H., and Henry, R. J. (2021). «Arsenic Accumulation in Rice Grain as Influenced by Water Management: Human Health Risk Assessment». *Agronomy*, 11(9), 1741. Available at: <https://doi.org/10.3390/agronomy11091741>
- Institute for Health Metrics and Evaluation. (2021). «Occupational exposure to arsenic: Level 4 risk». Available at: <https://www.healthdata.org/research-analysis/diseases-injuries-risks/factsheets/2021-occupational-exposure-arsenic-level-4>
- Katz, S. A. (2019). On the use of hair analysis for assessing arsenic intoxication. *International Journal of Environmental Research and Public Health*, 16(6), 977. Available at: <https://doi.org/10.3390/ijerph16060977>
- Kuivenhoven, M., and Mason, K. (2026). Arsenic Toxicity. In: *StatPearls*. Treasure Island: StatPearls Publishing.
- Lam-Vivanco, A. M., Morales-Barba, G. E., Zambrano-Cabrera, C. A., Tacuri-Ullauri, X. A., and Márquez-Jaramillo, X. C. (2022). «Exposición laboral al arsénico inorgánico». *Polo del Conocimiento*, 7(5), pp. 1426-1438. Available at: <https://polodelconocimiento.com/ojs/index.php/es/article/view/4037>
- Linares, A. M., Thaxton-Wiggins, A., and Unrine, J. M. (2024). «Concentrations of lead and arsenic in mother's milk and children's blood in Peruvian breastfeeding dyads». *Journal of Human Lactation*, 40(1), pp. 69-79. Available at: <https://doi.org/10.1177/08903344231212430>
- Linares, A. M., Unrine, J. M., Thaxton Wiggig, A., Tantalean, J. C., and Radulescu, V. C. (2021). «Blood's concentration of lead and arsenic associated with anemia in Peruvian children». *Journal of Environmental and Public Health*, 2021, 18. Available at: <https://doi.org/10.1155/2021/7283514>
- Lindberg, A.-L., Goessler, W., Grandér, M., Nermell, B., and Vahter, M. (2007). «Evaluation of the three most commonly used analytical methods for determination of inorganic arsenic and its metabolites in urine». *Toxicology Letters*, 168(3), pp. 310-318. Available at: <https://doi.org/10.1016/j.toxlet.2006.10.028>
- Luo, Y.-L., Pan, Y.-R., Wang, X., Wang, Z.-Y., Daigger, G., Ma, J.-X., Tang, L.-H., Liu, J., Ren, N.-Q., and Butler, D. (2025). «Leveraging the water-environment-health nexus to characterize sustainable water purification solutions». *Nature Communications*, 16, 1269. Available at: <https://doi.org/10.1038/s41467-025-56656-6>
- Málaga Apaza, J. (2023). «Contenido de arsénico, conocimiento y actitud en el consumo del agua de pozo familiar». *Vive*, 6(18). Available at: <https://doi.org/10.33996/revistavive.v6i18.264>
- Marchetti, M. D., Tomac, A., and Pérez, S. (2021). «Perfil de riesgo para la inocuidad de alimentos: Presencia de arsénico en Argentina». *Revista Argentina de Salud Pública*, 13, e47e47. <https://rasp.msal.gov.ar/index.php/rasp/article/view/650>
- McClintock, T. R., Chen, Y., Bundschuh, J., Oliver, J. T., Navoni, J., Olmos, V., Lepori, E. V., Ahsan, H., and Parvez, F. (2012). «Arsenic exposure in Latin America: Biomarkers, risk assessments and related health effects». *Science of the Total Environment*, 429, pp. 76-91. Available at: <https://doi.org/10.1016/j.scitotenv.2011.08.051>
- McGowan, J., Sampson, M., Salzwedel, D. M., Cogo, E., Foerster, V., and Lefebvre, C. (2016). «PRESS Peer review of electronic search strategies: 2015 Guideline statement». *Journal of Clinical Epidemiology*, 75, pp. 40-46. Available at: <https://doi.org/10.1016/j.jclinepi.2016.01.021>
- Medel-Jara, P., Gejman, C., Chávez, B., Saavedra, M., Paredes, F., Valenzuela, A., Rebolledo, D., and Ríos, J. C. (2023). «Metal exposure in Arica, Chile: Examining toxic elements». *Revista Médica de Chile*, 151(4), pp. 420-427. Available at: <https://doi.org/10.4067/s0034-98872023000400420>
- Medina-Pizzali, M., Robles, P., Mendoza, M., and Torres, C. (2018). «Ingesta de arsénico: el Impacto en la alimentación y la salud humana». *Revista Peruana de Medicina Experimental y Salud Pública*, 35(1), pp. 93-102. Available at: <https://doi.org/10.17843/rpmesp.2018.351.3604>
- de Meyer, C. M. C., Berg, M., Rodríguez, J., Carpio, E., García, P., and Wahnfried, I. (2019). «Exploring arsenic and other geogenic groundwater contaminants in the vast and scarcely studied Amazon basin». In: P. Bhattacharya, J. Bundschuh, R. Naidu, H. Guo, Y. Zhu, and A. Ahmad (eds.), *Environmental Arsenic in a Changing World*. Boca Raton: CRC Press.
- Ministerio del Ambiente del Perú. (2017). Decreto Supremo N.º 004-2017-MINAM. Available at: <https://www.minam.gob.pe/wp-content/uploads/2017/06/DS-004-2017-MINAM.pdf>



- Mohammed Abdul, K. S., Jayasinghe, S. S., Chandana, E. P. S., Jayasumana, C., and De Silva, P. M. C. S. (2015). «Arsenic and human health effects: A review». *Environmental Toxicology and Pharmacology*, 40(3), pp. 828-846. Available at: <https://doi.org/10.1016/j.etap.2015.09.016>
- Moon, K. A., Oberoi, S., Barchowsky, A., Chen, Y., Guallar, E., Nachman, K. E., Rahman, M., Sohel, N., D'Ippoliti, D., Wade, T. J., James, K. A., Farzan, S. F., Karagas, M. R., Ahsan, H., and Navas-Acien, A. (2017). «A dose-response meta-analysis of chronic arsenic exposure and incident cardiovascular disease». *International Journal of Epidemiology*, 46, pp. 1924-1939. Available at: <https://doi.org/10.1093/ije/dyx202>
- Mori Sosa, L. J. P., Morales Cabrera, D. U., Florez Ponce de León, W. D., Hinojosa Ramos, E. A., and Torres Ventura, A. Y. (2025). «Study of arsenic contamination in the Caplina Basin, Tacna, Peru: Arsenite and arsenate analysis using inductively coupled plasma mass spectrometry and high-performance liquid chromatography». *Sustainability*, 17(2), 611. Available at: <https://doi.org/10.3390/su17020611>
- National Heart Lung and Blood Institute. (2021). «Study Quality Assessment Tools». Available at: <https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools>
- National Research Council (US). (1999). «Biomarker of arsenic exposure». In: *Arsenic in Drinking Water* (Chap. 6). Washington, D. C.: National Academies Press. Available at: <https://doi.org/10.17226/6444>
- Naujokas, M. F., Anderson, B., Ahsan, H., Aposhian, H. V., Graziano, J. H., Thompson, C., and Suk, W. A. (2013). «The broad scope of health effects from chronic arsenic exposure: Update on a worldwide public health problem». *Environmental Health Perspectives*, 121(3), pp. 295-302. Available at: <https://pubmed.ncbi.nlm.nih.gov/23458756/>
- Navoni, J., De Pietri, D., García, S., and Villaamil Lepori, E. (2012). «Riesgo sanitario de la población vulnerable expuesta al arsénico en la provincia de Buenos Aires». *Revista Panamericana de Salud Pública*, 31(1), pp. 1-8. <https://www.scielosp.org/pdf/rpsp/v31n1/01.pdf>
- O'Callaghan-Gordo, C., Flores, J. A., Lizárraga, P., Okamoto, T., Papoulias, D. M., Barclay, F., Orta-Martínez, M., Kogevinas, and M., Astete, J. (2018). «Oil extraction in the Amazon basin and exposure to metals in indigenous populations». *Environmental Research*, 162, pp. 226-230. Available at: <https://doi.org/10.1016/j.envres.2018.01.013>
- O'Callaghan-Gordo, C., Rosales, J., Lizárraga, P., Barclay, F., Okamoto, T., Papoulias, D. M., Espinosa, A., Orta-Martínez, M., Kogevinas, and M., Astete, J. (2023). «Levels of arsenic, cadmium and mercury in urine of indigenous people living close to oil extraction areas in the Peruvian Amazon». *Environmental Health Perspectives*, 131(5), 057701. Available at: <https://pubmed.ncbi.nlm.nih.gov/37133291/>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P., and Moher, D. (2021). «The PRISMA 2020 statement: An updated guideline for reporting systematic reviews». *Systematic Reviews*, 10, 89. Available at: <https://doi.org/10.1186/s13643-021-01626-4>
- Pal, Parimal, Sen, M., Manna, A., Pal, J., Pal, Pratima, Roy, S., and Roy, P. (2009a). «Contamination of groundwater by arsenic: a review of occurrence, causes, impacts, remedies and membrane-based purification». *Journal of Integrative Environmental Sciences*, 6(4), pp. 295-316. Available at: <https://doi.org/10.1080/19438150903185077>
- Pal, Parimal, Sen, M., Manna, A., Pal, J., Pal, Pratima, Roy, S., and Roy, P. (2009b). «Contamination of groundwater by arsenic: a review of occurrence, causes, impacts, remedies and membrane-based purification». *Journal of Integrative Environmental Sciences*, 6(4), pp. 295-316. Available at: <https://doi.org/10.1080/19438150903185077>
- Pedraza, M. L., and Espinosa Ramírez, A. J. (2021). «El legado del arsénico y mercurio en el complejo cenagoso Ramsar de Ayapel, (Córdoba, Colombia): Aproximación a la macrocuenca Magdalena-Cauca». *Acta Biológica Colombiana*, 27(2). Available at: <https://doi.org/10.15446/abc.v27n2.89084>
- Pettigrew, S. M., Pan, W. K., Harrington, J., Berky, A., Rojas, E., and Feingold, B. J. (2022). «Adult exposures to toxic trace elements as measured in nails along the interoceanic highway in the Peruvian Amazon». *International Journal of Environmental Research and Public Health*, 19(10), 6335. Available at: <https://doi.org/10.3390/ijerph19106335>
- Rahaman, Md. S., Rahman, Md. M., Mise, N., Sikder, Md. T., Ichihara, G., Uddin, Md. K., Kurasaki, and M., Ichihara, S. (2021). «Environmental arsenic exposure and its contribution to human diseases, toxicity mechanism and management». *Environmental Pollution*, 289, 117940. Available at: <https://doi.org/10.1016/j.envpol.2021.117940>
- Ramírez, A. V., and Castillo, E. C. (1997). «Exposición ocupacional al arsénico en la industria minero metalúrgica del cobre en el Perú». *Revista Brasileira de Saúde Ocupacional*, 23(85-86), pp. 21-30.
- Ramos, W., Galarza, C., Ronceros, G., De Amat, F., Teran, M., Pichardo, L., Juárez, D., Anaya, R., Mayhua, A., Hurtado, J., and Ortega-Loayza, A. G. (2008). «Noninfectious dermatological diseases associated with chronic exposure to mine tailings in a Peruvian district». *British Journal of Dermatology*, 159(1), pp. 169-174. Available at: <https://doi.org/10.1111/j.1365-2133.2008.08630.x>
- Rivera, Z., Meliker, J. R., Linder, A. M., Nriagu, J. O. (2010). «Reliability of spot urine samples in assessing arsenic exposure». *International Journal of Hygiene and Environmental Health*, 213(4), pp. 259-264. Available at: <https://doi.org/10.1016/j.ijheh.2010.03.003>
- Rodríguez Padilla, C. (2021). «Intoxicación por arsénico». *Medicina Legal de Costa Rica*, 38(2), pp. 4-16. https://www.scielo.sa.cr/scielo.php?script=sci_arttext&pid=S1409-00152021000300004
- Ruffino, B., Campo, G., Crutchik, D., Reyes, A., and Zanetti, M. (2022). «Drinking Water Supply in the Region of Antofagasta (Chile): A Challenge between Past, Present and Future». *International Journal of Environmental Research and Public Health*, 19(21), 14406. Available at: <https://doi.org/10.3390/ijerph192114406>
- Sachs, J. D., LaFortune, G., Kroll, C., Fuller, G., and Woelm, F. (2022). «Sustainable Development Report 2022: From Crisis to Sustainable Development: the SDGs as Roadmap to 2030 and Beyond». Cambridge University Press. Available at: https://assets.cambridge.org/97810092/10089/frontmatter/9781009210089_frontmatter.pdf
- Sánchez-Rodríguez, B. L., Castillo-Maldonado, I., Pedroza-Escobar, D., Delgadillo-Guzmán, D., and Soto-Jiménez, M. F. (2023). «Association of obesity, diabetes and hypertension with arsenic in drinking water in the Comarca Lagunera province (North-Central Mexico)». *Scientific Reports*, 13, 9244. Available at: <https://doi.org/10.1038/s41598-023-36166-5>
- Schmoll, O., Howard, G., Chilton, J., and Chorus, I. (2006). *Protecting ground water for health. Managing the quality of drinking-water sources*. Albany: World Health Organization.
- Skröder Löveborn, H., Kippler, M., Lu, Y., Ahmed, S., Kuehnelt, D., Raqib, R., and Vahter, M. (2016). «Arsenic Metabolism in Children Differs from that in Adults». *Toxicological Sciences*, 152(1), pp. 29-39. Available at: <https://doi.org/10.1093/toxsci/kfw060>

- Swedish Council on Health Technology Assessment. (2017).** «Occupational health and safety - Chemical exposure: A systematic review and assessment of the social, medical and ethical aspects». Available at: <https://www.ncbi.nlm.nih.gov/books/NBK448041/>
- Ticona Castro, M. A., Tejada Vásquez, E., and Vargas Escobedo, H. Y. (2019).** «Contaminación del agua potable con arsénico y frecuencia de cáncer en la ciudad de Tacna 2010-2011». *Revista Médica Basadrina*, 6(1), pp. 4-6. Available at: <https://doi.org/10.33326/26176068.2012.1.461>
- United Nations. (2026).** «Sustainable Development. Goal 6: Ensure availability and sustainable management of water and sanitation for all». Available at: https://sdgs.un.org/goals/goal6#targets_and_indicators
- United Nations Children's Fund, World Health Organization. (2018).** «Arsenic Primer: Guidance on the Investigation & Mitigation of Arsenic Contamination». Available at: <https://www.unicef.org/documents/arsenic-primer-guidance-investigation-mitigation-arsenic-contamination>
- Valskys, V., Hassan, H. R., Wołkowicz, S., Satkūnas, J., Kibirkištis, G., and Ignatavičius, G. (2022).** «A review on detection techniques, health hazards and human health risk assessment of arsenic pollution in soil and groundwater». *Minerals*, 12(10), 1326. Available at: <https://doi.org/10.3390/min12101326>
- Vormittag, E., Saldiva, P., Anastacio, A., and Barbosa, F. (2021).** «High levels of metals/metalloids in blood and urine of residents living in the area affected by the dam failing in Barra Longa, District, Brazil: A preliminary human biomonitoring study». *Environmental Toxicology and Pharmacology*, 83, 103566. Available at: <https://doi.org/10.1016/j.etap.2020.103566>
- World Health Organization. (2022a).** «Arsenic». Available at: <https://www.who.int/news-room/fact-sheets/detail/arsenic>
- World Health Organization. (2022b).** *Guidelines for drinking-water quality. Fourth edition incorporating the first and second addenda*. Geneva: World Health Organization.
- Xu, S., Hansen, S., Sripada, K., Aarland, T., Horvat, M., Mazej, D., Alvarez, M. V., and Odland, J. Ø. (2022).** «Maternal blood levels of toxic and essential elements and birth outcomes in Argentina: The EMASAR study». *International Journal of Environmental Research and Public Health*, 19(6), 3643. Available at: <https://doi.org/10.3390/ijerph19063643>
- Yadav, M. K., Saidulu, D., Gupta, A. K., Ghosal, P. S., and Mukherjee, A. (2021).** «Status and management of arsenic pollution in groundwater: A comprehensive appraisal of recent global scenario, human health impacts, sustainable field-scale treatment technologies». *Journal of Environmental Chemical Engineering*, 9(3), 105203. Available at: <https://doi.org/10.1016/j.jece.2021.105203>

