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Mercury and selenium in oysters *Saccostrea palmula* and *Crassostrea corteziensis* from coastal lagoons of the southeastern Gulf of California: molar ratio and risk assessment on human health

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Abstract

Total mercury (Hg) and selenium (Se) contents were determined in oysters *Saccostrea palmula* and *Crassostrea corteziensis* soft tissues from four coastal lagoons of the southeastern Gulf of California. The annual Hg mean concentrations for *S. palmula* (0.09 ± 0.04 µg g^{-1}, wet weight) and *C. corteziensis* (0.08 ± 0.04 µg g^{-1}) were similar ($p > 0.05$) among the lagoons and did not exceed the limit established by the Norma Oficial Mexicana and World Health Organization (< 1.0 µg g^{-1} Hg). On the other hand, the annual mean concentrations of Se for *S. palmula* (3.34 ± 0.96 µg g^{-1}) and *C. corteziensis* (2.79 ± 0.89 µg g^{-1}) were higher ($p < 0.05$) in El Colorado lagoon. The Se/Hg molar ratios were above 1; the positive selenium health benefit value index suggested that Se load in oysters could reduce the Hg potential toxic effect. The hazard quotient for Hg in both species was below 1. Therefore, the consumption of oysters does not represent a risk due to Hg ingestion.

Keywords Bivalves · Human health · Potentially toxic elements · Molar ratio · Spectrophotometry · Gulf of California

The emission factors of mercury (Hg) and selenium (Se) in the coastal ecoregions of the southeastern (SE) Gulf of California, Mexico are due to the combination of various natural sources (e.g., geological weathering, volcanic eruptions, forest fires, hydrothermalism, and fossil deposits), as well as anthropogenic activities (e.g., gold mining, coal combustion, deforestation, agriculture, aquaculture, and manufacturing industry). Eventually, these elements are accumulated in different reservoirs and subsequently biomagnified in top predators and humans (Páez-Osuna et al. 2017). Mercury is a highly toxic metal without any known biological function; its organic forms, mainly methylmercury, are the most toxic. This metal is responsible for various environmental and human health problems, even at low concentrations (Schroeder and Munthe 1998; Apeti et al. 2012). Among several harmful effects on human health, Hg causes mitochondrial disorders, lung-kidney damage, myocardial infarction, effects on the central nervous system (mainly in children), cardiovascular atherosclerosis (Ratcliffe et al. 1996), and can cross the maternal placenta, for which this element is considered as teratogenic and mutagenic (Ask et al. 2002).

On the other hand, Se is an essential metalloid in the formation of selenocysteine-rich proteins within the cells of most organisms; it also intervenes in brain function, growth, thyroid hormone metabolism, calcium regulation, and oxidative stress control in humans (Ralston et al. 2016). Due to its high affinity to form stable non-toxic Hg–Se compounds (mercury selenide), without specifically modulating Hg absorption or excretion, the bioavailability of mercury toxicity can be reduced when Se/Hg molar ratio is > 1 (Burger and Gochfeld 2013). However, Se deficiency in human nutrition can lead to infertility (mainly in men) and diseases, such as Keshan (heart muscle or myocardial involvement)

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and Kashin-Beck (osteoarticular involvement), while at elevated levels, it can cause selenosis (Rayman 2012).

The oysters *Saccostrea palmula* (Carpenter 1857) and *Crassostrea corteziensis* (Hertlein 1951) are filter-feeding bivalves distributed along the Pacific coast from Mexico to Peru and Panama, respectively (Lodeiros et al. 2020). These ostreids have been used to monitor Hg concentration on the SE coasts of the Gulf of California (Frías-Espericueta et al. 2018 and literature therein). On the other hand, the knowledge of Se dynamics in both oyster species is scarce. To our knowledge, only one report evaluating the presence of Se in the oysters *C. gigas* and *C. virginica* from San Francisco Bay (California, USA) (Okazaki and Panietz 1981) has been found, and no information on the Se/Hg molar ratio in oysters (Scopus 2022) is available. Within this context, the purpose of this research is to determine Hg and Se seasonal concentrations and their molar ratios in *S. palmula* and *C. corteziensis* soft tissues from four coastal lagoons of the SE Gulf of California and use this information to assess human health risk.

Materials and Methods

The oysters were sampled in September (Summer 2019), December (Autumn 2019), March (Winter 2020) and June (Spring 2020) in ten sites distributed within four coastal lagoons of the SE Gulf of California: Altata (AL, three), Macapule (ML, two), Navachiste (NL, three), and El Colorado (ECL, two) (Fig. 1). However, oyster species did not coexist at all sampling sites; therefore, *S. palmula* (72.15 ± 4.95 mm average size, $n = 1800$) was collected in six sites and *C. corteziensis* (73.57 ± 5.31 mm average size, $n = 2700$) in nine sites. From each site and by species, 75 oysters were detached from the mangrove roots by hand, placed in metal-free polyethylene bags and transported on ice to the laboratory, where they were cleaned, measured (mm), weighed (g), and chipped.

In the laboratory, the oyster soft tissue samples were lyophilized (Labconco, Kansas City, MO, USA) at low temperature (-85 °C) and high vacuum (0.035 mBar) for 96 h; then, they were ground in a Teflon mortar and homogenized by quartering. Two ~ 1.0 g aliquots of each sample were predigested (~ 12 h) at room temperature with 10 mL of concentrated nitric acid (trace metal grade) in polyetrafluoroethylene vessels (60 mL capacity, Savillex, MN, USA). Digestion was performed on a heating plate (Barnstead) at 120 °C for 4 h; subsequently, each sample was diluted with deionized water to a final volume of 50 mL and stored in polyethylene containers (MESL 1997). All materials used in the sampling and laboratory were acid washed (Moody and Lindstrom 1977). Total Hg was determined by atomic absorption spectrophotometry (AAS) coupled to a cold vapor generator (Perkin-Elmer, Analyst 100, coupled MHS 15) (Muñoz-Sevilla et al. 2017); whereas total Se quantification was analyzed by AAS in a graphite furnace, using a Perkin-Elmer AAnalyst 800 instrument with Zeeman correction effect (Acosta-Lizárraga et al. 2020). The precision of the analytical method and the results were validated by using certified reference material (DOLT-5®; National Research Council Canada, NRCC, USA) with a recovery percentages of 116.76 ± 4.46 and 90.29 ± 1.90% for Hg and Se ($n = 10$ for both elements), respectively. Analytical blanks were used to check samples for possible

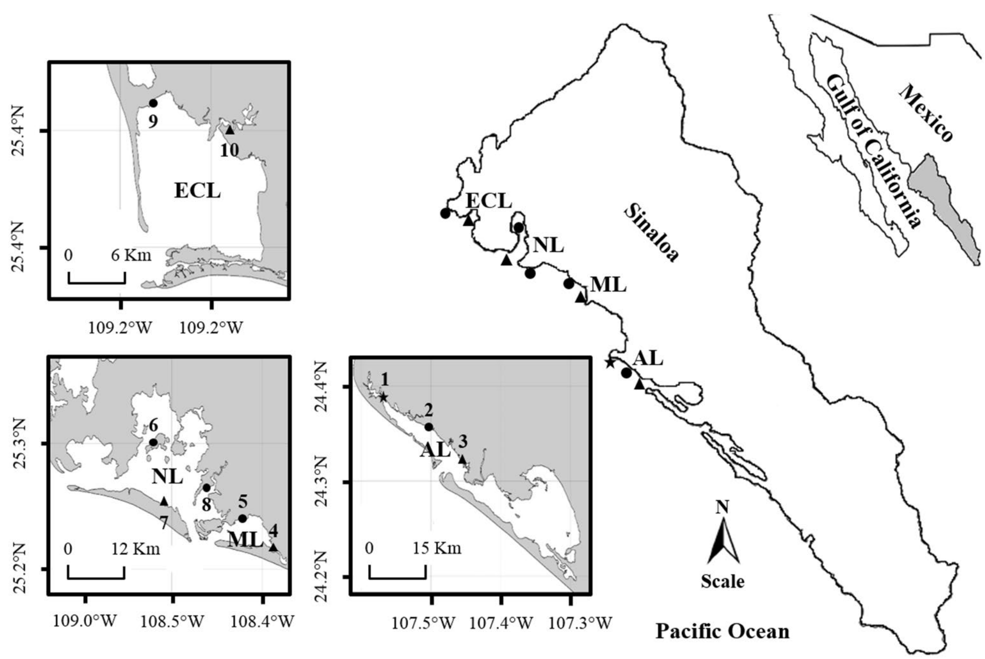

Fig. 1 Location of sampling sites in the coastal lagoons of the SE Gulf of California. *Saccostrea palmula* (★), *Crassostrea corteziensis* (▲), both species of oysters (•). *AL* Altata lagoon, *ML* Macapule lagoon, *NL* Navachiste lagoon, *ECL* El Colorado lagoon

contamination. The detection limits (two times the standard deviation of a blank) were 0.002 μg g^{-1} for Hg and 0.013 μg g^{-1} for Se. The coefficient of variation for duplicate samples was < 7.67%. Mercury and Se concentrations are expressed as μg g^{-1} wet weight (ww, 80.74 ± 1.60% moisture content was used for all samples).

The Se/Hg molar ratio in the oysters was calculated according to Burger and Gochfeld (2013), dividing the concentration of the element by its molecular weight (78.96 and 200.59 g mol^{-1} for Se and Hg, respectively). The Se health benefit value (HBV_{Se}) was calculated with the equation proposed by Ralston et al. (2016): $\mathrm{HBV_{Se}} = \left(\frac{(\mathrm{Se-Hg})}{\mathrm{Se}}\right) \times (\mathrm{Se} + \mathrm{Hg})$. For the estimation of HBV_{Se}, the element concentration is shown as μmol kg^{-1} ww. A positive HBV_{Se} value is considered healthy, while a negative value indicates health risks associated with Hg exposure; the magnitude of the value means the degree of Se surplus or deficit, related to the consumption of oysters (Ralston et al. 2016).

The hazard quotient (HQ) was used to assess the potential non-carcinogenic risk to human health from *S. palmula* and *C. corteziensis* consumption (Newman and Unger 2002), as follows: HQ = EWI/RfD, where EWI and RfD are the estimated weekly intake and reference dose for total Hg (0.0005 μg g^{-1} body weight day^{-1}: FDA 2006). Estimated weekly intake was calculated as $EWI = C \times I/W$, where C is the mean Hg concentration (μg g^{-1}, ww) and I represents the apparent weekly consumption (0.49 kg $person^{-1}$ $year^{-1}$ = 9.39 g $person^{-1}$ $week^{-1}$: CONAPESCA 2015) of the oysters. Average body weights (W) of the population (70 kg for adult men, 60 kg for adult women, and 16 kg for five year-old children) were included in the analyses.

Normality and homoscedasticity of data were analyzed with the Kolmogorov-Smirnov and Bartlett tests, respectively. Comparisons of Hg and Se average concentrations among the coastal lagoons, sampling sites, and seasons of the year were assessed by analysis of variance (ANOVA) and post-hoc Tukey's tests. The differences between Hg and Se contents in *S. palmula* and *C. corteziensis* were detected with the Student's t test for independent variables. The level of significance was $\alpha = 0.05$ for all statistical analyses (Zar 2010), which were performed using the STATISTICA 7 software package (StatSoft, Tulsa, OK, USA).

Results and Discussion

The total Hg concentrations in *S. palmula* and *C. corteziensis* soft tissues were 0.03–0.16 and 0.02–0.17 μg g^{-1} (ww), respectively. This interval is comparable to that found in bivalve mollusks by García-Rico et al. (2010) in Bacochibampo Bay, Sonora (Mexico), Delgado-Alvarez et al. (2015) in coastal lagoons, Sonora, Sinaloa and Nayarit (NW Mexico), and Olivares-Rieumont et al. (2012) in Villa Clara, Cuba. In most of the sampling sites, the highest and lowest seasonal Hg mean concentrations were respectively recorded in summer – autumn 2019 and winter – spring 2020 ($p < 0.05$, Table 1). Regarding the seasonal influence,

Table 1 Seasonal mean concentrations and standard deviation of total mercury (Hg) and selenium (Se) (μg g^{-1} ww) in the soft tissue of *S. palmula* and *C. corteziensis* at the sampling sites (SE Gulf of California)

Site	Total Hg				Total Se			
	Summer 2019	Autumn 2019	Winter 2020	Spring 2020	Summer 2019	Autumn 2019	Winter 2020	Spring 2020
S. palmula								
AL1	0.15 ± 0.03^{c}	0.13 ± 0.02^{c}	0.09 ± 0.00^{b}	0.07 ± 0.00^{a}	1.34 ± 0.03^{a}	1.96 ± 0.06^{b}	2.87 ± 0.02^{c}	1.70 ± 0.03^{b}
AL2	0.16 ± 0.05^{c}	0.14 ± 0.04^{c}	0.08 ± 0.02^{b}	0.04 ± 0.00^{a}	3.03 ± 0.02^{b}	2.33 ± 0.02^{a}	2.06 ± 0.01^{a}	2.94 ± 0.04^{b}
ML5	0.12 ± 0.03^{b}	0.11 ± 0.02^{b}	0.04 ± 0.00^{a}	0.04 ± 0.00^{a}	1.17 ± 0.03^{a}	1.71 ± 0.03^{b}	2.16 ± 0.02^{c}	1.80 ± 0.03^{b}
NL6	0.07 ± 0.02^{c}	0.08 ± 0.01^{c}	0.05 ± 0.01^{b}	0.03 ± 0.00^{a}	1.98 ± 0.30^{b}	1.79 ± 0.04^{a}	3.03 ± 0.23^{c}	2.86 ± 0.13^{c}
NL8	0.15 ± 0.01^{d}	0.13 ± 0.01^{c}	0.04 ± 0.00^{a}	0.06 ± 0.01^{b}	1.97 ± 0.03^{c}	1.52 ± 0.03^{b}	0.99 ± 0.02^{a}	1.60 ± 0.03^{b}
ECL9	0.13 ± 0.02^{d}	0.10 ± 0.01^{c}	0.03 ± 0.00^{a}	0.05 ± 0.01^{b}	2.33 ± 0.03^{a}	2.88 ± 0.01^{b}	3.60 ± 0.02^{c}	4.55 ± 0.02^{d}
C. corteziensis								
AL2	0.16 ± 0.01^{d}	0.14 ± 0.03^{c}	0.06 ± 0.00^{b}	0.02 ± 0.00^{a}	1.69 ± 0.02^{a}	2.97 ± 0.04^{b}	3.05 ± 0.02^{b}	3.29 ± 0.04^{c}
AL3	0.11 ± 0.06^{c}	0.10 ± 0.04^{c}	0.07 ± 0.02^{b}	0.03 ± 0.00^{a}	1.86 ± 0.03^{b}	1.35 ± 0.01^{a}	2.33 ± 0.02^{c}	3.05 ± 0.02^{d}
ML4	0.10 ± 0.01^{c}	0.10 ± 0.00^{c}	0.08 ± 0.01^{b}	0.03 ± 0.00^{a}	0.81 ± 0.00^{a}	2.42 ± 0.13^{c}	2.11 ± 0.07^{c}	1.28 ± 0.08^{b}
ML5	0.09 ± 0.01^{c}	0.07 ± 0.01^{b}	0.04 ± 0.00^{a}	0.02 ± 0.03^{a}	1.60 ± 0.02^{a}	1.62 ± 0.02^{a}	1.53 ± 0.11^{a}	2.88 ± 0.04^{b}
NL6	0.06 ± 0.01^{c}	0.09 ± 0.01^{c}	0.06 ± 0.01^{a}	0.05 ± 0.00^{b}	1.86 ± 0.03^{b}	1.51 ± 0.04^{a}	2.87 ± 0.02^{c}	3.33 ± 0.02^{d}
NL7	0.10 ± 0.01^{c}	0.11 ± 0.01^{c}	0.03 ± 0.01^{a}	0.04 ± 0.00^{b}	2.94 ± 0.07^{c}	2.41 ± 0.08^{b}	2.43 ± 0.06^{b}	1.17 ± 0.04^{a}
NL8	0.14 ± 0.01^{d}	0.15 ± 0.02^{c}	0.11 ± 0.01^{a}	0.09 ± 0.02^{b}	2.21 ± 0.02^{d}	0.90 ± 0.02^{a}	1.08 ± 0.01^{b}	1.69 ± 0.04^{c}
ECL9	0.12 ± 0.03^{b}	0.10 ± 0.02^{b}	0.05 ± 0.00^{a}	0.05 ± 0.01^{a}	2.05 ± 0.08^{a}	2.43 ± 0.12^{b}	2.59 ± 0.06^{b}	4.08 ± 0.05^{c}
ECL10	0.17 ± 0.04^{d}	0.11 ± 0.01^{c}	0.06 ± 0.01^{b}	0.03 ± 0.00^{a}	2.10 ± 0.04^{a}	2.96 ± 0.05^{b}	1.93 ± 0.05^{a}	3.27 ± 0.03^{c}

AL Altata lagoon, *ML* Macapule lagoon, *NL* Navachiste lagoon, *ECL* El Colorado lagoon. For Hg and Se, rows with different superscript letters denote significant differences ($p < 0.05$) between sampling stations and oyster species

Páez-Osuna and Osuna-Martínez (2015) and Muñoz-Sevilla et al. (2017) reported higher Hg concentrations in *C. corteziensis*, *S. palmula*, and *C. gigas*, respectively, during the rainy season (summer–autumn), which were related to the continental runoff from the intensive and vast agricultural areas that reaches the coastal lagoons with increased wet deposition. Additionally, Frías-Espericueta et al. (2018) reported higher Hg concentrations in *C. corteziensis* collected in the Urías lagoon (Mazatlán, Sinaloa, Mexico) in November 2012 (autumn). In this study, a similar trend occurred since the highest Hg level in both oyster species was recorded during summer–autumn 2019 (rainy season) (Table 1).

In both oyster species, the level of Se showed an order of magnitude higher than those determined for Hg, according to Okazaki and Panietz (1981), who analyzed the soft tissue of *C. gigas* and *C. virginica* from San Francisco Bay (CA, USA). However, the Se concentration reported by these authors was lower compared with the level found in this study (Table 1), which could have been due to this element bioavailability in coastal lagoons and the differences in size and life stage of the sampled organisms, among other factors. The Se content in *S. palmula* and *C. corteziensis* showed a seasonal variation, with intervals from 0.99 to 4.55 and 0.81–4.08 μg g^{-1}, respectively. In both species, the Se showed a tendency to increase seasonally; the lowest concentrations were recorded in summer 2019 and increased in autumn 2019; subsequently, the level of this metaliod increased in winter 2020, and its maximum level was reached in spring 2020 ($p < 0.05$, Table 1).

Table 2 Annual mean concentrations and standard deviation of total mercury (Hg) and selenium (Se) (μg g^{-1} ww), molar ratio (Se/Hg) and Se health benefit value (HBV_{Se}) in the soft tissue of *S. palmula* and *C. corteziensis* in the SE Gulf of California

Site	Total Hg	Total Se	Se/Hg	HBV_{Se}
S. palmula				
AL1	0.11 ± 0.04	1.97 ± 0.65^{ab}	51.30	24.90
AL2	0.11 ± 0.06	2.59 ± 0.47^{b}	84.94	32.80
ML5	0.08 ± 0.04	1.71 ± 0.41^{ab}	79.56	21.62
NL6	0.06 ± 0.02	2.41 ± 0.62^{b}	126.66	30.56
NL8	0.09 ± 0.05	1.52 ± 0.41^{a}	48.76	19.23
ECL9	0.08 ± 0.04	3.34 ± 0.96^{c}	149.59	42.28
C. corteziensis				
AL2	0.09 ± 0.07	2.75 ± 0.72^{c}	155.37	34.81
AL3	0.08 ± 0.04	2.15 ± 0.72^{b}	117.69	27.20
ML4	0.08 ± 0.03	1.66 ± 0.74^{ab}	67.38	20.96
ML5	0.05 ± 0.03	1.41 ± 0.35^{a}	74.95	17.82
NL6	0.06 ± 0.02	2.39 ± 0.85^{bc}	107.36	30.29
NL7	0.07 ± 0.04	2.24 ± 0.75^{b}	103.03	28.32
NL8	0.12 ± 0.03	1.47 ± 0.60^{a}	31.72	18.59
ECL9	0.08 ± 0.04	2.79 ± 0.89^{c}	116.74	35.30
ECL10	0.09 ± 0.06	2.57 ± 0.65^{bc}	124.03	32.49

AL Altata lagoon, *ML* Macapule lagoon, *NL* Navachiste lagoon, *ECL* El Colorado lagoon. Column with different superscript letters denotes significant differences ($p < 0.05$) between the sampling sites and oyster species

The annual Hg mean concentrations for *S. palmula* (0.09 ± 0.04 μg g^{-1}) and *C. corteziensis* (0.08 ± 0.04 μg g^{-1}) were similar ($p > 0.05$) among the sampling sites (Table 2), which could be partially explained by the natural and continuous contribution of leaching from the soils-rocks and waste from mining, which represent a key Hg source (Delgado-Alvarez et al. 2015). Such wastes have been transported along rivers and streams that originate in the Sierra Madre Occidental (an area rich in minerals) and, eventually, end up in the coastal lagoons of the SE Gulf of California at low concentration (Murray and Busty 2015). Since the colonial period until the beginning of the 20th century, the mining industry has used approximately 200,000 t of Hg in the silver and gold extraction process, estimating that under half of that used Hg is still present in mine tailings. The Hg used by the mining activity in the state of Sonora (the main gold producer in Mexico) is transported atmospherically to the coastal lagoons of the SE Gulf of California and accumulated on the sediments and different trophic levels; in this manner, its impact could reach areas with a low contamination level far from its sources of origin (Schroeder and Munthe 1998). In addition, Hg levels in coastal lagoons may increase due to upwelling events and the continuous renewal of seawater (Páez-Osuna and Osuna-Martínez 2015). Another important source of this metal is the intensive agriculture effluents in the SE Gulf of California, since Hg-based fungicides are still used to control plant pests (Osuna-Martínez et al. 2010; Góngora-Gómez et al. 2017). Mercury can also reach lagoons due to various causes, such as: continental runoff, untreated wastewater systems, paint waste, batteries, cement plant waste, and dental objects (Páez-Osuna et al. 2017).

The Hg bioaccumulation in *S. palmula* and *C. corteziensis* could be due to their benthic and feeding habits since they filter large volumes of seawater (around 6 L h^{-1}) where the metal is suspended (Jonathan et al. 2017). Mercury – one of the most persistent chemical elements – can be distributed and accumulated in various tissues and organs of aquatic organisms; in addition, it is characterized by biomagnified from lower trophic levels to humans (Ordiano-Flores et al. 2012). Oysters live mainly attached to the roots of mangroves (*i.e. Rhizophora* spp.) and on rocky surfaces, exposed and/or buried in muddy sediments with a high content of organic matter, which favors retention of metals, such as Hg (Rojas de Astudillo et al. 2005; Aguilar et al. 2012). Therefore, the sediments in the study area may be inferred as one of the most important routes of Hg accumulation in these bivalves (Sepúlveda et al. 2020). Despite the natural sources and anthropogenic activities that contribute with Hg deposition in the coastal lagoons of the SE

Gulf of California, the Hg concentrations in *S. palmula* and *C. corteziensis* were below the maximum permissible limit of 1.0 μg g^{-1} (ww) established by the Mexican legislation (Norma Oficial Mexicana NOM-031-SSA1-1993), World Health Organization (WHO 1982), and the United States Food and Drug Agency (FDA 2006).

On the other hand, the annual mean concentrations of Se for *S. palmula* (3.34 ± 0.96 μg g^{-1}) and *C. corteziensis* (2.79 ± 0.89 μg g^{-1}) were higher ($p < 0.05$) in ECL9 (Table 2). This site is located in one of the most contaminated areas by potentially toxic elements within the El Colorado lagoon (Páez-Osuna and Osuna-Martínez 2015), which is part of the Agiabampo-Bacorehuis-Río Fuerte Antiguo lagoon system, which receives the contributions of the Fuerte River and runoff from the highly technical agricultural activities of the municipality of Ahome (~194,482.23 ha; SIAP 2020), municipal waste (~459,310 inhabitants; INEGI 2020) and shrimp farms (~12,639 ha; CESASIN 2020). Santos et al. (2015) mention that the aquatic environment can be contaminated by Se due to agriculture, urban drainage, mining waste, thermoelectric plants, oil refineries, and metallic minerals.

The Se/Hg molar ratio in the oysters varied among the sampling sites; the lowest values in *S. palmula* (48.76) and *C. corteziensis* (31.72) were observed in NL8, while the highest ones (149.59 and 155.37) were in ECL9 and AL2, respectively (Table 2). Selenium has been documented to neutralize the toxic Hg effect if its Se/Hg molar ratio is > 1 (Burger and Gochfeld 2013). Selenium intervenes in the Hg demethylation process through the selenocysteine protein, transforming the metal to its inorganic and less toxic form. In this manner, Hg can be excreted more easily through pseudofeces and spawning (Medina-Morales et al. 2020; Vega-Sánchez et al. 2020). This study reports the Se/Hg molar ratio in *S. palmula* and *C. corteziensis* in the SE Gulf of California and in the distribution area of these two species (Pacific coast from Mexico to Peru; Lodeiros et al. 2020). The Se/Hg ratio has been always greater than 1 in both oyster species, which can be explained by the low Hg level found. These results are similar to the Se/Hg > 1 molar ratios reported in different groups of organisms, as shrimps *Farfantepenaeus californiensis* and *Litopenaeus stylirostris* (NW Mexico) (Frías-Espericueta et al. 2016), the mahi mahi fish *Coryphaena hippurus* (Gulf of California) (Bergés-Tiznado et al. 2019), Pacific hake *Merluccius productus* (Gulf of California) (Acosta-Lizárraga et al. 2020), crustaceans like the crab *Callinectes arcuatus* (NW Mexico) (Delgado-Alvarez et al. 2020), and elasmobranchs like the shark *Mustelus henlei* (Mexican Pacific Ocean) (Medina-Morales et al. 2020). The value of the health benefit by Se (HBV_{Se}) (Table 2), indicates a benefit provided by a higher concentration of Se in comparison to Hg in the soft tissue of oysters. The HBV_{Se} values above 1 have been reported for some fish species (*Thunnus albacares* = 64.54, *Vinciguerria lucetia* = 19.41, *Lagocephalus lagocephalus* = 298.40, and *C. hippurus* = 1.77), squids (*Dosidicus gigas* = 12.82, *Thysanoteuthis rhombus* = 30.30, and *Sthenotheuthis oualaniensis* = 63.52), the crab *Pleuroncodes planipes* (13.26) (Ordiano-Flores et al. 2012; Vega-Sánchez et al. 2020); as well as the shark *Carcharhinus falciformis* (52.30; Bodin et al. 2017).

A comparison of the Hg level in the soft tissues of oysters from several coastal lagoons in Mexico shows that the intervals of the data found in this study (0.03–0.16 and 0.02–0.17 μg g^{-1} for *S. palmula* and *C. corteziensis*, respectively) are similar to most of the results reported in the literature (Table 3). Nevertheless, they are lower than those found for *C. virginica* in the Términos lagoon (Gulf of Mexico), mainly affected by oil, agricultural and urban activities (Aguilar et al. 2012). Compared with other regions of the world, the Hg levels determined in *S. palmula* and *C. corteziensis* are similar to those reported for *C. gigas* and *C. rhizophorae* in Morocco (Maanan 2008) and Cuba (Olivares-Rieumont et al. 2012) but higher than those determined for *C. rhizophorae* in the Santos and Paranaguá estuary, Brazil (Torres et al. 2012), C. *gigas* in Ebro Delta, Catalonia, Spain (Ochoa et al. 2013)d *virginica* and *C. rhizophorae* in the Gulf of Paria, Venezuela and Trinidad (Rojas de Astudillo et al. 2005). However, the Hg concentration in this study was lower than those recorded for *C. gigas* in Minamata Bay, Japan (Eisler 1987) and in some coastal and marine regions of Italy where the Japanese oyster *C. gigas* is cultivated (Burioli et al. 2017) (Table 3). These differences could be due to Hg abundance in the continental crust (the mean is higher than 0.056 μg g^{-1}) since the Hg level worldwide is not homogeneous and some regions are more enriched than others (Wedepohl 1995). Additionally, Hg concentration can vary among oyster species because of their biological aspects, related to their metabolic activity, differences between sizes, and reproductive period.

Recent studies have highlighted the importance of evaluating the potential risk to human health from the ingestion of potentially toxic elements contained in commercially important fishery products (including oysters). The annual consumption of oysters is double or more than that established as national apparent consumption (0.49 kg $person^{-1}$ $year^{-1}$ = 9.39 g $person^{-1}$ $week^{-1}$, especially in cities and coastal communities dedicated to seafood capture and production; CONAPESCA 2015). The HQ values obtained in this study remained below the risk level ($HQ < 1$); therefore, Hg ingestion due to the consumption of *S. palmula* and *C. corteziensis* does not represent a risk to human health. These results are similar to those in the studies by Delgado-Alvarez et al. (2015), Frías-Espericueta et al. (2018), and

Table 3 Total mercury (Hg) interval concentrations (μg g^{-1} ww) in different *Saccostrea* and *Crassostrea* oyster species from some coastal lagoons of the SE Gulf of California and other worldwide regions

Species	Area (sampling year)	Total Hg	Author
Coastal lagoons of the SE Gulf of California			
C. corteziensis	Bacochibampo Bay, Sonora	0.03–0.04	García-Rico et al. (2010)
*C. corteziensis**	Coastal lagoons, Sinaloa	0.03–0.11	Osuna-Martínez et al. (2010)
*C. gigas**	Coastal lagoons, Sinaloa	0.01–0.18	Osuna-Martínez et al. (2010)
*C. virginica**	Términos lagoon, Campeche	0.08–0.40	Aguilar et al. (2012)
*C. virginica**	Northern Gulf of Mexico, USA	0.01–0.10	Apeti et al. (2012)
Crassostrea spp.*	Coastal lagoons, Sonora-Nayarit	0.02–0.05	Delgado-Alvarez et al. (2015)
*S. palmula**	Coastal lagoons, Sinaloa	0.04–0.15	Páez-Osuna and Osuna-Martínez (2015)
*C. corteziensis**	Coastal lagoons, Sinaloa	0.03–0.12	Páez-Osuna and Osuna-Martínez (2015)
C. gigas	La Pitahaya estuary, Sinaloa	0.00–0.04	Góngora-Gómez et al. (2017)
C. gigas	Navachiste lagoon, Sinaloa	0.00–0.03	Jonathan et al. (2017)
*C. gigas**	Coastal lagoons, Sinaloa	0.03–0.14	Muñoz-Sevilla et al. (2017)
*C. corteziensis**	Urías lagoon, Sinaloa	0.01–0.05	Frías-Espericueta et al. (2018)
C. gigas	Coastal waters, Sonora	0.01–0.13	García-Rico & Tejeda-Valenzuela (2018)
S. palmula	Coastal lagoons, Sinaloa	0.03–0.16	This study
C. corteziensis	Coastal lagoons, Sinaloa	0.02–0.17	This study
Other worldwide regions			
*C. gigas**	Minamata Bay, Japan	2.00**	Eisler (1987)
*C. rhizophorae**	Gulf of Paria, Venezuela	0.00–0.01	Rojas de Astudillo et al. (2005)
*C. virginica**	Gulf of Paria, Venezuela	0.00–0.01	Rojas de Astudillo et al. (2005)
C. gigas	Oualidia lagoon, Morocco	0.02–0.21	Maanan (2008)
*C. rhizophorae**	Villa Clara, Cuba	0.03–0.13	Olivares-Rieumont et al. (2012)
*C. rhizophorae**	Santos estuarie, Brazil	0.02–0.07	Torres et al. (2012)
*C. gigas**	Ebro Delta in Catalonia, Spain	0.02–0.05	Ochoa et al. (2013)
C. gigas	Coastal waters, Korea	0.00–0.02	Mok et al. (2015)
C. gigas	Coastal marine ecosystems, Italy	0.01–0.34	Burioli et al. (2017)

*Calculated from dry weight, assuming 80% moisture. **Only the mean value was available

García-Rico & Tejeda-Valenzuela (2018) who reported HQ values below 1 in ostreids from the SE Gulf of California.

The results obtained in this study indicate that Hg concentrations in *S. palmula* and *C. corteziensis* were similar among the four coastal lagoons (SE Gulf of California) when the highest concentrations of this metal occurred in summer – autumn 2019, without exceeding the maximum permissible limit of 1.0 μg g^{-1} established by national and international regulations. On the other hand, the total concentrations of Se in both oyster species were higher in the northernmost lagoon during spring 2020. Furthermore, Hg and Se levels of *S. palmula* and *C. corteziensis* in each lagoon were similar, which can be explained because they share the same habitat, implying being exposed to the same water conditions, exposure levels of the elements, and feeding on the same resources. Moreover, the high Se concentrations in this soft tissue could reduce the Hg potential toxic effect, indicating that consumption of raw oysters is safe for human health.

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Declarations

Conflict of interest The authors have no competing interests to declare.

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