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POTENTIALLY TOXIC ELEMENTS IN THE CARIBBEAN COASTAL REGION: A REVIEW

Elementos potencialmente tóxicos en la región costera del Caribe: una revisión

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Key words: Potentially toxic elements, metals, metalloids, trace metals, contamination.

ABSTRACT

Marine pollution by potentially toxic elements (PTEs) represents a significant environmental challenge for the Caribbean coastal region. This article reviews research published between 1990 and 2022 on pollution in coastal environments in different countries. The results revealed the presence of As, Cu, Cd, Cr, Hg, Pb, Mn, Ni, and Zn, in various samples. Concentration levels in sediments and aquatic samples from various locations suggest possible environmental, toxicological, and public health risks due to contamination. Considerable accumulations were found in some marine organisms, and certain areas show severe contamination; others show lower levels, which indicates the existence of multiple and complex pollution sources, mainly of anthropogenic origin. The article aims to provide an overview of the status of PTEs pollution in the Caribbean, to understand the state of research on the topic and establish a basis for future studies. This review compiles existing knowledge to support multinational efforts. to integrate pollution monitoring and prevention programs in the Caribbean region. Findings from the samples examined vary concerning sampling schemes, parameters, and analytical techniques, as well as differences in data presentation (i.e., dry weight versus wet weight, or fraction of sediment analyzed). These differences make it difficult to make meaningful comparisons between the available data. Limited data are available for most of these contaminants for most of the countries in the region, and any attempt to develop a regional-scale assessment from contaminant data available in the open literature is made difficult by this limitation.

Palabras clave: elementos potencialmente tóxicos, metales, metaloides, metales traza, contaminación.

RESUMEN

La contaminación marina por elementos potencialmente tóxicos (EPT) es problema que afecta a la región costera del Caribe. Este artículo revisa las investigaciones publicadas entre 1990 y 2022 sobre contaminación en ambientes costeros en diferentes países de la región. Los resultados revelaron presencia de As, Cu, Cd, Cr, Hg, Pb, Mn, Ni y Zn, en varias matrices. Los niveles de concentración en sedimentos y matrices acuáticas de varios lugares sugieren posibles riesgos ambientales, toxicológicos y de salud pública debido a la contaminación. Se encontraron concentraciones acumuladas considerables en algunos organismos marinos. Algunos países y áreas muestran contaminación severa; otros muestran niveles más bajos, lo que indica existencia de fuentes múltiples y complejas de contaminación, principalmente de origen antrópico. El artículo tiene como objetivo brindar una visión general del estado de la contaminación por EPT en la región del Mar Caribe, con el fin de comprender el estado de investigación sobre el tema y establecer una base para futuros estudios. Se recopila el conocimiento existente para guiar esfuerzos multinacionales dirigidos a la integración de programas de monitoreo y prevención de la contaminación en el Caribe. Los hallazgos de las muestras examinadas varían con respecto a los esquemas de muestreo, parámetros y técnicas analíticas, así como en la presentación de datos (es decir, peso seco versus peso húmedo, o fracción de sedimento analizado). Estas diferencias dificultan hacer comparaciones significativas entre los datos disponibles. Se dispone de datos limitados sobre la mayoría de estos contaminantes en gran parte de los países de la región, cualquier intento de desarrollar una evaluación a escala regional a partir de datos de contaminantes disponibles en la literatura abierta se dificulta debido a dicha limitación.

INTRODUCTION

The ecosystems of the Wider Caribbean Region (WCR) provide services to the region that are critical for the economic support and development of the local population (Fernandez et al. 2007). The Caribbean region faces marine pollution from a broad spectrum of pollutants. These include bacteria, viruses, parasites, fertilizers, pesticides, pharmaceuticals, nitrates, phosphates, plastics, fecal waste, and potentially toxic elements (Ramírez 2014, Covarrubias and Cabriales 2017). PTEs such as arsenic (As), copper (Cu), lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), manganese (Mn) , nickel (Ni), and zinc (Zn), among others, are characterized by their potential toxicity even at low concentrations (Alvarez-León 2006, Eisler 2010, Mancera-Rodríguez and Tiznado 2022). Mineral extraction activities, particularly the extraction of Ni in Cuba, have caused its release into the marine environment (González and Torres 1990). The discharge of potentially toxic elements (PTEs) has negatively affected the quality of environmental matrices, such as water and sediment (Johnston and Roberts 2009). Once introduced into coastal and marine systems, PTEs undergo various physical, chemical, and biological processes that govern their migration and distribution within these environments (Díaz et al. 2006). The bioaccumulation of these elements in marine organisms such as fish and mollusks, is a threat to food security and public health in the region (Ping et al. 2009, Reyes et al. 2016). The Caribbean Sea Commission (CSC), a regional intergovernmental organization, works tirelessly for the conservation and management of the marine and coastal resources of the Caribbean Sea. In close collaboration with its member states, the CSC can test regulatory parameters and guideline frameworks that are important to ensure that the health, wealth, safety and security of the Caribbean Sea is maintained (Parris 2016).

The effects of contamination with metals in sediments, which were investigated in some studies, were evaluated in comparison to reference values established by Buchman (2008) to assess the impacts of contaminants on biological endpoints. Guidance values include the Threshold Effect Level (TEL) and the Probable Effects Level (PEL) values (NOAA 1999, Martínez 2020). Below these levels, contaminants are not considered to be a significant hazard to aquatic organisms. This is the lower limit of contaminant concentration, which is associated with adverse biological consequences for aquatic systems. Within this range, contaminant concentrations may potentially be related to adverse biological consequences (NOAA 1999).

Origin of potentially toxic elements (PTEs)

Pollutants may originate from natural processes, such as vulcanization and geological weathering. Metals are usually found in the Earth's crust as components of minerals and rocks (Alloway 2013, Menéndez and Muñoz 2021). Geological processes such as erosion, volcanic activity, and atmospheric deposition contribute to the presence of these elements in the environment (Alloway 2013, Torres and De los Ríos 2022). However, human activities, also called anthropogenic sources, such as mining, industry, agriculture, and urbanization, have significantly increased PTEs emissions into the environment in recent decades, exceeding natural levels (Rodríguez 2017). The continuous application of compounds such as pesticides with elements such as Cd and Pb in agriculture is concerned with their persistence and adverse environmental effects (Peralta-Videa 2024).

It is crucial to monitor and regulate the application of agricultural compounds containing elements such as Cd and Pb to mitigate their persistence, minimize adverse environmental effects, and promote sustainable agricultural practices. Failure to address this issue, along with other anthropogenic sources of pollution, complicates the scientific assessment of the marine environmental status in the affected areas. In addition to agriculture, mining activities also represent a major source of PTEs. According to Mora et al. (2016), inadequate management of mining leachates has significantly contributed to the release of pollutant elements into aquatic ecosystems, with the Puyango River basin (including the Calera and Amarillo rivers) in Ecuador, serving as a notable example.

Furthermore, Herrera et al. (2013) support these findings by emphasizing the risks associated with PTEs sources of anthropogenic origin, highlighting their detrimental effects on aquatic biota, human health, and overall environmental quality. These pollutant inputs can be either direct, such as the discharge of industrial wastes, or indirect, through the atmospheric deposition of contaminated particles (Rizzo et al. 2010, Reyes et al. 2016). Human activities have significantly disrupted the natural cycles of metals, leading to an increased contribution of PTEs concentrations to the environment (Reyes et al. 2016). Other main anthropogenic sources are smelting activities, which release PTEs such as Hg, Pb, and Cd during the extraction and processing of minerals (Prieto et al. 2009, Alloway 2013, Palacios et al. 2018); industrial processes such as electroplating, leather tanning, and the manufacturing of batteries and pigments; fuel burning; untreated wastewater discharges (Prieto et al. 2009). These anthropogenic activities have contributed to elevated levels of metals in air, water, and soil, representing a risk to human health and the ecosystems (Rodríguez 2017, Condori 2023). To develop effective environmental management strategies, it is necessary to distinguish anthropogenic sources of pollution.

Addressing the causes and consequences appropriately will facilitate the reduction of anthropogenic inputs and the mitigation of natural effects, thereby promoting environmental sustainability (Rizzo et al. 2010, Casanova 2013).

PTEs contamination

PTEs contamination can have adverse health effects, such as damage to the nervous, circulatory, and reproductive systems (Järup 2003). Furthermore, these elements can alter the structure and function of ecosystems, affecting biodiversity and productivity (Järup 2003). Their presence in the marine environment can cause damage to the health of aquatic organisms and, therefore, the food chain. The bioavailability and toxicity of metals should also be considered in the evaluation of environmental effects (Rizzo et al. 2010, Reyes et al. 2016).

This article aims to provide an overview of PTEs pollution in the Caribbean region, to understand the state of research on this topic and establish a basis for future studies.

MATERIALS AND METHODS

Study area

According to the Association of Caribbean States (ACS 2002), the WCR (**Fig. 1**), comprises continental and island countries, including the United States, Bahamas, Turks and Caicos Islands, Cuba, Jamaica, Haiti, Dominican Republic, Puerto Rico, Guyana, Venezuela, Colombia, Panama, Costa Rica, Nicaragua, Honduras, Belize, El Salvador, Guatemala, Mexico, United States Virgin Islands (USVI), the British Virgin Islands (BVI), Anguilla, St. Martin/ Sint Maarten, St. Barthelemy, Saba, St. Eustatius, St. Kitts and Nevis, Barbuda, Antigua, Montserrat, Guadeloupe, Marie-Galante, Dominica, Martinique, Saint Lucia, Saint Vincent and the Grenadines, Grenada, Barbados, Tobago and Trinidad, Bonaire, Curacao, Aruba, Cayman Brac, Little Cayman, and Grand Alligator.

Data sources and search strategy

Two comprehensive databases, Google Scholar and Lens.org were used to search for relevant studies published between 1990 and 2022. The use of advanced search technologies, such as Google Scholar and Lens.org, is justified by their unique capabilities to ease the retrieval of relevant scientific information. These platforms provide advanced functionalities that surpass those of conventional search engines, allowing researchers to improve their queries and access academic content more efficiently. The use of Google

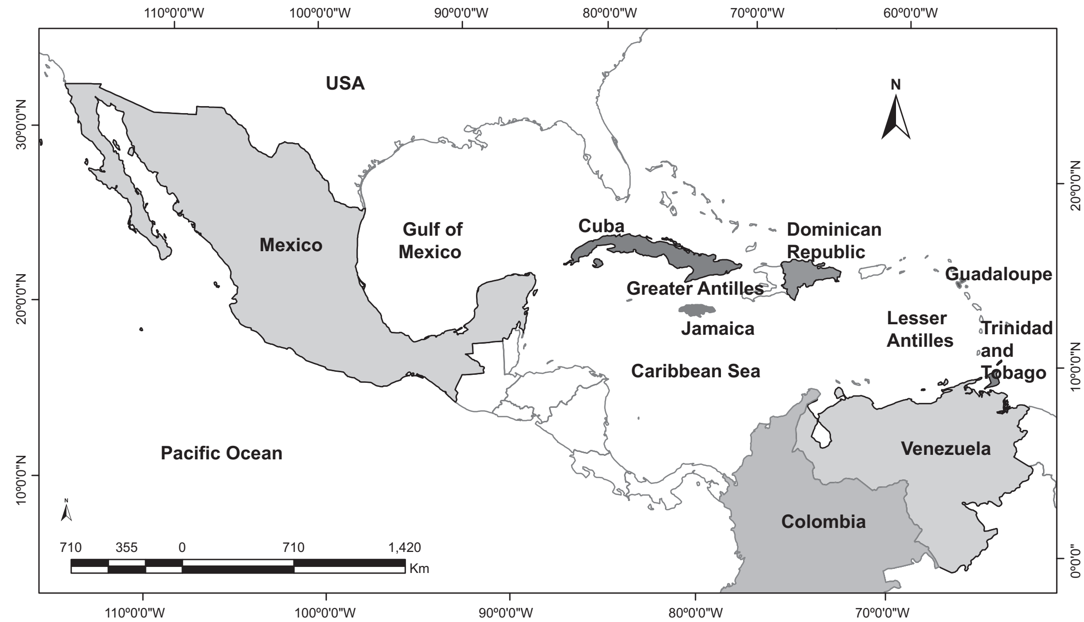

Fig. 1. Map of the Wider Caribbean region.

Scholar offers options to perform advanced research and improve the precision of the results.

These options include the use of Boolean operators as well as searching by author, journal title, and publication date; using these Boolean operators allows you to specify where words should appear such as "AND", "OR" and "NOT" (Carranza 2018), combined with these Boolean operators and limited to studies in English and Spanish. Google Scholar is a search engine specializing in academic literature that indexes a wide variety of sources, including peer-reviewed articles, theses, books, abstracts, and gray literature. This provides access to a large volume of scientific information relevant to the topic of interest.

On the other hand, Lens.org is a platform that eases the search and analysis of open access patents and academic literature (Velayos-Ortega and López-Carreño 2021). The platform provides information on technological trends and collaborations between inventors, which are not found in other search tools. The patents searched are complemented by Google Scholar's coverage of academic literature.

Lens.org allows researchers to find technological trends, collaborations between inventors and the impact of patents, which is essential for understanding the state of the art in a research field (Velayos-Ortega and López-Carreño 2021). By including both scientific publications and patent documents, this platform makes it possible to find not only academic research, but also technological aspects related to the topic of interest.

This is particularly relevant when seeking information about practical applications and innovative solutions to address environmental problems, such as in the case of PTEs pollution in the Caribbean Sea. Additionally, Lens has direct access to this vast academic database, which includes approximately 270 million documents, making it among the largest in the world (Velayos-Ortega and López-Carreño 2021).

Through these databases, documents are selected in a selected time interval (1990-2022), which is justified by the following factors: 1990 marks an important turning point in the research and management of PTEs in the environment, with the implementation of stricter regulations and policies at the international level, such as the Rio Declaration on Environment and Development (UN 1993). Search terms included "potentially toxic elements," "metals," "metalloids," "trace metals," and "contamination".

Study selection: A multi-step process was followed to find relevant studies:

- Initial projection: Titles and abstracts were reviewed to assess their relevance to the topic.
- Full text review: Potentially relevant studies (primary sources) were retrieved, and their eligibility was assessed according to predefined criteria.

The reasons for exclusion at each stage are based on the eligibility criteria set up at the beginning of the review. The main variables for which data were looked for in this study are the following:

- Geographic location: refers to the specific countries within the Greater Caribbean region where the studies were conducted. The inclusion of this variable allows a comparative analysis of contamination by PTEs in various locations.
- Type of PTEs: refers to the specific Cd, Cr, Cu, Hg, Pb, Mn, Ni, Zn examined in the studies. This variable is crucial to understanding the variety of elements that contribute to marine pollution in the region.
- Source of contamination: These variables find whether the source of PTEs is natural (e.g., vulcanization, geological weathering) or anthropogenic (e.g., oil spills, industrial and agricultural wastewater discharges, uncontrolled urban waste generation). Understanding the source can help design strategies to mitigate contamination.
- Concentration of PTEs: Refers to the measured concentrations in the marine environment. This variable is critical to evaluating the severity of the contamination.
- Impact on marine life: These variables measure the effect of pollution on marine ecosystems. It could include impacts on species diversity, abundance, and health, this helps to understand the ecological consequences of contamination.
- Risk factors are specific conditions or activities that increase the probability of contamination by PTEs. They could include industrial activities, and wastewater discharge. Identification of risk factors can help prevent contamination.
- Protective factors: These are conditions or actions that reduce the probability of contamination or mitigate its impact. They could include regulations, cleanup activities, and the use of less toxic materials. Understanding protective factors can inform strategies to manage and reduce pollution.

These variables were chosen because they offer a comprehensive view of the problem of contamination by PTEs in the Caribbean Sea, from the sources and types of pollutants to the impacts and practical solutions.

- ***Final selection***: Studies that met all criteria were included in the review.

Data extraction and management:

Data relevant to the analysis were extracted from the selected studies, including:

- Potentially toxic elements: name and concentrations of various metals found in the samples.
- Environmental compartments: biological species and substrates (water, sediments, organisms, and plants) were analyzed.
- Location and date: sampling location and date.
- Analytical methods: techniques used to measure concentrations.
- Quality assurance/control: measures taken to ensure the accuracy and reliability of the data.

The extracted data was recorded in a standardized format, checked for errors or inconsistencies, and stored in a secure and accessible Microsoft Excel database. Metadata and documentation were included for clarity and future reference.

RESULTS AND DISCUSSION

During the literature review, a total of 150 records were retrieved through advanced searches conducted in Google Scholar and Lens.org. These sources included scientific articles, academic theses, and technical reports addressing the occurrence of potentially toxic elements (PTEs) in coastal environments of the Caribbean and other regions. From the total number of documents reviewed, 35 scientific publications were finally selected for inclusion (**Table I**).

These studies report quantitative concentrations of PTEs in sediments, organisms, and water bodies across the Caribbean, and were chosen for providing comparable, standardized, and useful data for synchronic analysis. The geographic distribution of these studies was mainly from Colombia (65.1%), followed by Cuba (11.1%), Venezuela (9.5%), Mexico (6.3%), the Dominican Republic and Guadeloupe (3.2% each), and Jamaica (1.6%) (**Fig. 2**).

Most of the reviewed papers focused on marine contamination and evaluated potentially toxic elements (PTEs) in different matrices, with special emphasis on sediment, water, and biota. Sediment was the most sampled matrix, followed by fish, with results generally reported in parts per million (ppm) on a dry weight basis. **Table I** summarizes the studies by country, presenting concentrations of As, Cd, Pb, Cr, Cu, and Zn from the Bay of Chetumal and comparable ecosystems. Concentrations were standardized to ppm to facilitate interpretation and comparison across studies. Values are presented as full ranges (minimum-maximum), with some means also indicated, to better reflect potential exposure or bioaccumulation levels from a precautionary perspective regarding ecological and human health risks.

TABLE I. CONCENTRATIONS OF POTENTIALLY TOXIC ELEMENTS IN ORGANISMS, SEDIMENT AND WATER.

Country	Sampling matrix	Element and concentration	Units	Reference[a]
Cuba	Sea urchin *(Echinometra lucunter)*	**Cr** 3.6-8.3, **Cu** 0.58-2.9, **Mn** BDL-0.90, **Ni** BDL-3.0, **Zn** 163-412 (mean)	ppm dw	1
	Rhizophora mangle	**Mn** 82-297, **Ni** BDL-23.6, **Zn** 2.2-4.7 (mean)		2
	Loggerhead *(Caretta caretta)* tissue	**Cd** 0.81-5.8, **Mn** 1.22-7.48, **Pb** (BLD) , **Zn** 100-186		3
	Green turtle *(Chelonia mydas)* tissue	**Cu** 0.446-100, **Cd** 0.113-39.2, **Mn** 0.826-8.92, **Pb** 0.044-0.07, **Zn** 62.1-82.5	ppm ww	3
	Fish muscle	**As** 0.01-2.93, **Cr** 0.01-0.58 ,**Cu** 0.23-45.69, **Pb** 0.01-0.84, **Zn** 4.9-29.9		4
Dominican Republic	Bivalves	**Al** 3.80-2240, **Cd** 0.04-2.57, **Cr** 1.66-10.7, **Cu** 3.08-866, **Fe** 50.9-3400, **Hg** 0.29-7.02, **Ni** 1.25-7.92, **Pb** 0.09-1.49, **Zn** 22.9-4380	ppm dw	5
	Pelagic *Sargassum* tissue	**As** 14-42, **Cd** 0.1-0.3, **Cr** 2-56 ,**Cu** 2-12, **Mn** 16-32, **Pb** 1-2 , **Zn** 13-21, **Ni** 10-33		6
Mexican Caribbean	*Rhizophora mangle*	**Cd** 0-0.5, **Cr**<2.38, **Hg** 0-15, **Pb** 0-7.3	ppm	7
	Oysters	**Cd** 5-23, **Cr**<2.38, **Hg** 0-15, **Pb** 0-7.3		7
	Jaiba Azul (*Callinectes sapidus* Rathbun*)*	**Cu** 5.1-8.4, **Cr** 0.01-0.17, **Cd** 0.1-0.7, **Hg** 18.7-58.2, **Pb** <0.003, **Zn** 14.0-18.0		8
Venezuela	Coral *(Porites astreoides)*	**Cu** 3.33-89.57, **Cr** 0.16-23.9, **Pb** 0.029-4.74 , **Zn** 0.83-42.45	ppm dw	9
	Echinoderm *(Holothuria mexicana)*	**Cu** 47.5-3043.2, **Mn** 0.0-40.5, **Ni** 0.0-224.5, **Pb** 49.4-1334.7, **Zn** 17.5-2165		10
	Echinoder*m (Isostichopus badionotus*)	**Cu** 59.0-3854.0, **Mn** 0.0-46.8, **Ni** 0.0-219.8, **Pb** 73.7-2018.6, **Zn** 14.6-4472.5		10
	Bivalve *(Isognomon alatus)*	**Cd** 0.33-0.91, **Cr** 0.46-1.2, **Cu** 9-14, **Ni** 11-18, **Pb** 0.4-0.71, **Zn** 0.25-2.1		11

Values are expressed in ppm. BDL = Below Detection Limit; nd = not detected. The concentration unit is given once per row and applies to all elements beneath it. 'nd' indicates 'not detected', and '<' denotes values below detection or quantification limits. When not explicitly specified in the original study, concentration units are reported as 'ppm' without distinction of weight basis (dry or wet). This table includes data from all 35 scientific publications reviewed for this study, as listed in the references.

[a]1, González et al. (1999); 2, Gonzalez and Ramirez (1995); 3, Andreany et al. (2008); 4, Mesa et al. (2021); 5, Sbriz et al. (1998); 6, Rodríguez et al. (2020); 7, Ochoa and Gonzàlez (2016); 8, Deveze (2011); 9, Bastidas and Garcia (1999); 10, Laboy-Nieves and Conde (2001); 11, Jaffe´ et al. (1998); 12, Jaffe´et al. (1995); 13, Zapata-Vivenes et al. (2020); 14, Olivero et al. (2016); 15, Salinas et al. (2014); 16, Olivero et al. (2015); 17, Marrugo et al. (2015a); 18, Ruiz et al. (2014); 19, Marrugo et al. (2010); 20, Gracia et al. (2010); 21, Fernandez-Maestre et al. (2018); 22, Vergara and Rodríguez (2015); 23, Fuentes et al. (2018); 24, López and Barragán (2016); 25, Burgos et al. (2017); 26, Barros -Barrios et al. (2016); 27, Cadavid-Velásquez et al. (2019); 28, González and Torres (1990); 29, Marín-Leal et al. (2022); 30, Gonzales et al. (2008); 31, Greeneway and Rankine Jones (1992); 32, Jaffe´ et al. (2003); 33, Bernard (1995); 34, Persad and Rajkumar (1995); 35, Díaz -Asencio, et al. (2011).

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Country	Sampling matrix	Element and concentration	Units	Reference[a]
Colombia	Bivalve (*Tivela mactroidea*)	**Cd** 2.2-3.3, **Cr** 1.6-4.6, **Cu** 58.9-152, **Ni** 12.0-30.7, **Pb** 2.0-3.1, **Zn** 226-266		12
	Fish tissue	**Cd** 0.35-16.01 , **Cu** 6.4-29.44, **Pb** 0.69-7.90, **Zn** 61.91-125.51	ppm dw	13
	Diferents fish muscle	**Hg** mean :		
		0.10-1.80		14
		1.30-2.45, 1.73-2.35		15
		0.02-0.45		16
		0.18-1.14		17
		0.11-1.75		18
		0.14-0.43		19
		0.15-0.74		20
	Diferents fishs muscle	**Cd** 0.0019-0.012 , **Ni** 0.050-0.500, **Pb** 0.004-0.039 , **Zn** 0.330-3.90		21
		Hg 0.13 , **Pb** 0.3	mean, ppm ww	22
		Cd 0.04-0.06 , **Hg** 0.08-0.16 , **Pb** 0.08-0.18		23
		As 0.02-0.05, **Cd** 0.004-0.007 , **Hg** 0.02-0.06 , **Pb** 0.02-0.06		24
		Hg 0.10--0.67, **Pb** 0.04-0.12		25
		As 0.005 , **Hg** 0.04-0.05 , **Pb** 0.06-0.07		26
	Macromycete fungi	**Cu** 4.24-19.99, **Cd** 0.077-0.107, **Cr** 2.32-3.41, **Hg** 0.02-0.05, **Ni** 4.26-11.59, **Pb** 0.48-4.13 ,**Zn** 10.40-30.31	ppm dw	27
Cuba	Sediment	**Cr** 22-339, **Cu** 18-716, **Hg** 0.64-76, **Mn** 79-251, **Ni** 11-112, **Pb** 44-903, **Zn** 72-3736 (mean)	ppm dw	28
	Water	**As** 0.0006, **Cr** 0.0076-0.0209, **Cu** 0.0038-0.0081, **Cd** 0.00002-0.00016, **Pb** 0.0242-0.0822, **Zn** 0.0181-0.0431	ppm	4
Dominican Republic	Sediments	**Al** 276-33,000, **Cd** 0.028-0.435, **Cr** 8.88-186, **Cu** 1.01-111, **Fe** 230-48.700, **Hg** 0.096-0.565, **Ni** 1.71-124, **Pb** 0.42-81.8, **Zn** 2.34-244	ppm dw	5

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Country	Sampling matrix	Element and concentration	Units	Reference[a]
Caribbean Mexican	Sediment	**Cu** 0.3-6.9, **Cd** < 0.020-0.2, **Cr** 1.7-26.4, **Pb** 0.8-10.9, **Zn** 21.7-34.2	ppm	29
		As 0.16-0.63 ,**Cd** 0.00-1.00, **Hg** 0.00-0.70, **Pb** 0.00-2.84		30
		As 0.84, **Cr** 16.6-53.1, **Mn** 33-649		31
Jamaica	Sediments	**As** 1.4-7.03, **Cr** 5.0-48.0, **Cu** 3.5-73.8 ,**Cd** nd-10.0, **Hg** 0.05-0.30, **Ni** 3.7-23.9, **Pb** 6.4-31.1, **Zn** 7.9-70.0		32
Guadalupe (Eastern Region Caribbean)	Sediments	**Cu** 9.3-187.2, **Cd** <0.3 to 0.6 , **Pb** 1.7-235.7, **Zn** 19-664.3	ppm dw	33
Trinidad and Tobago	Sediments	**Cu** 0.06-421, **Cd** 0.04-67.90 , **Pb** nd-20.91, **Zn** 0.10-39.29	ppm	34
	Seawater	**Cu** 0.50-14.27, **Cd** 0.06-1.13, **Pb** 0.50-6.94, **Zn** 0.50-92.23		34
	Sediments	**Cr** 365, **Hg** 1.4, **Pb** 123, **Zn** 450		35

Values are expressed in ppm. BDL = Below Detection Limit; nd = not detected. The concentration unit is given once per row and applies to all elements beneath it. ‘nd’ indicates ‘not detected’, and ‘<’ denotes values below detection or quantification limits. When not explicitly specified in the original study, concentration units are reported as ‘ppm’ without distinction of weight basis (dry or wet). This table includes data from all 35 scientific publications reviewed for this study, as listed in the references.

[a]1, González et al. (1999); 2, Gonzalez and Ramirez (1995); 3, Andreany et al. (2008); 4, Mesa et al. (2021); 5, Sbriz et al. (1998); 6, Rodríguez et al. (2020); 7, Ochoa and Gonzàlez (2016); 8, Deveze (2011); 9, Bastidas and Garcia (1999); 10, Laboy-Nieves and Conde (2001); 11, Jaffe´ et al. (1998); 12, Jaffe´et al. (1995); 13, Zapata-Vivenes et al. (2020); 14, Olivero et al. (2016); 15, Salinas et al. (2014); 16, Olivero et al. (2015); 17, Marrugo et al. (2015a); 18, Ruiz et al. (2014); 19, Marrugo et al. (2010); 20, Gracia et al. (2010); 21, Fernandez-Maestre et al. (2018); 22, Vergara and Rodríguez (2015); 23, Fuentes et al. (2018); 24, López and Barragán (2016); 25, Burgos et al. (2017); 26, Barros -Barrios et al. (2016); 27, Cadavid-Velásquez et al. (2019); 28, González and Torres (1990); 29, Marín-Leal et al. (2022); 30, Gonzales et al. (2008); 31, Greeneway and Rankine Jones (1992); 32, Jaffe´ et al. (2003); 33, Bernard (1995); 34, Persad and Rajkumar (1995); 35, Díaz -Asencio, et al. (2011).

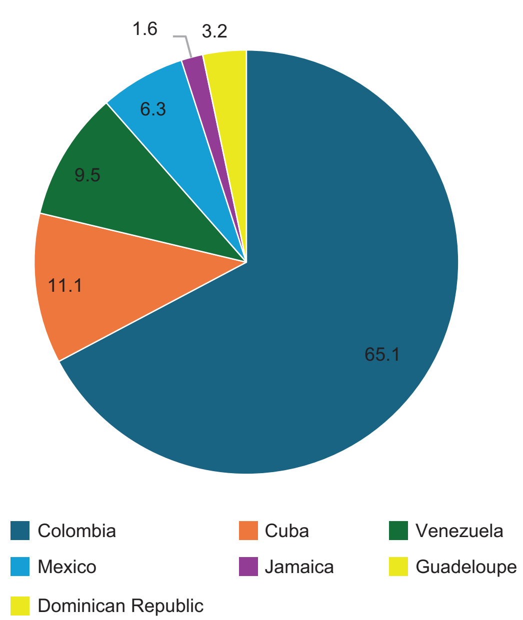

Fig. 2. Distribution of potentially toxic elements studies by country in the Wider Caribbean Region.

PTEs detection

Several of the studies reviewed from the Caribbean region analyzed As, Cu, Cd, Cr, Hg, Pb, Mn, Ni, and Zn, in samples of different matrices and living organisms that were collected in areas known to be affected by direct inputs of pollutants. These suggest that PTEs concentrations are detected in nearby areas with mainly anthropogenic activities. Pernia et al. (2018), report the presence in sediments and organisms in the marine ecosystem Estero Salado de Guayaquil that exceeds the permissible limits proved for metals such as Cd and Pb in areas with industries and population settlements near the ecosystem.

Meanwhile, a study in Guajira, Colombia (Fernández-Maestre et al. 2018) evaluated the levels of Cd, Hg, Pb, Ni, and Zn in biological tissues of fish in six coastal areas. Significant correlations were found between Pb and Zn metals, suggesting sources of similar origin. In addition, it was found that these metallic elements can be incorporated into this marine system through mining activity and wastewater discharges (Díaz et al. 2006). Some studies on the presence of these elements reveal an important environmental problem that requires attention (Díaz et al. 2006, Ojeda and Aglayde 2006). Additionally, it is emphasized that the chemical elements mentioned are characterized by their potential for toxicity, even at low concentrations (Ramírez 2014).

In a study conducted in the Caribbean areas of Costa Rica and Panama (Guzmán and Jiménez 1992), high concentrations of Al, Fe, and Mn were detected in coral skeletons and reef sediments, showing long-term transport of metal contaminants. Other research conducted on bivalves suggests such metal mobility in Venezuela near the mouth of the Tuy River. Jaffe' et al. (1995) reported elevated levels of Cd, Cu, and Ni and the potential effects of these chemicals over a large geographic area, both in terms of water quality and ecology.

The data described by different countries vary in terms of sampling systems, parameters determined, environmental matrices analyzed, and analytical techniques used in the analysis of PTEs, and differ in the presentation of the available data, which makes comparison difficult. Most countries in the WCR have limited or no data available.

Concentrations of PTEs in sediment

The contaminant levels mentioned in this study are compared to standards provided by the National Oceanic and Atmospheric Administration (NOAA), which provides fundamental guidelines for assessing the effects of contaminants on aquatic ecosystems. According to NOAA, the Threshold Effects Level (TEL) and Probable Effects Level (PEL) are key benchmarks for identifying potential toxicity risks to aquatic organisms. In this context, the results obtained in Cuban sediments - where PEL values are exceeded for metals such as Cr, Cu and Pb - suggest the existence of ecotoxicological scenarios that can negatively affect local biota (**Fig. 3**).

This highlights the need for adequate monitoring and management of contaminants to safeguard ecosystem health, in line with NOAA recommendations on water quality and environmental integrity. Elevated Cr concentrations have been reported in residential and industrial areas of Havana, demonstrating the direct influence of anthropogenic activities on urban pollution (Gonzalez and Torres 1990). Additionally, recent studies have identified moderate Zn contamination in industrial soils and agricultural areas, submitting a regional dispersion pattern of this element (Yaylalı-Abanuz 2011, Díaz et al. 2019).

In this context, rice (a crop with high consumption in the region) could serve as a transfer pathway for these metals into the food chain, either through bioaccumulation in contaminated soils or by using Zn-enriched agricultural inputs (Díaz et al. 2009). In Guadeloupe, the highest levels of Zn have been recorded in areas where residential, agricultural and industrial activities overlap (Bernard 1995). Similarly, the presence of metallurgical industries in the WCR is a recognized source of Zn contamination (Alonso et al. 2024).

Cr concentrations are significantly higher in Cuba (up to 339 ppm) compared to Mexico (below 0.020 ppm). Pb levels also show notable variation: Cuba exhibits the highest reported values (up to 903 ppm), followed by Trinidad and Tobago (123 ppm), whereas Mexico shows much lower concentrations (ranging from 0.00 to 2.84 ppm). These values correspond to the upper extremes of the ranges presented in **Table I** and reflect the most elevated levels reported in the reviewed literature for each country.

Concentrations of PTEs in water

The results of the water samples show varying concentrations of PTEs among Cuba and Trinidad and Tobago. Each country applies unique sampling parameters, analytical methods, and regulatory limits, which complicates direct comparisons. The elevated concentrations of Pb and Zn observed in Cuba and Trinidad and Tobago may be linked to emissions from industrial facilities and occupational exposure related to metal-processing activities.

Table I shows that Zn concentrations in water exhibit substantial variations: Cuban waters display

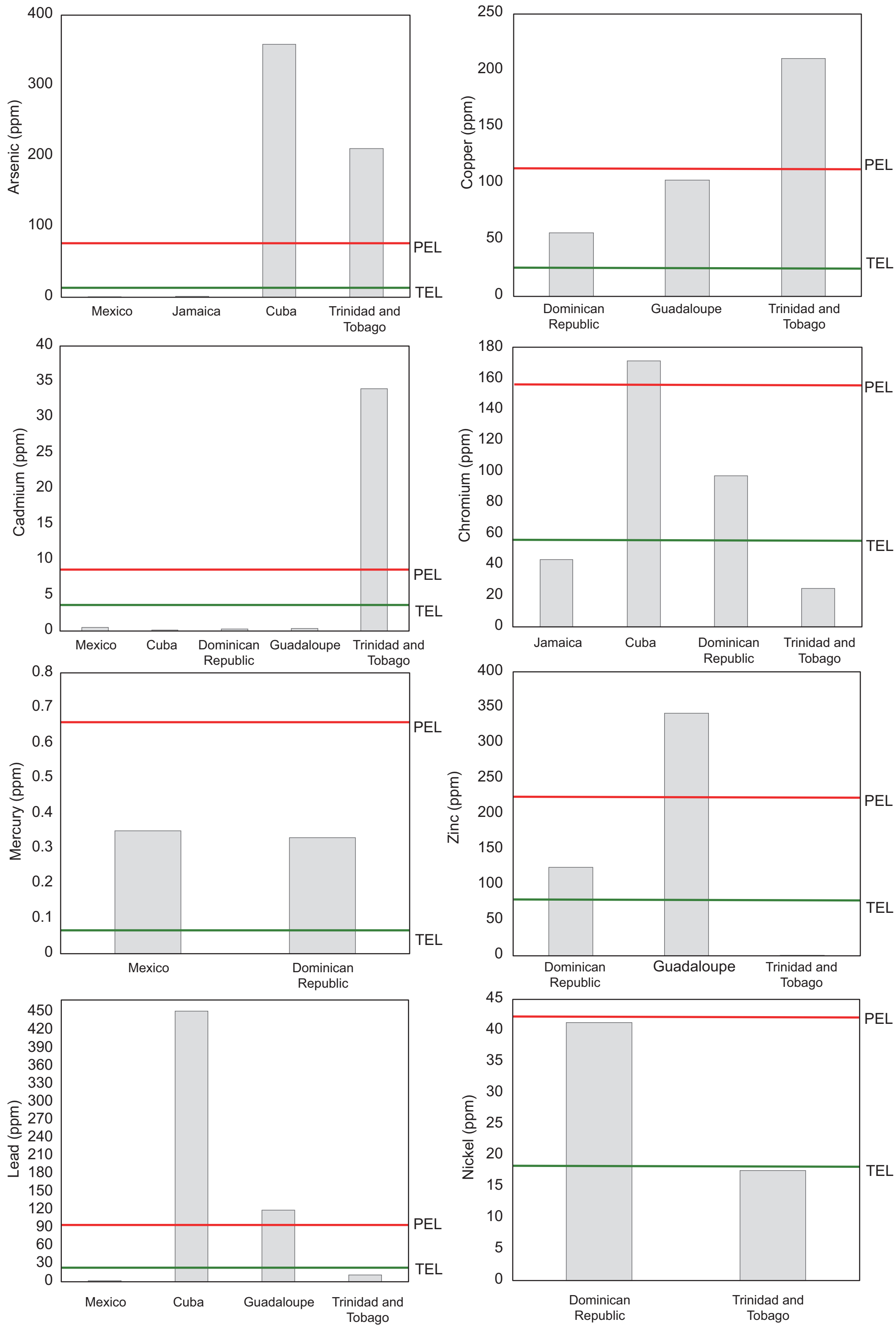

Fig. 3. Comparison of potentially toxic elements values in sediments with the Threshold Effect Level (TEL) and Probable Effect Level (PEL) values established in ppm dw by NOAA (1999), Buchman (2008). The TEL (Threshold Effect Level) and PEL (Probable Effect Level) lines indicate the concentration levels above which adverse effects on the environment are expected, and it can be observed that several potentially toxic elements concentrations in countries exceed these thresholds, suggesting potential ecological damage (Buchman 2008).

values ranging from 0.0181 to 0.0431 ppm, whereas those of Trinidad and Tobago range from 0.50 to 92.23 ppm. This difference of several orders of magnitude may reflect the greater industrial and urban activity in Trinidad and Tobago (Norville 2005). Finally, on the data on Mn in Jamaica, maximum concentrations reach up to 649 ppm followed by Cuba with 251 ppm.

The marked variability in PTEs concentrations among Cuba, Mexico, and Trinidad and Tobago suggests significant disparities in pollution sources, industrial activities, environmental regulations, and the effectiveness of wastewater treatment systems. In the case of Cu, the highest concentrations are reported in Trinidad and Tobago (14.27 ppm), followed by Cuba (0.0081 ppm). These elevated concentrations can largely be attributed to anthropogenic pressures, particularly intensive mining operations and industrial discharges. Metallic mining has been consistently identified as a major source of Cu contamination in aquatic environments across various countries (Hernández-Jatib et al. 2014, CAMIPE 2019, Téllez and Azamar 2021).

Cd concentrations are relatively low across the countries analyzed, with values below 0.06 ppm in Trinidad and Tobago, and ranging from 0.00002 to 0.00016 ppm in Cuba. Zn concentrations in water also show notable disparities. In Cuba, reported values range from 0.0181 to 0.0431 ppm, while in Trinidad and Tobago, concentrations range from 0.50 to 92.23 ppm. These differences likely reflect variations in industrial discharge, urban runoff, and environmental management strategies.

PTEs concentrations in living organisms. Comparative analysis of reported values

Concentration values detected in organisms result from environmental contamination, bioavailability, and bioaccumulation processes (Wang and Rainbow 2008, Reis et al. 2010, Rizzo 2010, Bhat et al. 2019,). These elements significantly affect Caribbean biodiversity, disrupting marine fauna and ecosystem stability (Guyvenchy et al. 2023). Metal-induced oxidative stress promotes cellular damage and mortality (Rizzo 2010. Valko et al. 2005), impairs competitive abilities, and inhibits photosynthesis in species lacking efficient defense mechanisms (Naranjo-Sánchez and Troncoso-Olivo 2008, Rizzo 2010, Chen et al. 2017, Kumar et al. 2014). The ingestion of metals through the food chain has a negative impact on both human health and the environment, especially in areas with high levels of contamination (Garai et al 2021, Bishnu et al. 2024, Peralta-Videa 2024). This phenomenon also affects the economy of coastal communities, as the reduction of biodiversity and the productivity of marine ecosystems can have a significant impact on fisheries and aquaculture (Khalil 1998, Khushbu et al. 2022, Sharma et al. 2025).

According to the Food and Agriculture Organization of the United Nations (FAO), several countries have concentrations of potentially toxic elements (PTEs) in fish and shellfish tissues that exceed the established limits (5 ppm dry weight). Studies by Laboy-Nieves and Sbriz et al. (1998) document the lowest values in the Dominican Republic, while Conde (2001) indicate that Venezuela reports the highest values of Cu and Ni. Several factors, such as water dynamics, sediment characteristics, pH and redox potential, the presence of ligands, as well as bioaccumulation and biomagnification through the food chain, significantly influence the concentrations of PTEs in fish tissues.

The concentration values of several elements (As, Cu, Cd, Cr, Hg, Mn, Ni, Pb, and Zn) in countries such as Cuba, Mexico, and Trinidad and Tobago exhibit interesting patterns of variability. For instance, the *Callinectes sapidus* (blue crab) in the Mexican Caribbean exhibits Zn values ranging from 14.0 to 18.0 ppm, while several species in Cuban coastal ecosystems, such as *Echinometra lucunter* and *Caretta caretta*, show considerably higher concentrations, reaching up to 412 ppm. These differences may reflect varying levels of environmental exposure, bioaccumulation capacity, and proximity to contamination sources such as urban or industrial effluents (Mesa et al. 2021).

Venezuela presents high values of Cd (16.01 ppm) in tissues (Zapata-Vivenes et al. 2020), while the lowest values (0.0019 ppm) are presented by Colombia (Fernández-Maestre et al. 2018). Cr is reported in Dominican Republic with a maximum of 10.7 ppm (Sbriz et al. 1998), while the lowest values (0.1 ppm) were reported in Mexico by Deveze Arcos (2011), the highest values of Cu (3854 ppm) were reported by Laboy-Nieves and Conde (2001) in Venezuela, while the lowest values (1.01 ppm) were reported by Sbriz et al. (1998) in Dominican Republic.

The presence of considerable concentrations of PTEs in fish and mollusks tissues can be explained by a combination of factors such as bioaccumulation in aquatic organisms (Liu and Ren 2019, Hernández 2020) transfer across trophic levels; bioavailability of metals or metalloids affected by factors such as pH and marine salinity; regional differences in contamination levels and management practices;

and interspecies variations, bioaccumulation rates and detoxification mechanisms (Zapata-Vivenes et al. 2020).

In echinoderm and mollusk tissue, the highest values of Pb (2018.6 ppm dw) were reported by Laboy-Nieves and Conde (2001) in Venezuela, while the lowest values (0.004 ppm) were reported by Fernández-Maestre et al. (2018) in Colombia. Furthermore, the Zn and Cr values reported in bivalves and tissue of Dominican Republic are higher than the limit stipulated by the FAO (5 ppm dry weight). Through bioaccumulation and biomagnification processes, benthic organisms can accept PTEs and transfer them through the food chain (Guillama et al. 2022, Camargo 2023). Factors such as the species, age, size and physiological state of the fish can influence the accumulation of these elements in their tissues (Farkas et al. 2003).

Influence of physical and chemical factors on the distribution of PTEs in marine ecosystems

Physical, chemical and biological factors play an important role in aquatic systems (Cala et al. n.d., Salas et al. 2020). When analyzing data on the concentrations of these elements in organisms, it is essential to take these factors into account, as they influence the distribution, transport, retention and dispersion of these pollutants (Socarras et al. 2022). Particle size strongly influences: finer particles such as silt and clay have a higher adsorption capacity due to their specific surface area (Förstner and Wittmann 2012), which enhances the sediment's ability to transport adsorbed elements (Jiménez 2016, Condori 2023), particularly heavy metals like Zn and Mn, as demonstrated in recent studies analyzing sediment granulometry and organic matter interactions (Flores et al 2018 , Guillama et al. 2022, Socarras et al. 2022, Mendoza et al. 2023). This should be considered when interpreting sediment PTEs data, as they decide the spatial and temporal distribution of contaminants. On the other hand, from a chemical point of view, the reducing conditions and the slightly acidic pH in the water favors the mobility of metals such as Cd, Pb, Zn (Guillama et al. 2022, Socarras et al. 2022).

CONCLUSIONS

It is clear from this review that there is an urgent need for standard environmental quality data for trace metals and metals and organic pollutants in most of the WCR. As currently existing environmental sampling data vary in terms of sampling schemes, environmental matrices analyzed, as well as differences in data reporting formats, make meaningful comparisons of the available data is difficult. Sediments turned out to be adequate indicators of PTEs contamination but, in general, there is considerable variability in the values reported by the authors of the reviewed literature. Furthermore, for many of these pollutants, there is limited or no available data from most countries in the WCR.

Although the available data provides straightforward evidence of coastal pollution in many areas of the WCR, an assessment of these pollutants on a regional scale is not possible due to the lack of a regional scale. However, the available data say that concentrations of contaminants can be found throughout much of the region, including in significantly industrialized and agricultural locations, and that the potential for environmental effects may be high. High concentrations of pollutants are perceived and can be found in estuaries of major rivers, from agricultural areas. In some cases, contaminant levels exceeded TEL and/or PEL standards, suggesting the existence of ecotoxicological scenarios.

Many sites exceeded the PEL values for a few PTEs which may indicate potential values of possible ecotoxicological consequences on biota in this region. Therefore, further studies should be initiated to determine the extent and magnitude of these occurrences. In general, this review reflects the presence of various pollutants in the WCR and therefore environmental policies, and long-term monitoring programed, should be instituted that cover the entire geographical area of the WCR. Without addressing this need, it will be difficult to scientifically assess the state of the marine environment in this region. This information is essential for sound and effective coastal resource management and environmental decision-making.

It is important to promote the use of clean technologies and the implementation of sustainable agricultural practices in the region, in order to reduce the application of these compounds and mitigate their potential persistence and negative impacts on the environment. In addition, the region is a marine biodiversity hotspot, and its economies are driven by coastal tourism and fisheries, hence, the integrity of the marine environment is paramount for its sustainable future.

Finally, it is necessary to propose strategies to mitigate pollution, in coordination with the efforts of the countries concerned. The formulation and implementation of national and international environmental policies to address the contaminants present in the WCR can greatly contribute to the conservation of marine biodiversity.

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