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Review

Heavy metals in macroinvertebrates (*Penaeus*) in the Mexican coasts of the Gulf of Mexico: status, sources, and regulations

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ABSTRACT. The present work analyzes the current situation of scientific research on heavy metals and current regulations in macroinvertebrates (*Penaeus*) from the coastal region of the Gulf of Mexico. Its association with public health was identified based on national and international permissible limits for this fishery resource. The research analysis identified a high percentage of studies that report concentrations within the permissible limits established by the Mexican Official Standards and European regulations, reflecting a high percentage of consumption of this fishery resource that does not represent a risk to public health. However, specific cases exceeded national and international concentration limits, which justifies the importance of monitoring this fishery resource with emphasis on compliance with current regulations, supporting the need to redefine regulatory policies to address the current situation. Likewise, it is important to quantify these metals in a homogeneous, systematic, and continuous way to contrast the different studies on macroinvertebrates as environmental health bioindicator organisms and to know the distribution of these pollutants in the ecosystems inhabited by this important fishery resource.

Keywords: shrimp; environmental contamination; bioaccumulation; public health; toxicity; Gulf of Mexico

INTRODUCTION

Heavy metals are chemical elements with a density greater than 4 g cm^{-3}, mass, and atomic weight greater than 20 (g mol^{-1} or Da), which sometimes have a toxic effect at low concentrations. The heavy metals group includes Pb, Cd, Hg, As, and Cu, which have no biological function and are not required during metabolism (Rendina 2014, Londoño-Franco et al. 2016, Yilmaz et al. 2018). The increase in heavy metal concentrations is associated with their use as raw materials in various industrial activities, anthropogenic waste, and the development of commercial activities (Yahya et al. 2018). Anthropogenic sources that generate heavy metals contribute directly to altering trace concentrations. These can increase significantly in environments where their presence was usually negligible due to the contribution of these elements through different natural and anthropogenic pathways entering the environment (Zuluaga-Rodríguez et al. 2015, Pabón et al. 2020).

Coastal aquatic ecosystems are among the most susceptible sites to increase heavy metals concentration, as they are sites where the exchange of materials occurs between the terrestrial and aquatic environments (Mendoza-Carranza et al. 2016, Vazquez-Sauceda et al. 2019). Rivers receive, along with their course's important inputs of pollutants such as heavy metals, becoming the main access route of these pollutants to the coastal zone (Pérez-Castresana et al. 2019, Castañeda-Chávez et al. 2020, Navarrete-Rodríguez et al. 2020).

Heavy metals have no degradation capacity and accumulate by deposition in sediments, which are the

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main reservoir of these elements. When these directly affect aquatic species, many may disappear, and others may present an accumulation process (Fuentes-Hernández et al. 2019, Rosales-Ortega et al. 2020, Venelinov et al. 2021).

The analysis of the concentrations of heavy metals in aquatic ecosystems is a topic of interest due to the harmful effects they cause on the aquatic biota. Different investigations report its high capacity for persistence and biomagnification throughout the food chain (ATSDR 2012a, Vazquez-Sauceda et al. 2019). Biomagnification of Hg, and partial bioaccumulation of Cu and Cd, are reported in fragments along food chains (David 2012). Another study evaluated the trophic transfer of four toxic metals Cd, Cr, Cu, and Hg. In this study, the biomagnification of Hg and Cr was reported, while Cu and Cd did not show a clear trend along the food chain (Liu et al. 2019).

Monitoring studies of these elements use phyto-planktonic and macrobenthic organisms as pollution bioindicators due to their ability to grow in the water column as well as their capacity to interact with sediments in their habitat, and this favors pollutant incorporation into tissues and their entry into the food chain (Ke & Wang 2002, Soto-Jiménez 2011, Yilmaz et al. 2018).

Some metals, such as Pb, Cd, and Hg, can cause genotoxic damage at low concentrations (Pis et al. 2014). In marine ecosystems, benthic organisms, particularly crustaceans, are widely used to estimate the presence and effect of heavy metals due to their sensitivity to different pollutants (Mendoza-Carranza et al. 2016, Bueñaño et al. 2018, Rosales-Ortega et al. 2020). Benthic animals such as shrimp can incorporate and bioaccumulate metals through their gills in direct contact with marine sediments (Frías-Espericueta et al. 2011, Vazquez-Sauceda et al. 2019). The bioaccu-mulation capacity of shrimp contributes to being considered bioindicator organisms of sediment and water quality in their natural habitat. They also provide information on the bioavailable fraction of heavy metals in coastal freshwater and marine ecosystems (Páez-Osuna 2005).

Sustainability and responsible fishing are great challenges in Mexico, implying conserving biodiver-sity and richness, especially in coastal ecosystems (INAPESCA 2006). These ecosystems act as areas for larval development, feeding, refuge, and recruitment site for numerous species, standing out for their economic, biological and ecological importance due to the high productivity of fishery resources and materials they generate (Contreras-Espinosa et al. 2002, Vazquez-Sauceda et al. 2019). Likewise, in the coastal region of the Gulf of Mexico, there are important ports, fishing, industrial, and commercial complexes where extensive agriculture is carried out, generating 90% of hydrocarbons and producing 90% of natural gas. The capture area constitutes 40% of the demersal fisheries in the Gulf of Mexico (Guzmán-Amaya et al. 2005, Ramírez-Ayala et al. 2020). Together, the activities mentioned above constitute the main sources of heavy metal incorporation into the coastal environment.

This review aimed to analyze the research focused on heavy metals in macroinvertebrate communities and their association with the risk to public health from consuming these fishery products. Research conducted in recent decades on analyzing heavy metal concentrations in macroinvertebrates in the coastal ecosystems of the Gulf of Mexico is considered insufficient (Ramírez-Ayala et al. 2020), as it only refers to geographically specific and heterogeneous sites. They are making it difficult to compare results for animals and elements analyzed. The need to conduct and analyze studies on these elements' concentration in benthic animals such as shrimp was identified. These studies should be conducted systematically according to the distribution and seasonality of the species that make up this fishery resource.

Sources of heavy metals in the coastal zone

Heavy metals and metalloids are released into aquatic ecosystems through natural and anthropogenic path-ways (Zuluaga-Rodríguez et al. 2015, Yahya et al. 2018). The latter pathway represents the largest contribution through soils, mainly due to industrial and agricultural activities to which wastewater discharge is added (Méndez et al. 2009). Together the sources of these heavy metals represent risks to living beings that depend on point habitats and feeding sites (Díaz et al. 2019, Navarrete-Rodríguez et al. 2020).

The pathways of incorporation of heavy metals into different ecosystems vary according to the type of anthropogenic activities developed in certain regions and the chemical properties of these elements. The main anthropogenic sources of heavy metals incorpo-ration have been widely documented. Pb and Hg can be released into the environment mainly by mining acti-vities (ATSDR 2012a). The latter is also produced by agricultural activities and combustion (Covarrubias & Peña-Cabriales 2017, Ramírez-Ayala et al. 2020). Meanwhile, Cd is used to manufacture nickel-cadmium batteries (Mead 2011, ATSDR 2012b) and Cr is used in manufacturing plastic coating, among others (ATSDR, 2012c).

Wastewater discharges are the largest contributor of heavy metals in rivers ending in coastal and marine zones. Because these are the product of various anthropogenic activities, mainly industrial, which increase water sources pollution and another anthropogenic source is the discharge of human settlements without treatment (Castañeda-Chávez et al. 2020). All these activities contribute to the increase in the concentration of heavy metals in water and increase the risk of exposure to these elements to public health and biota (Calao & Marrugom 2015, Pabón et al. 2020). Therefore, surface waters such as rivers are exposed to various types of pollutants such as heavy metals during their course. To these must be added the contribution they receive from the different effluents discharged in the final section of hydrological basins and the coastal zone (Calao & Marrugom 2015, Díaz et al. 2019, Navarrete-Rodríguez et al. 2020, Pabón et al. 2020).

Crustaceans as bioindicator animals

Bioindicator animals generate information on their habitat's environmental conditions, such as their presence, absence, and behavior (Soto-Jiménez 2011, Vidal-Martínez 2020, Castillo et al. 2021). These are indicators of the disturbances they are subjected to in their systems (Amésquita 2017, Ramírez-Ayala et al. 2020). Therefore, these animals provide relevant information about their existence in a site, expressing at certain times their response capacity by adapting to different environmental factors that signal some processes of alteration in the environment (Soto-Jiménez 2011, Vidal-Martínez 2020). Pernía-Santos et al. (2018) indicated that the concept of bioindicator refers to species selected for their sensitivity or tolerance to various factors. Generally, pollution indicators are used due to their specificity and easy monitoring.

The use of aquatic bioindicator animals to analyze the presence of heavy metals in the environment has a relevant role in providing information on the contamination level of these elements and the associated risks to public health and the environment (Omobepade et al. 2020). Crustaceans have been used as pollution bioindicators in aquatic environments, mainly due to their high ecological plasticity, ability to alter their physiological and biochemical functions to survive in the presence of pollutants, and their wide distribution (Soto-Jiménez 2011, Ramírez-Ayala et al. 2020).

The crustacean group is considered a bioindicator, has narrow environmental tolerances, and is abundant in sites where other species would be absent in abnormal conditions. In addition, some species of this group have low mobility or are sedentary, expressing a positive relationship between the concentration of the pollutant in their tissues and the concentration of the same in the environment (Hagger et al. 2006, Bautista-Covarrubias et al. 2015).

The Crustacea subphylum has a great variety of species, particularly in the order Decapoda, which represents one of the most diverse crustacean order. This group includes species of commercial importance for human consumption, such as shrimp, prawns, lobsters, and crabs (Álvarez-Noguera et al. 2011). The extensive group of decapods, including those that have a shrimp morphological pattern, it is highlighting those included in the suborder Dendrobranchiata, which includes approximately 500 species distributed in seven families: Aristeidae, Benthesicymidae, Penaeidae, Sicyoniidae, Solenoceridae, Luciferidae and Sergestidae (Farfante & Kensley 1997, Arreguín-Sánchez & Arcos-Huitrón 2011). Penaeidae and Sicyoniidae include species captured commercially in the tropics and subtropics worldwide (Spivak 1997, Lira et al. 2017); these have also been used as important bioindicators of environmental pollution in coastal zones.

The Penaeidae family excels in socioeconomic importance by providing the largest food resources worldwide. Therefore, penaeids are an important group as a source in the food industry, which generates economic income for the human population worldwide. In Mexico, the total shrimp catch is obtained from offshore fishing and aquaculture activities, including species such as *Penaeus vannamei*, *Litopenaeus stylirostris*, *L. setiferus*, *Farfantepenaeus californiensis*, *F. duorarum*, *F. aztecus*, among others (INAPESCA 2006, Blanco-Martínez et al. 2020). Likewise, the shrimp group is ecologically important due to its wide diversity, temporal presence, and permanence in estuarine coastal areas. They are an abundant numerical component, apart from being essential links in the food web by transferring energy to higher trophic levels (Almeida et al. 2013, Blanco-Martínez & Pérez-Castañeda 2017). These contribute to nutrient recycling through fecal depositions and favor the maintenance of submerged aquatic vegetation habitats (Barba 2012).

Heavy metals in shrimp from the Gulf of Mexico

Several investigations have shown that the input of heavy metals in freshwater, coastal, and marine ecosystems is reflected in the quality of their sediments, by the concentration of metals reported to be in direct contact with animals such as shrimp (Lango-Reynoso et al. 2013, Castañeda-Chávez et al. 2014, Vazquez-Sauceda et al. 2019, Ramírez-Ayala et al. 2020, Aguilar et al. 2021). Some of these investigations have evaluated the concentration of heavy metals in the sediment surface layer, with an average thickness of 0-5 cm, because this fraction corresponds to the layer with the highest biological and chemical activity (Páez-

Osuna & Osuna-López 1990, Vazquez-Sauceda et al. 2019). Therefore, this portion of the sediments has a marked influence on water quality and benthic animals such as shrimp (Fig. 1), as a result of the existing interaction in the interrelationship between water and sediment (Vazquez-Sauceda et al. 2019, Navarrete-Rodríguez et al. 2020, Venelinov et al. 2021).

Scientific research reports the capacity of benthic animals as bioindicators, mainly for the presence of heavy metals in the coastal and marine environment. However, only scientific research published in peer-reviewed, indexed journals was considered in this paper to give a better heavy metals behavior appraisal of the genus *Penaeus* in the Gulf of Mexico (Table 1). It was also identified that all the studies focused on the Gulf of Mexico used acid digestion to analyze edible shrimp tissue samples, which correspond to different species caught in the coastal and littoral zone of the Gulf of Mexico. Methodological variations associated with the equipment used to quantify the elements analyzed were also identified.

In research studies on heavy metals, it was identified that they had focused mainly on two species, *L. setiferus*, and *F. aztecus*. Together, these species are an important fishing resource in the Gulf of Mexico, which are considered bioindicator animals in the different coastal lagoon systems and the marine zone. The species mentioned above are not the only ones exploited as a fishery resource; therefore, it is important to monitor all shrimp species and other crustaceans for human consumption in Mexico.

It was identified in this review that scientific research on the presence of heavy metals in crustaceans such as shrimp is scarce. Most studies have been conducted in specific geographic areas. Coinciding with the above, Ramírez-Ayala et al. (2020) reported that coastal ecosystems in Mexico have been the most studied, among which the coastal ecosystems of the Gulf of California stand out. The authors also pointed out a small number of studies on the concentration of Cd and Pb in freshwater crustaceans. Consequently, the lack of scientific research prevents comparisons between these studies. Most of them are geographically isolated studies. Some are unique in some regions, have a narrow scope, and lack homogeneity and temporality, generating disparity and a gap in knowledge about the presence of heavy metals in penaeid shrimp from the Gulf of Mexico. However, Ramírez-Ayala et al. (2020) reported that, generally, the contamination levels reported in Mexican aquatic ecosystems are similar to those found in other regions of the world. They highlight Mexico's ecological richness, particularly in aquatic ecosystems where the information reported on environmental pollutants is scarce (Ramírez-Ayala et al. 2020).

The present review identified a marked heterogeneity among the concentrations of heavy metals reported in shrimp species in different lagoon systems and coastal zones in Mexico. It was also detected that the maximum metals concentrations were reported by Vazquez-Sauceda et al. (2019) in *L. setiferus* shrimp in the San Andrés Lagoon with Fe 90.55 ± 63.55 μg g^{-1} and Cu with a concentration of 88.65 ± 69.90 μg g^{-1} (Table 1). The maximum Cd concentration was also reported in this lagoon at 1.72 ± 0.16 μg g^{-1} (Vazquez-Sauceda et al. 2019). Likewise, Vazquez et al. (2001) reported a similar value for this element with 1.21-6.11 μg g^{-1} in the southern zone of the Campeche Sound.

In the San Andrés lagoon, Vazquez-Sauceda et al. (2019) reported in *L. setiferus* that the maximum concentration of Pb was 1.68 ± 0.32 μg g^{-1} and Ni with 2.46 ± 0.90 μg g^{-1}. Regarding Ni Vidal-Martínez et al. (2006) reported in the species *F. duorarum* from the Campeche Sound a range of 2.46-149 μg g^{-1}. Meanwhile, Hg presented minimum values in most investigations analyzed; the maximum concentration was reported by Lango-Reynoso et al. (2013) in the Alvarado lagoon in *L. setiferus* with 0.1215 ± 0.0344 μg g^{-1}.

Heavy metal concentrations in the study area reported by Vazquez-Sauceda et al. (2019) for Cd, Pb, Cu, Fe, and Ni in the Laguna San Andrés-Río Tigre, were generally higher than those reported in other research. The differences between the concentrations of metals in the study areas can be attributed to different causes, such as the point and diffuse sources of pollution in these lagoon systems and coastal zones, plus the hydrological processes that occur in them. In addition, the physiological characteristics of the different shrimp species analyzed in this research may difference heavy metals behavioral patterns (Palomarez-García et al. 2009, Vazquez-Sauceda et al. 2019).

The contrasts between the research analyzed the different shrimp species in the Gulf of Mexico are focused on monitoring a specific group. Most of the research analyzed does not include the analysis of the relationship between sediments, water, and animals. The need to study the implications and physiological effects of heavy metals on the development of animals and the risks to public health is highlighted. It is noted that there is a need for comprehensive knowledge on this problem since there is research on specific monitoring studies, in the evaluation of heavy metals in shrimp, in the studies by Palomarez-García et al. (2009), Vazquez-Sauceda et al. (2017, 2019). However, these works have a limited contribution to the knowledge of trophic transfer processes, accumulation,

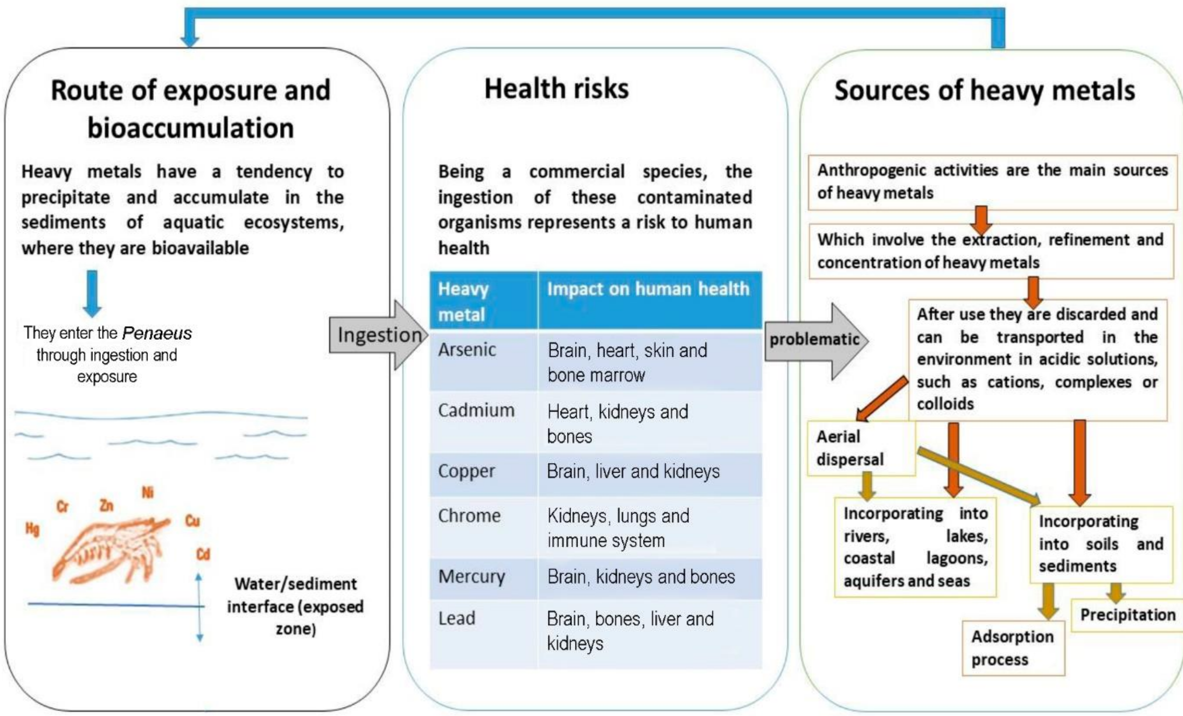

Figure 1. Bioavailability pathway of heavy metals in *Penaeus* of food-importance.

and biomagnification of trace elements. Most of them are only focused on quantifying the concentration of these pollutants as individual elements. They do not consider their effects on the environment or social impact or discuss their long-term repercussions making it difficult to create and implement preventive actions to reduce public health risks due to heavy metals.

The information analysis identified a lack of homogenization among the monitoring processes, including many sampling sites and times of the year in the investigations analyzed for heavy metals in shrimp tissue. Contributes to integrating information that broadly covers anthropogenic pollution gradients to establish Mexico's environmental reference sites.

The need to quantify heavy metals in different matrices and incorporate biomonitoring with biomarkers is highlighted to estimate changes in the ecosystem and the interaction of different nuances in the mobility or accumulation of these pollutants (Portillo 2010). Metallothionein (MT) is considered a specific biomarker of metal contamination in aquatic animals, whose advantages are the speed of response to the presence of heavy metals in fish and gastropods (Ureña-Robles 2006).

Toxicological effects on shrimp

The evaluation of public health risks and the permissible levels of toxic substances incorporated into the natural environment due to natural and anthropogenic activities are the justification for considering the toxicological effects on biological systems (Fig. 1). Various heavy metal toxicity tests in juvenile stages of *P. vannamei* indicate that even low concentrations of a mixture of heavy metals such as Cd, Cu, Fe, Hg, Mn, Pb, and Zn can have a lethal effect in the medium term. Frías-Espericueta et al. (2008) agree with the importance of explaining the metals and sublethal concentration interaction with their synergistic effect.

Macroinvertebrate exposure to metals and their subsequent accumulation can cause alterations in animals, depending on the exposure time and the concentration of the different essential and non-essential metals (Bainy 2000). According to Frías-Espericueta et al. (2008), the exposure of *P. vannamei* juveniles to individual lethal concentrations for 96 h generated dose- and time-dependent damage in the hepatopancreas, gills, epipodites, and midgut tissues of the organisms during the experiment, highlights the importance of using bioindicator animals and the analysis of this type of research.

Another investigation conducted on *P. vannamei* postlarvae showed that the growth of these animals could be affected proportionally by the heavy metal mixture concentration. In addition, they associated the decrease in the growth of the shrimp with the use of a

Table 1. Research on the determination of heavy metals (μg g^{-1}) in edible crustacean tissue in lagoon systems and coastal zone of the Gulf of Mexico. *ND: means not detected or that the detection limit is outside the operating conditions of the equipment; **average values.

Reference	Species	Study zone	Heavy metal	Concentrations (μg g^{-1})
Vazquez-Sauceda et al. (2019)	*Litopenaeus setiferus*	Laguna San Andrés-Río Tigre, Tamaulipas	Cd	1.72 ± 0.16
			Pb	1.68 ± 0.32
			Cu	88.65 ± 69.90
			Fe	90.55 ± 63.55
			Ni	2.46 ± 0.90 (máximum)
Vazquez-Sauceda et al. (2017)	*Farfantepenaeus aztecus*	Laguna Madre, Tamaulipas	Cd	0.130 - 0.680
			Pb	0.38 - 0.95
			Hg	< 0.125
Aguilar-Ucán et al. (2014)	*Litopenaeus setiferus*	Laguna de Término, Campeche	Cd	*ND - 0.015
			Pb	*ND
			Cu	41.620 - 58.470
			Fe	0.103 - 0.197
			Zn	0.3698 - 0.4846
Castañeda-Chávez et al. (2014)	*Litopenaeus setiferus*	Lagoon system Carmen-Pajonal-Machona, Tabasco	Cd	*ND
			Pb	0.059 **
			Cu	0.516 **
Lango-Reynoso et al. (2013)	*Farfantepenaeus aztecus*	Tamiahua Lagoon, Veracruz	Cd	0.032 ± 0.019
			Pb	0.119 ± 0.12
			Cu	18.51 ± 4.109
			Hg	*ND
	Litopenaeus setiferus	Alvarado Lagoon, Veracruz	Pb	0.8115 ± 0.3420
			Cd	0.0750 ± 0.0108
			Cu	*ND
			Hg	0.1215 ± 0.0344
Palomarez-García et al. (2009)	*Farfantepenaeus aztecus*	Tamiahua Lagoon, Veracruz	Pb	0.119 **
			Cd	0.032**
			Cu	18.51**
Vidal-Martínez et al. (2006)	*F. duorarum*	Campeche Sound	Fe	2.24 - 492.4
			Cu	6.12 - 36.42
			Ni	2.46 - 149
			Zn	26.46 - 42.26
			V	6.03 - 214
Vazquez et al. (2001)	*Litopenaeus setiferus*	South zone of the Campeche Sound	Cd	1.21 - 6.11
			Fe	59.3 - 123
			Cu	17.1 - 18.6
			Mn	0.1 - 0.74
			Zn	55 - 156
			Cr	1.20 - 9.99

considerable amount of metabolic energy to protect their cells from the toxic effects of these elements (Frías-Espericueta et al. 2009). Likewise, Bautista-Cobarrubias et al. (2015) indicated that *P. vannamei* juveniles weighing 11.7 g were exposed to Cu for 5, 48, and 96 h. They reported that survival was similar in all treatments, but the coagulation time was significantly higher in the two maximum concentrations used; likewise, hemocyanin presented lower values after 5 h. Therefore, these investigations associated the dose-response relationship with the expression of sublethal effects that can affect the development of wild shrimp populations.

Regarding detoxification mechanisms, Chiodi-Boudet et al. (2019) identified in non-tolerant and tolerant *Palaemon argentinus* crustacean populations exposed to Cd that MT induction was the main exposure pathway for the non-tolerant population, while the formation of metal-rich granules was the main mechanism of expression for tolerant shrimp (Chiodi-Boudet et al. 2015, 2019). Bautista-Covarrubias et al. (2015) indicated that concentrations of heavy metals such as Cu are below the risk level; these elements can affect the defense response capacity of aquatic organisms.

The different bioconcentrations of metals among the various species may be due to different metabolic pathways of detoxification. Chiodi-Boudet et al. (2013, 2019) concur that the differences between species could be related to each population's environmental history and health status. Also, they highlight in their conclusions the sensitivity of the *P. argentinus* species and provide information for interpreting the results under laboratory and field conditions (Chiodi-Boudet et al. 2015).

It is necessary to research other existing detoxification mechanisms among the different shrimp species; those that exist have focused mainly on commercially important aquaculture species such as *P. vannamei*. There is a need to know what other mechanisms influence the modulation of sublethal toxicological effects in other species for human and wild consumption (Fig. 1).

Permissible limits and public health

Shrimp are used as bioindicator animals in the research analyzed in the present review due to their commercial and nutritional importance and ecological relevance. Therefore, the estimation of the risk to public health due to the presence of heavy metals in these fishery products can generate an effect on food safety that would affect their commercialization.

In the research conducted by Lango-Reynoso et al. (2013), the presence of Cd and Pb in both species was reported for *F. aztecus* from the Tamiahua lagoon and *L. setiferus* from the Alvarado lagoon. Meanwhile, Cu presented a maximum concentration of 18.51 ± 4.109 µg g^{-1} (Table 1); however, Cu presence was detected in *F. aztecus* but not in *L. setiferus*. In contrast, in the case of Hg, an inverse pattern was identified in the concentration reported in these species.

It was also identified that the concentrations detected in *F. aztecus* met the specifications of NOM-242-SSA1-2009 (DOF 2011); these concentrations were less than 0.5 µg g^{-1} for both metals (Cd and Pb) (Table 2). In contrast, they reported that concentrations in *L. setiferus* exceeded the limits for Cu, established by the European Community in Regulation (EC 1881/2006, 2008). This regulation established a permissible limit of 20.0 µg g^{-1} and the value indicated by the FDA (1993) according to Nauen (1983) with 32.5 µg g^{-1} and the level established by the FAO (1983) for Cu with a value of 30 µg g^{-1} (wet weight). It should be noted that this metal is not regulated by the official Mexican standards (Lango-Reynoso et al. 2013), making it difficult to establish permissible limits for the consumption of fishery products.

The national and international regulations analyzed for heavy metals can be considered limited concerning the number of heavy metals included in these guidelines and the homogeneity of the permissible limits, which could be identified in the case of the permissible limit for Pb; this value is the same for both regulations (Table 2). The concentrations reported in the investigations analyzed in this paper were lower than the permissible ones, except in the case of the investigations conducted by Vazquez-Sauceda et al. (2017) in Madre lagoon and by Lango-Reynoso et al. (2013) in Alvarado lagoon. In the case of Cd, the values allowed by the official Mexican regulations and the European Community about the concentration allowed for this element identified that the only research that reported concentrations higher than those established by international regulations was the study was conducted by Vazquez et al. (2001) in the southern area of the Campeche Sound.

Mexican regulations, NOM-242-SSA1-2009 (DOF 2011) on permissible limits for Hg (methylmercury) does not establish a reference value for crustaceans specifically, and the permissible limit specified for other species was considered. Therefore, the European regulations should be considered a reference since the concentrations found exceeded the permissible value in none of the cases analyzed. Concerning As and Sn, the investigations analyzed did not include these heavy metals, and there are no national or international reference values to contrast.

Some of the heavy metals reported in the analyzed studies do not have a biological function and may represent an additional stress factor for aquatic animals such as shrimp. Due to the sublethal effects reported for exposure to low concentrations of heavy metals, these could affect fishery production rates and influence the sustainability of shrimp production in Mexico (Vazquez-Sauceda et al. 2019, Ramírez-Ayala et al. 2020).

Some studies report that heavy metals do not have a biological function and can represent an additional stress factor for aquatic animals such as shrimp. Due to reported sub-lethal effects of heavy metals exposure at low concentrations, these could contribute to and affect fishery production rates and influence the sustainability of shrimp production in Mexico, as is the study reported by Frías-Espericueta et al. (2009). Exposure to a mix-

Table 2. Regulatory standards for heavy metals concentration in crustaceans and aquatic organisms to establish the public health risk.

Standard	Reference	Permissible limit ($\mu g\ g^{-1}$)				
		Pb	Cd	As	Sn	Hg
NOM-242-SSA1-2009. Products and services.	Fresh, refrigerated, frozen, and processed fishery products. Sanitary specifications and test methods.	0.5	2.0	80	100	0.5
European Union legislation on chemical contaminants in foodstuffs	Regulation (EC) 1881/2006, (2008)	0.5	0.5	--	200 (processed)	0.5

ture at different levels of equitoxic concentrations of Cd, Cu, Fe, Hg, Mn, Pb, and Zn, between 5 and 0.5% of median lethal concentrations of 96 h (0.05-0.005 application factors, AF), caused dose and time-dependent damage to the hepatopancreas, gills, epipodites, and midgut tissues of juvenile *P. vannamei*. After one month, 50-100% of the R cells of the hepatopancreas and the tubules' regular structure were lost. Branchial alterations were observed between two and three weeks with 0.05-0.025 and 0.005 AF, respectively. Epipodites showed time- and dose-dependent increasing degrees of melanization, and hemocytic enteritis was observed with 0.025 and 0.01 AF, showing that even at low concentrations, the mixture of these metals can have a lethal effect in the medium term. Evaluating the risk and safety levels of toxic substances added to any natural environment through human or natural sources should not overlook the effects caused by the interaction of trace amounts of toxic substances in biological systems, which would be harmless unless combined, as is the case in the environment where heavy metals constantly interact (Frías-Espericueta et al. 2008).

CONCLUSIONS

Of the point and diffuse sources of heavy metals in the Gulf of Mexico, the importance of continuous monitoring of fishery resources such as shrimp is highlighted due to the toxicological potential of heavy metals such as Pb, Cd, and Hg, among the main ones. Likewise, the generation of research contributes to updated scientific information that allows for accurately evaluating environmental problems to define scenarios on the potential effects of the introduction and dispersion of heavy metals in this region.

Shrimp as benthic macroinvertebrates were positioned as important due to their feeding habits, ease of capture and economic importance, and ability to express susceptibility to various types of contaminants and bioaccumulation potential bioindicators of environmental quality in the coastal zone of the Gulf of Mexico.

The research analyzed in this document describes the fishery situation concerning heavy metals and their association with the ecosystem's state of health where these aquatic animals develop. It contributes to identifying that most of the heavy metals concentrations values reported in these investigations are within the maximum permissible values, with exceptions of specific values, which implies the need to conduct systematic studies that can corroborate if these values correspond to a persistent phenomenon in this study area.

It was identified that the regulations on heavy metals in macroinvertebrates for human consumption in Mexico and the European regulations are limited; they need to be updated and adapted to the current knowledge of public health and environmental risk. The need to establish interaction between scientific and governmental research through universities and research centers to generate research related to the substitution of certain heavy metals in the industry to reduce the impact of these elements on public health and the environment was also highlighted.

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