Marine Pollution Bulletin 222 (2026) 118780

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

First report of the mercury, cadmium and lead concentrations in the tissues of wild amberjacks (*Seriola* spp.) caught in Gran Canary (Canary Islands, Spain)

Ayoze Castro-Alonso [a], Carmen Verónica Martin-León [b], Ángelo Santana-del-Pino [c], Lucia Caballero-Hernández [a], Fernando Real-Valcárcel [a], Natalia García-Álvarez [a], María José Ramos-Sosa [a], Antonio Fernández [a], María José Caballero [a,*]

[a] *Institute of Animal Health and Food Safety (IUSA), Veterinary School, University of Las Palmas of Gran Canaria, Trasmontaña s/n, Arucas, 35413 Las Palmas, Spain*
[b] *Public Health Laboratory, C/ Tomás Morales, 122, 35004, Las Palmas de Gran Canaria, Spain*
[c] *Department of Mathematics, University of Las Palmas of Gran Canaria, Edf. Informática y Matemáticas, Campus Universitario de Tafira, 35017, Las Palmas, Spain*

ARTICLE INFO

Keywords:
Heavy metals
Liver
Muscle
Gonad
Seriola genus
Eastern North Atlantic

ABSTRACT

Amberjack (*Seriola* spp.) is a commercially valuable fish species in the Canary Islands, yet data on toxic heavy metals in its tissues remain scarce. This study presents the first assessment of mercury (Hg), cadmium (Cd), and lead (Pb) concentrations in muscle, liver, and gonads of wild specimens caught in Gran Canaria and confiscated due to ciguatoxin presence. Hg levels in muscle tissue were notably high, with 73 % of specimens exceeding the European legal limit (median: 0.80 mg/kg). Cd and Pb levels in muscle remained below detection thresholds. Liver tissues showed substantial accumulation of Hg (median: 1.72 mg/kg) and Cd (median: 3.00 mg/kg), with 100 % of specimens surpassing the Cd legal limit. Gonadal tissues exhibited lower concentrations, with a significant negative correlation between Cd levels and gonad weight, suggesting possible elimination during spawning. Despite elevated Hg concentrations in muscle, the human health risk assessment—based on Estimated Daily Intake (EDI) and Target Hazard Quotient (THQ)—indicated values below critical thresholds for both adults and children, suggesting no immediate health risk under current consumption patterns. These findings highlight the liver as a key organ for heavy metal bioaccumulation and underscore the limitations of current food safety regulations, which focus solely on muscle tissue. Expanding monitoring protocols to include liver and gonads is recommended to better reflect toxicological risks and safeguard public health in regions where *Seriola* spp. is regularly consumed.

1. Introduction

Fish products provide substantial health benefits (Li et al., 2020). They are a rich source of protein, calories, and essential nutrients, serving as a primary nutritional component for over 3 billion people globally (FAO, 2020). Owing to their nutritional value, fish are widely recommended in both national and international dietary guidelines. The World Health Organization (WHO) and the European Society of Cardiology (ESC) advise consuming fish at least once or twice per week (Visseren et al., 2021). In Europe, recommended fish intake ranges from 100 to 482 g per week, typically equating to one to two servings (Lofstedt et al., 2021). Some countries, such as Spain, recommend even higher consumption—two to four servings per week (Marí et al., 2010). Consequently, food-based dietary guidelines emphasize the importance of fish as a key component of a healthy diet, not to be substituted by other protein sources (Tlusty, 2021).

Despite the global significance of fish consumption, fishery products are susceptible to contamination by environmental pollutants released into aquatic ecosystems from both natural and anthropogenic sources. These include heavy metals (e.g., mercury [Hg], lead [Pb], and cadmium [Cd]), industrial chemicals (e.g., PCBs and dioxins), and agricultural runoff containing pesticides and herbicides. These substances are persistent pollutants that resist biodegradation, follow global ecological cycles, and often biomagnified through the food chain, resulting in elevated concentrations in predatory species (Zupo et al., 2019; Butler et al., 2022). These contaminants tend to accumulate in the

* Corresponding author.
E-mail address: mariajose.caballero@ulpgc.es (M.J. Caballero).

https://doi.org/10.1016/j.marpolbul.2025.118780
Received 6 August 2025; Received in revised form 25 September 2025; Accepted 26 September 2025
Available online 10 October 2025
0025-326X/

edible tissues of fish, mollusks, crustaceans, and algae (Ali et al., 2019; Bezerra et al., 2019; Lozano-Bilbao et al., 2024), posing potential risks to human health and affecting the safety and quality of seafood products (Afonso et al., 2017; Afonso et al., 2018; Kalogeropoulos et al., 2012).

Among these contaminants, Hg is one of the most prevalent in aquatic environments, with its organic form, methylmercury (MeHg), representing the greatest toxicological concern due to its neurotoxic effects, particularly on the developing nervous system (Davidson et al., 2004). Cd, although naturally occurring, anthropogenic cadmium from industrial and agricultural activities is more problematic due to its greater bioavailability, often in soluble forms (e.g., Cd^{2+}), making it more readily absorbed by plants, animals, and humans (Hayat et al., 2019). Chronic exposure to Cd has been associated with renal dysfunction, osteoporosis, and certain cancers (Satarug et al., 2017). Pb, a naturally occurring toxic metal, became a widespread source of human exposure through its historical use in gasoline, although this has been largely phased out since the 1990s. Pb exposure can impair the central nervous system in infants (Bellinger, 2008) and, in adults, may affect blood pressure, reproductive health, kidney function, and induce genetic alterations. In response, the European Union has established legal maximum values (LMVs) for toxic heavy metals in food. For fish, LMVs apply to muscle tissue, or to the whole fish when consumed entirely. The most recent update—Commission Regulation (EU) 2023/915 of April 25, 2023—sets LMVs at 0.5 mg/kg for Hg (except for species listed in 3.3.1.2), 0.05 mg/kg for Cd (except for species listed in 3.2.14.2, 3.2.14.3, and 3.2.14.4), and 0.30 mg/kg for Pb.

Additionally, the European Union operates the Rapid Alert System for Food and Feed (RASFF), a control mechanism enabling authorities to share information on food safety risks. Notifications are accessible to contact points within the European Commission, EFSA, EFTA countries, and EU Member States. In 2024, RASFF recorded 62 notifications concerning elevated Hg levels in fish and fishery products, and 8 related to Cd. These alerts triggered a series of coordinated responses aimed at protecting public health and ensuring food safety across the EU.

Upon notification, RASFF facilitated immediate information exchange among member states, enabling swift action by national food safety authorities (European Commission, 2024a). This often led to product recalls and market withdrawals, especially when contaminated items had already reached consumers (European Commission, 2024a). In cases involving imports, border rejections were implemented to prevent entry of non-compliant products into the EU market (European Commission, 2024b).

The marine ecosystem of the Canary Islands is characterized by unique geographic, oceanographic, physical, and ecological features that support high biodiversity (Valdés and Déniz-González, 2015). A defining factor is the steep drop-off of the ocean floor, which limits coastal habitats for species such as dentex, parrotfish, comber, grouper, and dusky grouper, while favoring pelagic species like tuna, sardines, and mackerels. The amberjack (*Seriola* spp.) is a large teleost fish valued for its high flesh quality and market demand and is considered a promising candidate for aquaculture diversification (Mylonas et al., 2016). Four *Seriola* species are found in the western North Atlantic Ocean: the greater amberjack (*Seriola dumerili* (Risso 1810)), the lesser amberjack (*Seriola fasciata* (Bloch, 1793)), the almaco jack (*Seriola rivoliana* (Valenciennes, 1833)), and the banded rudderfish (*Seriola zonata* (Mitchill, 1815)) (Smith-Vaniz, 2003; Swart et al., 2015).

Lozano-Bilbao et al. (2021) analysed metal concentrations in tissues of wild and farmed *S. dumerili* from the Mediterranean Sea. Their findings indicated that liver and muscle tissues of wild specimens contained higher concentrations of Al, Cd, Pb, Cu, Mn, Mo, Ni, Sr, V, Zn, and macronutrients such as K, but lower levels of Co, Fe, and Na compared to farmed counterparts. Metal concentrations showed minimal sex-related differences, although variations in female tissues were likely linked to nutrient mobilization during spawning. Importantly, no toxicological risk from Pb or Cd was identified in either wild or farmed fish.

To date, no data are available on heavy metal concentrations in amberjacks caught in the Canary Islands. However, this species has been identified as a risk vector for ciguatoxin (CTX) poisoning in the archipelago. CTX is a marine biotoxin responsible for ciguatera fish poisoning, a human illness caused by compounds such as gambiertoxin-4 A, produced by dinoflagellates like *Gambierdiscus toxicus* (Sanchez-Henao et al., 2019). CTX poisoning has been reported primarily in tropical and subtropical regions, including the Caribbean Sea, Indian Ocean, Pacific Ocean, and more recently, the eastern Atlantic Ocean (Lewis, 2001; Boada et al., 2010). In response, the Directorate General of Fisheries of the Canary Islands has implemented a monitoring protocol for CTX detection in specific fish species and sizes at authorized first-sale points. Fish testing positive for CTX are confiscated and excluded from the market (DG of Fisheries of the Canary Government, 2024). These specimens represent valuable material for assessing fish meat quality and safety. Within this context, and based on currently available data, the aim of this study is to report, for the first time, the concentrations of Hg, Cd, and Pb in the muscle, liver, and gonad tissues of amberjacks (*Seriola* spp.) caught in Gran Canaria (Canary Islands, Spain) and confiscated due to CTX levels exceeding the established threshold, as determined by the Official Ciguatoxin Monitoring Programme of the Government of the Canary Islands.

2. Material and methods

2.1. Samples and heavy metal analysis

Wild amberjacks (*Seriola* spp.), 29 females and 8 males, caught by local fishers at various locations around Gran Canaria Island during 2023 and 2024, and testing positive for ciguatoxin, were confiscated. The Directorate General of Fisheries of the Canary Islands Government authorized the Institute of Animal Health and Food Safety (IUSA_ULPGC) to use these specimens for research purposes.

Following standardized necropsy procedures (n = 37), samples of epaxial muscle (posterior to the dorsal fin), liver, and gonads were carefully excised and immediately stored at −20 °C until analysis. Liver and gonad weights were recorded. Gonad samples were available for only 18 specimens (14 females, 4 males), as analyses were conducted in two phases (first batch: 19 individuals; second batch: 18 individuals). After detecting elevated Hg concentrations in muscle tissue from the first batch, the second batch included gonad samples, which are locally consumed. Additionally, stomach contents were collected from some specimens in the second batch when whole fish carcasses were present.

Heavy metal analysis was performed at the certified Public Health Laboratory of the Canary Islands Government (PHL-CI). All procedures adhered to the protocols established in Commission Regulation (EC) No. 333/2007, which outlines the official sampling and analytical methods for determining levels of Hg, Cd, and Pb in foodstuffs (European Commission, 2007). Additionally, the methodology followed the recommendations provided in the Guide for the Preparation of Food and Feed Samples for the Analysis of Chemical Elements, issued by the Agro-Food Arbitration Laboratory—the Spanish National Reference Laboratory for heavy metals under the Ministry of Agriculture, Fisheries and Food (Agro-Food Arbitration Laboratory, 2022).

The analytical methods employed complied with the minimum quantification limits set forth in Commission Regulation (EU) 2023/915 of 25 April 2023, which defines maximum permissible levels for specific contaminants in food (European Commission, 2023). Quality assurance was supported by the most recent annual certification and quality control data (2025) from the PHL-CI, as detailed in Table S1 (supplementary material), using the certified reference material GSCMPA-1/2025 (mussel meat; GSC, Madrid, Spain) for Hg, Cd, and Pb detection. Limits of detection (LOD) and limits of quantification (LOQ) for each heavy metal are presented in Table S2 (supplementary material).

Method validation was continuously monitored through internal daily quality control procedures at PHL-CI. Recovery rates for Hg, Cd, and Pb ranged from 95.00 % to 110.40 %, falling within the acceptable limits defined for the applied methodologies.

Samples were processed using microwave-assisted acid digestion. Specifically, 1.5 g of tissue was digested with 8 ml of hyperpure nitric acid (HNO_3, 69 % *v*/v) and 2 ml of hydrogen peroxide (H_2O_2, 33 % v/v) under controlled power (800 W) for 30 min. The resulting solution was filtered and diluted to a final volume of 50 ml with ultrapure water (Milli-Q).

Pb and Cd concentrations were determined using Graphite Furnace Atomic Absorption Spectrophotometry (GFAAS), while mercury (Hg) was analysed using Cold Vapor Generation with a Flow Injection Mercury System (FIMS). The GFAAS method included preparation of standard solutions, calibration curves, absorbance measurements, and the use of background correction and standard addition techniques to enhance accuracy. The FIMS method, suitable for ultra-trace mercury analysis, involved reacting an aliquot of the digested sample with sodium borohydride ($NaBH_4$) to generate elemental mercury vapor. This vapor was transported by argon gas into an atomic absorption spectrometer, where absorbance was measured and correlated with Hg concentration.

2.2. Human risk assessment

The risk associated with the consumption of *Seriola* spp. was determined through the calculation of the Estimated Daily Intake (EDI) and the Target Hazard Quotient (THQ) for both adults and children (USEPA, 1989).

To facilitate the comparison between the EDI (μg/kg/bw) and the oral Reference Dose (RfDo) (mg/kg/day) established by the U.S. Environmental Protection Agency (US-EPA).

The calculation of EDI involved utilizing the following formula (Carrasco-Puig et al., 2024): $EDI = (C \times IR)/BW$, where C represented the concentration of the Hg (μg/kg, w.w.) in the muscle sample; IR corresponded to the daily average consumption of fish in Spain (0.1265 kg per capita/day) (EUMOFA, 2021) and BW was the body weight, for which the average weight of an adult and a child was used, being 70 and 16 kg respectively (Copat et al., 2013; Carrasco-Puig et al., 2024). The oral RfDo values used for the comparison with the estimated daily intake was 0.0003 (mg/kg/day) for Hg (U.S. EPA, 1995, 2001; Prabakaran et al., 2024, 2025).

Furthermore, the THQ was used to assess the potential health risks associated with the consumption of the Seriola spp. analysed in this present study. A THQ value below 1, suggests that the exposure level is lower than the oral RfDo, implying that a daily exposure of this concentration would not pose harm to human health (USEPA, 1989).

The calculation of THQ followed the formula (Carrasco-Puig et al., 2024): $THQ = (C \times IR \times EF \times ED)/(RfDo \times BW \times AT)/1000$, where C denoted the concentration of the Hg in the muscle sample (mg/kg, w.w.); IR corresponded to the daily average consumption of fish in Spain (0.1265 kg per capita/day) (EUMOFA, 2021); EF represented the frequency of exposure per year (from 365 days/year for people who eat fish seven times a week to 52 days/year for people who eat fish one time a week) (Copat et al. (2013)); ED was the exposure duration, which according to Copat et al. (2013) was 26 years for adults and 6 for children; RfDo was the oral Reference Dose established by US-EPA for Hg in 0.0003 (mg/kg/day) (U.S. EPA, 1995, 2001; Prabakaran et al., 2024, 2025). BW stood for the body weight for adults (70 kg) and children (16 kg) (Copat et al., 2013); and AT is the averaging time (it is equal to EF x ED) (Copat et al., 2013).

2.3. Statistical analysis

Continuous variables were tested for normality using the Shapiro–Wilk test. Normally distributed variables were described as mean ± standard deviation (SD), while non-normally distributed variables were reported as median and interquartile range (IQR, 25th–75th percentile). Categorical variables were compared using the Chi-square (χ^2) test or Fisher's exact test, as appropriate. Means were compared using the Student's *t*-test, and medians using the Wilcoxon rank-sum test for independent samples.

To identify factors independently associated with outcomes, a multivariate logistic regression analysis was performed. Variables showing significant associations in univariate analysis were included in the multivariate model. Variable selection was based on a complete enumeration algorithm and the Bayesian Information Criterion (BIC). Model results were presented as coefficients (± SE), *p*-values, and odds ratios with 95 % confidence intervals. Statistical significance was set at $p < 0.05$. Variables were also stratified by sex, with comparisons made using the Student's t-test for normally distributed variables and the Wilcoxon–Mann–Whitney test otherwise.

A linear mixed-effects model was used to assess differences in Hg and Cd concentrations among three tissues (muscle, liver, and gonads) within the same individual. Tissue type was treated as a fixed effect, and individual fish as a random effect to account for intra-individual variability. Hg concentrations were log-transformed to meet normality assumptions. After confirming significant differences via ANOVA based on the mixed-effects model, post-hoc pairwise comparisons were conducted. p-values were adjusted using Tukey's method to control for Type I error due to multiple comparisons.

Additionally, a logistic mixed-effects model was applied to compare the proportion of samples exceeding legal limits (Commission Regulation (EU) 2023/915) across tissues, with post-hoc comparisons performed similarly. Analyses were conducted using the lmer package (Douglas et al., 2015) and emmeans (Lenth, 2024) in R. All statistical analyses were performed using R version 3.1.1 (R Development Core Team, 2016).

3. Results

The standardized necropsy of all specimens revealed no significant lesions or pathological findings. Fish frequently exposed to natural toxins such as CTXs, may have developed mechanisms that allow them to tolerate and harbor these compounds for long periods of time. Physiological mechanisms, such as toxin storage in certain organs or rapid depuration to reduce the bioavailability of the toxin may occur in fish to avoid damage (Uno et al., 2012; Luckenbach et al., 2014; Ikehara et al., 2017; Soliño and Reis, 2020). Therefore, the sampled individuals can be considered healthy wild-caught amberjacks.

3.1. Morphometric data of the animals

Morphometric data for the analysed specimens are presented in Table 1. The average body weight was 29.41 ± 8.67 kg, and the mean total length was 142.34 ± 14.40 cm. Female specimens exhibited significantly higher body weight compared to males (32.68 ± 9.09 kg vs. 25.68 ± 4.95 kg; $p = 0.0133$), although the number of males was notably lower ($n = 8$) than females ($n = 29$).

The average liver weight was 334.08 ± 176.97 g, ranging from 112.2 g to 759.1 g. Gonad weight averaged 839.35 ± 698.82 g, with a minimum of 141.6 g and a maximum of 2700.1 g. The mean hepatosomatic index (HSI) and gonadosomatic index (GSI) were 1.0 % and

Table 1
The morphometric data, total length, fish weight, liver weight, gonad weight, hepatosomatic index (HSI) and gonadosomatic index (GSI) for the amberjack, *Seriola* spp. (average ± SD, minimum, maximun).

Variable	Average ± SD	Min	Max
Fish weight (kg)	29.41 ± 8.67	12.6	51.7
Total length (cm)	142.34 ± 14.40	97.0	163.0
Liver weight (g)	334.08 ± 176.97	112.2	759.1
Gonad weight (g)	839.35 ± 698.82	141.6	2700.1
HSI (%)	1.0 ± 0.3	0.6	1.6
GSI (%)	2.5 ± 2.1	0.5	6.7

2.5 %, respectively. Notably, six individuals presented GSI values between 3.2 % and 6.7 %.

3.2. Descriptive data of Hg, Cd and Pb tissue concentrations

The descriptive data of the Hg concentration values of the specimens are included in Table 2. Hg concentrations did not follow a normal distribution (Shapiro-Wilk test, $p < 0.05$), so they were described as median and IQR.

In muscle tissue, the median Hg concentration was 0.80 mg/kg, with 27 out of 37 specimens (73.0 %) exceeding the legal maximum value (LMV) of 0.5 mg/kg established by Commission Regulation (EU) 2023/915. The 95 % confidence interval (CI) for this proportion ranged from 0.556 to 0.856.

The results of Hg concentration in muscle tissue can be compared to the values published by other researchers conducted in various *Seriola* spp. and geographic area, as well as guideline values proposed by international organisations (Table 3). Most countries following international standards, sets the limit for total mercury (Hg) in fish muscle at 0.5 mg/kg for most fish and 1.0 mg/kg for predatory fish like shark, tuna, and swordfish, based on FAO (Food and Agricultural Organization).

In liver tissue, the median Hg concentration was 1.72 mg/kg. Although the LMV applies only to muscle tissue, 33 out of 37 specimens (89.2 %) exceeded the 0.5 mg/kg threshold. This proportion was statistically significant, with a 95 % CI ranging from 0.736 to 0.965.

In gonadal tissue, the median Hg concentration was 0.38 mg/kg. Seven out of 18 specimens (38.9 %) had Hg concentrations above the LMV. This proportion was also statistically significant, with a 95 % CI ranging from 0.183 to 0.639.

The linear mixed-effects model ANOVA revealed statistically significant differences in Hg concentrations among the three tissues analysed ($p < 0.0001$). Post-hoc pairwise comparisons indicated that Hg concentrations in the liver were significantly higher than those in the gonads ($p < 0.0001$) and muscle ($p = 0.0031$). No statistically significant difference was observed between muscle and gonad tissues ($p = 0.0802$) (Fig. 1).

Furthermore, a statistically significant positive correlation was found between Hg concentrations in muscle and liver tissues ($p = 0.0081$). In contrast, correlation analyses between Hg concentrations in other tissue pairs (muscle vs. gonads and liver vs. gonads) showed a negative trend, although these were not statistically significant (Supplementary material, Table S6).

Descriptive statistics for Cd concentrations are presented in Table 4. As Cd concentrations did not follow a normal distribution (Shapiro–Wilk test, $p < 0.05$), results are reported as median and IQR.

In muscle tissue, all specimens exhibited Cd concentrations below 0.02 mg/kg, which is under the detection threshold of the analytical equipment. In contrast, Cd concentrations in liver tissue were markedly elevated across all specimens, with a median value of 3.00 mg/kg (Table 4). Notably, 100 % of the individuals had liver Cd concentrations exceeding 1.39 mg/kg, far surpassing the 0.05 mg/kg limit established by Commission Regulation (EU) 2023/915 for Cd in fish meat.

Table 2
Descriptive and statistical values of the Hg concentrations in the muscle, liver and gonad of amberjacks, *Seriola* spp.

Hg (mg/Kg)					
Tissue	Median (IQR)	Nc	n	Estimate*	CI95%[¥]
Muscle	0.80 (0.44; 1.41)	27	37	0.730	(0.556, 0.856)
Liver	1.72 (0.95; 2.00)	33	37	0.892	(0.736, 0.965)
Gonad	0.38 (0.27; 0.71)	7	18	0.389	(0.183, 0.639)

[*] Estimate: proportion of fish that exceed 0.5 mg/kg of Hg.
[¥] CI95%: 95 % Confidence Interval for the proportion of individuals exceeding 0.5 mg/kg of Hg.

In gonadal tissue, the median Cd concentration was 0.04 mg/kg, and 6 out of 18 specimens (33.3 %) presented values exceeding the regulatory limit of 0.05 mg/kg (Table 4).

The linear mixed-effects model ANOVA revealed statistically significant differences in Cd concentrations among tissues, with liver concentrations being significantly higher than those in gonads ($p < 0.0001$) (Fig. 2). However, a negative correlation was observed between Cd concentrations in liver and gonads, although this was not statistically significant (Spearman $r = -0.21$; $p = 0.3920$).

Regarding Pb, concentrations in muscle, liver, and gonadal tissues were consistently below 0.05 mg/kg, with the exception of a single specimen that exhibited a Pb concentration of 0.19 mg/kg (see Supplementary Material).

3.3. Correlations between Hg and Cd concentrations and morphometric parameters

Correlations between Hg and Cd concentrations in tissues and the weights of the whole fish, liver, and gonads are summarized in (Supplementary material, Table S7). Hg concentrations in muscle, liver, and gonads showed a positive correlation with total body weight; however, only the correlation between liver Hg concentration and fish weight was statistically significant (Spearman $r = 0.500$, $p = 0.0016$) (Fig. 3A). Similarly, Cd concentration in the liver also showed a positive, though not statistically significant, correlation with fish weight (Fig. 3B). In contrast, Cd concentration in the gonads exhibited a negative correlation with total body weight (Supplementary material, Table S7).

Although most correlations were not statistically significant, both Hg and Cd concentrations in the liver showed a positive association with liver weight and as expected, with the HSI (Supplementary material, Table S7 and S8). Conversely, in gonadal tissue, both metals showed negative correlations with gonad weight and with the GSI (Fig. 3C and D; Supplementary material, Table S7 and S8). These negative correlations were statistically significant in the case of Cd concentrations.

Finally, no significant correlation was found between Hg or Cd concentrations and the sex of the specimens.

3.4. Concentrations of Hg, Cd and Pb in stomach contents

The concentrations of Hg, Cd, and Pb in the stomach contents of amberjack specimens are presented in Table 5. The prey items identified in the stomachs—teleost fish belonging to the family Sparidae, approximately 15–20 cm in total length—were found in seven individuals.

None of the prey fish exhibited Hg concentrations exceeding 0.5 mg/kg. Only one specimen (individual 1133/24) showed a concentration approaching this threshold, with a value of 0.32 mg/kg.

Cd concentrations in stomach contents ranged from 0.0084 mg/kg (minimum) to 0.089 mg/kg (maximum). In 5 out of 7 specimens (71 %), Cd concentrations exceeded the 0.05 mg/kg limit established by Commission Regulation (EU) 2023/915 for Cd in fish muscle.

Pb concentrations in all stomach content samples were below 0.01 mg/kg.

3.5. Human risk assessment

The mean EDI values of Hg in *Seriola* spp. muscle tissue, calculated for both adult and children populations (μg/kg body weight; Table 6), remained below the RfDo established by the United States Environmental Protection Agency (US EPA, 1995, 2001).

To further evaluate potential health risks associated with the consumption of *Seriola* spp., the THQ was determined (Table 6). All THQ values for Hg were consistently below the threshold value of 1, indicating that the estimated exposure does not exceed the RfDo (mg/kg body weight/day).

Table 3
Comparison of Hg concentration (mg/kg) of muscle from *Seriola* spp. with other similar studies and maximum permissible limit of Hg in fish muscles according to International regulations. NA: Not available.

References	Hg**	Weight range (kg)	Lenght range (mm, TL)	Species	Geographic area
This Study	0.80	29.0	1420	*Seriola* spp.	South Atlantic (Canary Islands)
Lowery and Garrett, 2005	0.53	NA	879	*S. dumerili*	Gulf of Mexico
Cai et al., 2007	0.60	NA	840	*S. dumerili*	Gulf of Mexico
Chung et al., 2008	0.79	2.4–2.6	590–620	*S. dumerili*	Hong-Kong
Chung et al., 2008	0.88	4.9	740-760	*S. lalandi*	South Pacific Ocean
Chung et al., 2008	0.86	3.0–3.5	670–700	*S. lalandi*	North Pacific Ocean
Thera and Rumbold, 2014	0.44	NA	594	*S. dumerili*	Southwest Florida
Bosch et al., 2017	0.16	2.5–15.6	675–1370	*S. lalandi*	West and South-East of South Africa
Sinkus et al., 2017	0.45	NA	983	*S. dumerili*	Southeastern USA
CAC (1995)	*0.5–1*				
FAO *(2020)*	*0.5–1*				
EC 2023/915	*0.3–0.5-1*				
MOH *(2013)*+	*0.5–1*				
*United Stated**	*0.5–1*				

CAC-Codex Alimentarius Commission; FAO-Food and Agricultural Organization; EC-European Commission; +Ministry of Health (China), * Zillioux, 2015.** It is assumed that Hg concentration values are also based on wet weight, even though this is not explicitly stated in the references, as wet weight is typically used in the analysis of fish for human consumption.

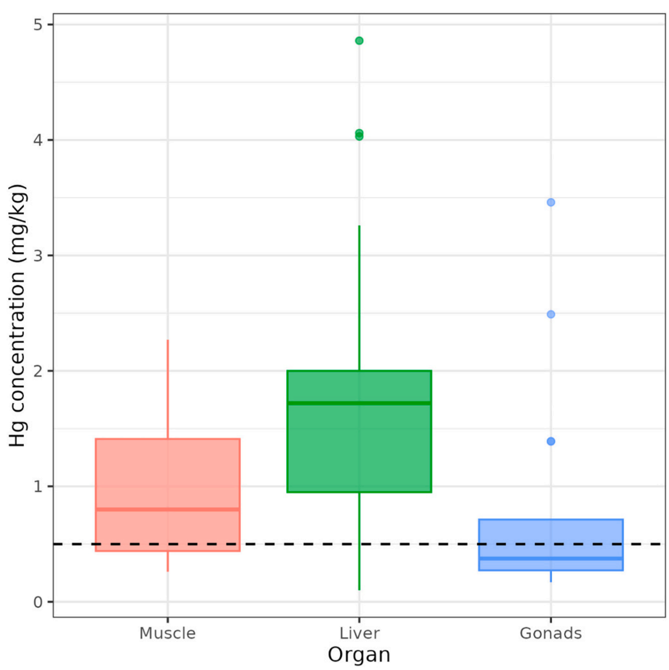

Fig. 1. Boxplot of the Hg concentrations in muscle, liver and gonad for the 37 amberjacks. Dotted line indicates the LMV (0.5 mg/kg for fish meat according to EC legislation).

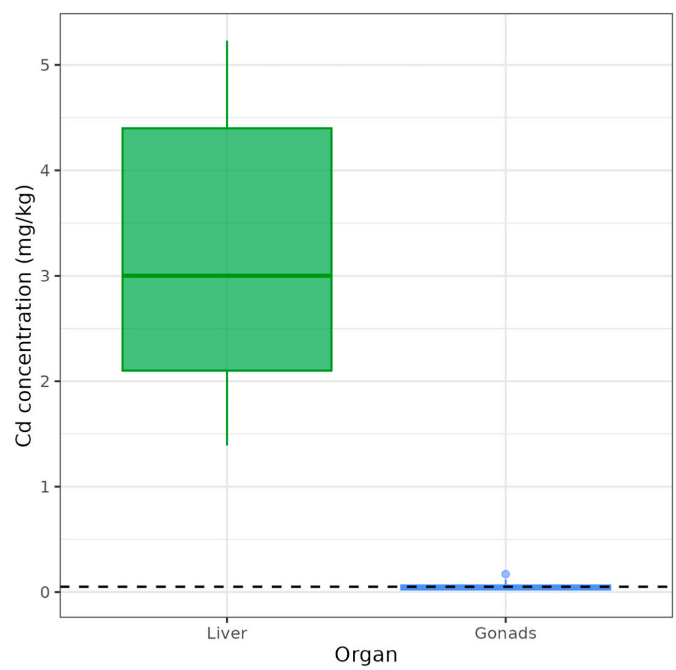

Fig. 2. Boxplot of the Cd concentrations in liver (n=37) and gonad (n=18). Dotted line indicates the LMV (0.05 mg/kg for fish meat according to EC legislation).

Table 4
Descriptive and statistical values (mg/Kg) of the Cd concentrations in the liver and gonad of amberjacks, *Seriola* spp.

Cd (mg/Kg)					
Tissue	Median (IQR)	Nc	n	Estimate*	CI95%¥
Liver	3.00 (2.10; 4.40)	37	37	1.000	(0.883, 1.000)
Gonad	0.04 (0.02; 0.06)	6	18	0.333	(0.144, 0.588)

[*] Estimate: proportion of fish that exceed 0.05 mg/kg, limit established by Commission Regulation (EU) 2023/915 for Cd in fish meat.
[¥] CI95%: 95 % Confidence Interval for that proportion.

4. Discussion

The analysis of heavy metals in amberjack (*Seriola* spp.) revealed concerning levels of Hg in muscle tissue, with a mean concentration of 0.80 mg/kg. Notably, 73 % of the specimens exceeded the legal limit of 0.5 mg/kg for fish meat established by Commission Regulation (EU) 2023/915. To date, there are few published studies reporting Hg concentrations in this genus (Table 3). For instance, Chung et al. (2008) detected total Hg and MeHg in imported *S. dumerili* and *S. lalandi* in Hong Kong, with mean values around 0.79 and 0.87 mg/kg, respectively. Bosch et al. (2017) analysed *S. lalandi* from the western and southeastern coasts of South Africa, reporting a mean muscle Hg concentration of 0.16 mg/kg in fish weighing approximately 3–15 kg. Sinkus et al. (2017) detected 0.45 mg/kg en *S. dumerili* in Southeastern USA. According to the Rapid Alert System for Food and Feed (RASFF), only one notification has been issued for Hg in *Seriola carpenteri* fillets, reporting a concentration of 0.7 ± 0.11 mg/kg in 2021.

In the Canary Islands, Hg concentrations have been reported in other fish species. For example, *Scomber colias* from Gran Canaria showed values of 0.11 mg/kg in 2021 (Lozano-Bilbao et al., 2023), while

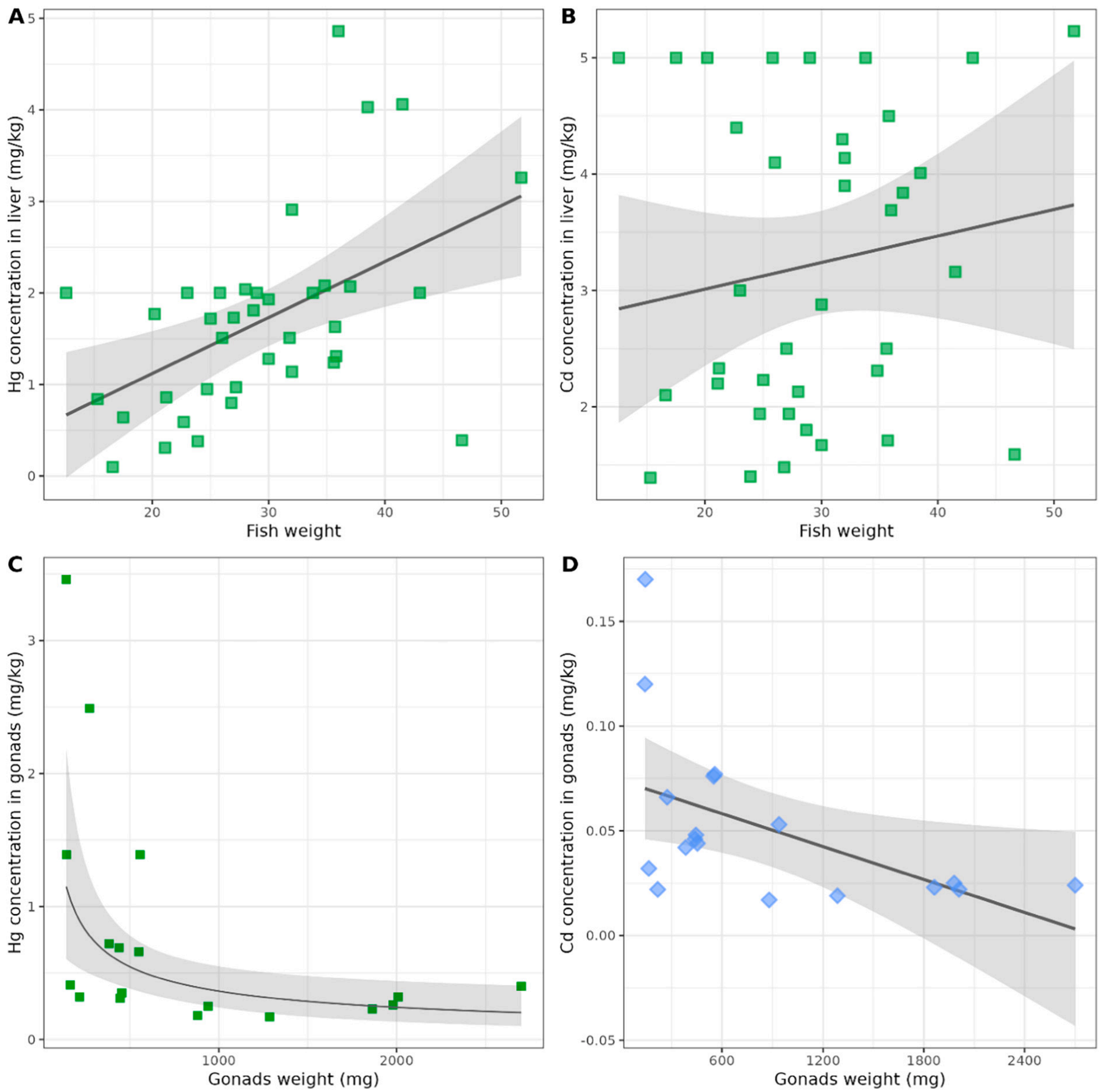

Fig. 3. Scatterplot of the positive correlation between the Hg (**3A**) and Cd (**3B**) concentration in liver and the fish weight, with the estimated regression line. Scatterplot of the negative correlation between Hg (**3C**) and Cd (**3D**) concentration in gonad and its weight, with the estimated regression line.

Table 5
Mean concentration (mg/kg) ± SD of the analysed Hg, Cd and Pb in the stomach content ($n = 7$) of amberjacks, *Seriola* spp.

Code individual	Hg	Cd	Pb
1119/24	0.081 ± 0.02	0.0084	<0.01
1120/24	0.068 ± 0.01	0.076	<0.01
1121/24	0.12 ± 0.03	0.089	<0.01
1124/24	<0.06	0.027	<0.01
1129/24	<0.06	0.062	<0.01
1130/24	<0.06	0.067	<0.01
1133/24	0.32 ± 0.09	0.056	0.056

demersal sharks caught in Macaronesian waters (Tenerife, Gran Canaria, and the Azores) exhibited Hg concentrations ranging from 50.35 to 264.4 µg/kg (Lozano-Bilbao et al., 2018). Within this context, the present study provides the first report of Hg concentrations in muscle tissue of *Seriola* spp. caught in the Canary Islands, highlighting a substantial proportion of specimens exceeding the EU regulatory threshold.

Table 6
Average EDI values (µg/kg/bw) and THQ values for Hg of the analysed *Seriola* spp. calculated for adults and children.

Consumer	EDI	THQ
Adults	1.44E-06	4.81E-03
Children	5.34E-06	2.10E-02

Nevertheless, the outcomes of the human health risk assessment performed in this study provided THQ values for Hg below 1, indicating that this metal is still within save consumption limits for humans.

Due to their ecological traits, large pelagic fish are widely regarded as effective sentinels for monitoring persistent marine pollutants such as mercury (Hg) on both regional and global scales. Their longevity, broad migratory routes, and apex positions within marine food webs contribute to the accumulation of elevated Hg concentrations in their tissues (Goyanna et al., 2023; Prabakaran et al., 2025). In the present study, *Seriola* spp. exhibited Hg levels that exceeded recommended safety limits, raising concern despite the favourable outcomes of the human health risk assessment. These findings are consistent with previous reports on other fish species intended for human consumption (Prabakaran et al., 2025), highlighting the need for continued vigilance and proactive measures to address this environmental health issue.

This study also presents, for the first time, significantly elevated Hg concentrations in the liver of amberjacks, with a median value of 1.72 mg/kg, surpassing those found in muscle tissue. A positive correlation between Hg concentrations in liver and muscle was observed. Previous studies have similarly reported higher metal accumulation in metabolically active organs such as the liver compared to muscle tissue (Hornung et al., 1993; Çoğun et al., 2006; Kravchenko et al., 2014; Afonso et al., 2017, 2018). These findings may be explained by the biological transformation of inorganic Hg into MeHg, a more toxic and persistent form with a strong tendency to bioaccumulate and a slower elimination rate (Vieira et al., 2017; Polak-Juszczak, 2018).

Moreover, MeHg in fish liver undergoes demethylation into inorganic Hg, which preferentially binds to metallothioneins produced in hepatic tissue, resulting in higher inorganic Hg concentrations in the liver compared to muscle (Bebianno et al., 2007).

In this study, and in contrast to the elevated Hg concentrations observed in muscle tissue, Cd levels in the muscle of *Seriola* spp. were consistently low, with all specimens showing concentrations below 0.02 mg/kg. These findings align with those of Lozano-Bilbao et al. (2021), who reported similarly low Cd levels in both wild and farmed greater amberjack, suggesting a minimal risk of Cd exposure through consumption of this species. Comparable results have been reported for other fish species caught in the Canary Islands, including *Sarpa salpa, Chelon labrosus, Diplodus sargus cadenati,* and *Sparisoma cretense*, all of which exhibited Cd concentrations below legal limits (Afonso et al., 2017, 2018). More recently, Lozano-Bilbao et al. (2024) concluded in a literature review that none of the commercially important fish species in the Canary Islands exceeded the maximum permitted Cd levels.

In contrast, Cd concentrations in the liver were remarkably high, with a median value of 3.00 mg/kg, and 100 % of the specimens exceeding the legal threshold of 0.05 mg/kg. These findings are consistent with those reported by Lozano-Bilbao et al. (2021), who also observed elevated Cd levels in the liver of *S. dumerili* from the Mediterranean Sea. The marked difference in Cd concentrations between muscle and liver tissues may be attributed to internal metabolic processes. Cd is absorbed in the intestinal tract via membrane transporters, including essential element channels and transporter proteins. Its transport is primarily mediated by metallothioneins (MTs), and to a lesser extent by low-molecular-weight serine-arginine-rich (SR) proteins capable of metal binding (Lee et al., 2025).

The liver and kidneys are particularly sensitive to Cd toxicity, likely due to their capacity to synthesize MTs. Le Croizier et al. (2016) described the long biological half-life of Cd in these organs—exceeding one year in rainbow trout—highlighting the inefficiency of Cd elimination from these tissues.

A notable finding of this study is that 71 % of the prey items found in the stomach contents of amberjacks exhibited Cd concentrations above the 0.05 mg/kg legal limit, despite being small, short-lived fish. Taken together, the results from liver, muscle, gonads, and stomach contents suggest that Cd bioaccumulates more rapidly in the liver than Hg, possibly due to less efficient metabolic elimination pathways.

A particularly noteworthy finding of this study is the low concentration of Hg and Cd detected in the gonadal tissue of *Seriola* spp. Specifically, a negative correlation was observed between gonadal concentrations of both metals and gonad weight. This pattern may be explained by the transfer of a portion of accumulated Hg and Cd from females to their egg mass, which is subsequently eliminated during spawning, as previously suggested by Hoffman et al. (2002). Supporting this hypothesis, Malinowski et al. (2021) reported elevated Hg concentrations in gametes of wild fish, with seasonal trends indicating that females offload significant amounts of Hg into their eggs during the reproductive season.

Species of the genus *Seriola* spp. are multiple spawners with indeterminate fecundity, meaning that vitellogenic oocytes are continuously recruited from the primary growth oocyte pool throughout the spawning season (Harris et al., 2007). In fact, it has been estimated that greater amberjack in the northwestern Atlantic Ocean spawn approximately every five days over a 73-day reproductive period, resulting in around 14 spawning events per season (Harris et al., 2007). This reproductive strategy may contribute to the observed reduction in heavy metal concentrations in gonadal tissue, particularly in females.

The analysis of Pb concentrations in muscle, liver, and gonadal tissues of amberjacks caught in the Canary Islands revealed consistently low levels of this heavy metal, with most values at or below the detection limit of 0.01 mg/kg. These findings are consistent with those reported by Lozano-Bilbao et al. (2021), who found no toxicological risk associated with Pb in wild and captive-reared *S. dumerili* from the Mediterranean Sea. Similarly, Bosch et al. (2017) reported low Pb concentrations in *Seriola lalandi* collected along the western coast of South Africa, with values well within regulatory guidelines.

Other fish species from the Canary Islands have also demonstrated Pb concentrations in muscle tissue below the legal limits for human consumption (Afonso et al., 2017; Afonso et al., 2018; Lozano-Bilbao et al., 2024). The progressive reduction of Pb in gasoline and the implementation of stricter regulations on industrial Pb emissions are likely contributing factors to the overall decline in environmental Pb bioaccumulation, thereby reducing its impact on marine ecosystems (Wood et al., 2019).

Increasing evidence supports the positive effects of these regulatory measures on wildlife health, including reduced mortality risks (Anderson et al., 2000; Newth et al., 2013), lower rates of Pb ingestion (Moore et al., 1998; Demendi and Petrie, 2006), and decreased Pb concentrations in biological tissues such as blood (Kelly et al., 2011) and bone (Stevenson et al., 2005).

An important factor influencing heavy metal bioaccumulation is its relationship with the animal's body condition. A substantial body of literature has examined the association between heavy metal concentrations and fish size and weight, revealing species-specific patterns. Van den Broek et al. (1981) reported positive correlations between Hg concentration and body length in several species, including bluenose, hapuku (*Polyprion oxygeneios*), striped marlin, spiny dogfish (*Squalus acanthias*), giant stargazer, and ling. In contrast, no positive correlations were found for species such as red cod, barracouta (*Thyrsites atun*), ghost shark, ribaldo, sea perch (*Helicolenus papillosus*), tarakihi (*Cheilodactylus macropterus*), white warehou (*Seriolella caerulea*), and black oreo dory (*Allocyttus* sp.).

In the present study, the amberjack specimens exhibited relatively high body weights, with an average of 29.41 ± 8.67 kg. Although no statistically significant correlation was found between muscle Hg concentration and fish weight, a positive trend was observed. Few studies have specifically investigated this relationship within the *Seriola* genus. Bosch et al. (2017), for example, reported a strong positive correlation between Hg levels and both size and weight in *Seriola lalandi*.

The absence of statistical significance in the present study may be attributed to the limited sample size and the narrow weight range of the specimens analysed. Expanding the dataset to include a broader range of fish sizes—particularly individuals in the lower weight range (10–14 kg)—could help clarify this relationship.

It is also important to note that previous research has demonstrated a strong positive correlation between ciguatoxin levels and fish weight in *Seriola* spp. (Sanchez-Henao et al., 2019). Based on this evidence, a legal weight threshold has been established in the Canary Islands, requiring official testing for ciguatoxin in *Seriola* spp. specimens exceeding a certain size. However, recent findings from the Official Ciguatoxin Control Programme suggest that ciguatoxin has been detected in a significant proportion of fish below the current threshold, prompting calls to reassess and potentially lower the legal weight limit (DG of Fisheries of the Canary Government, 2024).

An additional finding of this study relates to the correlation between heavy metal concentrations and fish weight. Specifically, Hg and Cd concentrations in the liver showed a positive association with body weight, with the correlation for Hg being statistically significant. Lozano-Bilbao et al. (2021) similarly reported an interaction between hepatic Cd concentrations and fish weight in wild amberjacks. These results underscore the toxicological relevance of the liver and support its consideration as a target organ for heavy metal monitoring. Moreover, they raise the possibility of expanding current legislation to include additional organs—particularly in species with known bioaccumulation patterns.

In line with this, Afonso et al. (2018) advised against regular consumption of liver from *Diplodus sargus cadenati* and *Sparisoma cretense* caught off the northern coast of Gran Canaria, due to elevated levels of Pb and Cd. Additionally, it is worth noting that in *Seriola* spp., ciguatoxins have also been strongly detected in the liver, prompting adaptations to the ciguatoxin control legislation in the Canary Islands (Ramos-Sosa et al., 2022).

5. Conclusions

This study provides the first report of elevated Hg concentrations in the muscle tissue of *Seriola* spp. caught in the Canary Islands, with a substantial proportion of specimens exceeding the legal limits established by European legislation—raising important public health concerns. However, when considering the EDI and THQ of Hg metal, the consumption of the analysed species would not pose a risk to humans. In contrast, Cd and Pb concentrations in muscle tissue were consistently below both regulatory thresholds and detection limits.

The liver was identified as a key organ for the bioaccumulation of Hg and Cd, with a statistically significant correlation between liver Hg concentration and fish weight. Additionally, the reproductive status of the specimens appeared to influence metal accumulation in the gonads, with Hg and Cd concentrations decreasing as gonadal weight increased.

These findings underscore the importance of continuous monitoring of *Seriola* spp., a species of high commercial and dietary relevance in the Canary Islands. Current regulations focus primarily on metal concentrations in muscle tissue, overlooking other organs that may pose significant toxicological risks. The results of this study suggest that liver and gonadal tissues should be considered in future regulatory frameworks for heavy metal monitoring.

Protecting public health must remain a priority. The data presented here should encourage further research aimed at improving food safety and enhancing consumer protection in regions where *Seriola* spp. are regularly consumed.

CRediT authorship contribution statement

Ayoze Castro-Alonso: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carmen Verónica Martin-León:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Ángelo Santana-del-Pino:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Lucia Caballero-Hernández:** Writing – review & editing, Validation, Methodology. **Fernando Real-Valcárcel:** Writing – review & editing, Validation, Supervision, Methodology, Investigation. **Natalia García-Álvarez:** Writing – review & editing, Validation, Methodology, Investigation. **María José Ramos-Sosa:** Writing – review & editing, Methodology, Investigation. **Antonio Fernández:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation. **María José Caballero:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Microsoft Copilot (GPT-4) in order to refine the English language, improve clarity, and ensure consistency in scientific terminology. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118780.

Data availability

Data will be made available on request.

References

Afonso, A., Gutiérrez, A.J., Lozano, G., González-Weller, D., Rubio, C., Caballero, J.M., Hardisson, A., Revert, C., 2017. Determination of toxic metals, trace and essentials, and macronutrients in *Sarpa salpa* and *Chelon labrosus*: Risk assessment for the consumers. Environ. Sci. Pollut. Res. 24, 10557–10569. https://doi.org/10.1007/s11356-017-8741-y.

Afonso, A., Gutiérrez, Á.J., Lozano, G., González-Weller, D., Lozano-Bilbao, E., Rubio, C., Caballero, J.M., Revert, C., Hardisson, A., 2018. Metals in *Diplodus sargus cadenati* and *Sparisoma cretense* — a risk assessment for consumers. Environ. Sci. Pollut. Res. 25, 2630–2642. https://doi.org/10.1007/s11356-017-0697-4.

Agro-Food Arbitration Laboratory, 2022. Guide for the preparation of food and feed samples for the analysis of chemical elements and related aspects (Rev. 001–04/22). Ministry of Agriculture, Fisheries and Food, Spain. Retrieved from. https://www.mapa.gob.es/dam/mapa/contenido/alimentacion/temas/laboratorios-agroalimentarios/laboratorio-arbitral-agroalimentario-laa/guiatratamientodemuestrasenelanalisisdeelementosquimicosrev001-04-22.pdf.

Ali, H., Khan, E., Ilahi, I., 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. J. Chem. 2019, 1–14. https://doi.org/10.1155/2019/6730305.

Anderson, W.L., Havera, S.P., Zercher, B.W., 2000. Ingestion of lead and nontoxic shotgun pellets by ducks in the Mississippi Flyway. J. Wildl. Manag. 64, 848–857. https://doi.org/10.2307/3802755.

Bebianno, M.J., Santos, C., Canário, J., Gouveia, N., Sena-Carvalho, D., Vale, C., 2007. Hg and metallothionein-like proteins in the black scabbardfsh Aphanopus carbo. Food Chem. Toxicol. 45, 1443–1452. https://doi.org/10.1016/j.fct.2007.02.003.

Bellinger, D.C., 2008. Very low lead exposures and children's eurodevelopment. Curr. Opin. Pediatr. 20, 172–177. https://doi.org/10.1097/MOP.0b013e3282f4f97b.

Bezerra, M.F., Lacerda, L.D., Lai, C.T., 2019. Trace metals and persistent organic pollutants contamination in batoids (Chondrichthyes: Batoidea): A systematic review. Environ. Pollut. (Barking, Essex: 1987) 248, 684–695. https://doi.org/10.1016/j.envpol.2019.02.070.

Boada, L.D., Zumbado, M., Luzardo, O.P., Almeida-González, M., Plakas, S.M., Granade, H.R., Abraham, A., Jester, E.L.E., Dickey, R.W., 2010. Ciguatera fish poisoning on the West Africa coast: An emerging risk in the Canary Islands (Spain). Toxicon 56, 1516–1519. https://doi.org/10.1016/j.toxicon.2010.07.021.

Bosch, A.C., O'Neill, B., Kerwath, S.E., Sigge, G., O., Hoffman, L.C., 2017. Metal concentrations and toxicity in South African snoek (*Thyrsites atun*) and yellowtail (*Seriola lalandi*). Mar. Pollut. Bull. 122, 360–365. https://doi.org/10.1016/j.marpolbul.2017.06.074.

Butler, E.C.V., Harries, S.J., McAllister, K.A., Windsor, J.O., Logan, M., Crook, D.A., Roberts, B.H., Grubert, M.A., Saunders, T.M., 2022. Influence of life history variation and habitat on mercury bioaccumulation in a high-order predatory fish in tropical Australia. Environ. Res. 212, 113152. https://doi.org/10.1016/j.envres.2022.113152.

CAC (Codex Alimentarius Commission) Codex general standard for contaminants and toxins in food and feed. In: CODEX STAN 193–1995 CAC, Rome, 1995.

Cai, Y., Rooker, J.R., Gill, G.A., Turner, J.P., 2007. Bioaccumulation of mercury in pelagic fishes from northern Gulf of Mexico. Can. J. Fish. Aquat. Sci. 64, 458e469.

Carrasco-Puig, P., Colmenero, A.I., Ruiz-García, D., Molera-Arribas, A.J., Hernández-Martínez, A.M., Raga, J.A., Barría, C., 2024. Heavy metal concentrations in sharks, rays and chimaeras from the western Mediterranean Sea. Mar. Pollut. Bull. 199 (2024), 115942. https://doi.org/10.1016/j.marpolbul.2023.115942.

Chung, S.W., Kwong, K.P., Tang, A.S., Xiao, Y., Ho, P.Y., 2008. Mercury and methylmercury levels in the main traded fish species in Hong Kong. Food Addit. Contam. Part B Surveill. 1 (2), 106–113. https://doi.org/10.1080/02652030802277586.

Çoğun, H.Y., Yüzereroğlu, T.A., Firat, Ö., Gök, G., Kargin, F., 2006. Metal concentrations in fish species from the northeast Mediterranean Sea. Environ. Monit. Assess. 121 (1), 431–438. https://doi.org/10.1007/s10661-005-9142-0.

Copat, C., Arena, G., Fiore, M., Ledda, C., Fallico, R., Sciacca, S., Ferrante, M., 2013. Heavy metals concentrations in fish and shellfish from eastern Mediterranean Sea: consumption advisories. Food Chem. Toxicol. 53, 33–37. https://doi.org/10.1016/j.fct.2012.11.038.

Davidson, P.W., Myers, G.J., Weiss, B., 2004. Mercury exposure and child development outcomes. Pediatrics 113 (Suppl. S4), 1023–1029. https://doi.org/10.1542/peds.113.S3.1023.

Demendi, M., Petrie, S.A., 2006. Shot ingestion in scaup on the lower Great Lakes after nontoxic shot regulations in Canada. Wildl. Soc. Bull. 34, 1101–1106. https://doi.org/10.2193/0091-7648(2006)34[1101:SIISOT]2.0.CO;2.

Development Core Team, R, 2016. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.

DG of Fisheries of the Canary Government, 2024. https://www.gobiernodecanarias.org/pesca/temas/Control_calidad_productos/ciguatera.html.

Douglas, Bates, Maechler, Martin, Bolker, Ben, Walker, Steve, 2015. Fitting Linear Mixed-Effects Models Using lme4. J. Stat. Softw. 67 (1), 1–48. https://doi.org/10.18637/jss.v067.i01.

EUMOFA, 2021. EU consumer habits regarding fishery and aquaculture products – final report. https://op.europa.eu/en/publication-detail/-/publication/4b26f444-825f-11eb-9ac901aa75ed71a1.

European Commission, 2007. Commission Regulation (EC) No 333/2007 of 28 March 2007 laying down the methods of sampling and analysis for the official control of the levels of lead, cadmium, mercury, inorganic tin, 3-MCPD and benzo(a)pyrene in foodstuffs. Off. J. Eur. Union L 88, 29–38. Retrieved from. https://eur-lex.europa.eu/eli/reg/2007/333/oj/eng.

European Commission, 2023. Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006. Off. J. Eur. Union L 119, 103–157. Retrieved from. https://eur-lex.europa.eu/eli/reg/2023/915/oj/eng.

European Commission, 2024a. Rapid Alert System for Food and Feed (RASFF). European Commission. Available online: https://food.ec.europa.eu/food-safety/rasff_en.

European Commission, 2024b. 2024 Annual Report: Alert and Cooperation Network. Directorate-General for Health and Food Safety. Available online: https://ec.europa.eu/newsroom/sante/items/882537.

FAO, 2020. The state of world fisheries and aquaculture. FAO, Rome. http://www.fao.org/documents/card/en/c/ca9229en.

Goyanna, F.A.A., Fernandes, M.B., da Silva, G.B., de Lacerda, L.D., 2023. Mercury in oceanic upper trophic level sharks and bony fishes-a systematic review. Environ. Pollut. 318, 120821.

Harris, P.J., Wyanski, D.M., White, D.B., Mikell, P.P., Eyo, P.B., 2007. Age, growth, and reproduction of greater amberjack off the Southeastern U.S. Atlantic Coast. Trans. Am. Fish. Soc. 136, 1534–1545. https://doi.org/10.1577/T06-113.1.

Hayat, M.T., Nauman, M., Nazir, N., Ali, S., Bangash, N., 2019. Cadmium Toxicity and Tolerance in Plants. In: Environmental hazards of cadmium: Past, present, and future. Elsevier, pp. 163–183. Amsterdam, The Netherlands.

Hoffman, D.J., Rattner, B.A., Burton Jr., G.A., Cairns Jr., J., 2002. Handbook of Ecotoxicology, 2nd edition. CRC press, Boca Raton, FL. https://doi.org/10.1201/9781420032505.

Hornung, H., Krom, M.D., Cohen, Y., Bernhard, M., 1993. Trace metal content in deep-water sharks from the eastern Mediterranean Sea. Mar. Biol. 115 (3), 331–338. https://doi.org/10.1007/BF00346351.

Ikehara, T., Kuniyoshi, K., Oshiro, N., Yasumoto, T., 2017. Biooxidation of ciguatoxins leads to species-specific toxin profiles. Toxins 9 (7), 205.

Kalogeropoulos, N., Karavoltsos, S., Sakellari, A., Avramidou, S., Dassenakis, M., Scoullos, M., 2012. Heavy metals in raw, fried and grilled Mediterranean finfish and shellfish. Food Chem. Toxicol. 50, 3702–3708. https://doi.org/10.1016/j.fct.2012.07.012.

Kelly, T.R., Bloom, P.H., Torres, S.G., Hernandez, Y.Z., Poppenga, R.H., Boyce, W.M., Johnson, C.K., 2011. Impact of the California Lead Ammunition Ban on Reducing Lead Exposure in Golden Eagles and Turkey Vultures. PLoS ONE 6 (4), e17656. https://doi.org/10.1371/journal.pone.0017656.

Kravchenko, J., Darrah, T.H., Miller, R.K., Lyerly, H.K., Vengosh, A., 2014. A review of the health impacts of barium from natural and anthropogenic exposure. Environ. Geochem. Health 36 (4), 797–814. https://doi.org/10.1007/s10653-014-9622-7.

Le Croizier, G., Schaal, G., Gallon, R., Fall, M., Le Grand, F., Munaron, J.M., Rouget, M.L., Machu, E., Le Loc'h, F., Laë, R., De Morais, L.T., 2016. Trophic ecology influence on metal bioaccumulation in marine fish: inference from stable isotope and fatty acid analyses. Sci. Total Environ. 573, 83–95. https://doi.org/10.1016/j.scitotenv.2016.08.035.

Lee, J.-W., Jo, A.-H., Kang, Y.-J., Lee, D., Choi, C.-Y., Kang, J.-C., Kim, J.-H., 2025. Review of cadmium bioaccumulation in fish exposed to cadmium. Toxics 13, 7. https://doi.org/10.3390/toxics13010007.

Lenth, R., 2024. _emmeans: Estimated Marginal Means, aka Least-Squares Means_. R package version, 1 (10), 6. https://CRAN.R-project.org/package=emmeans.

Lewis, R.J., 2001. The changing face of ciguatera. Toxicon 39, 97–106. https://doi.org/10.1016/S0041-0101(00)00161-6.

Li, N., Wu, X., Zhuang, W., Xia, L., Chen, Y., Wu, C., Rao, Z., Du, L., Zhao, R., Yi, M., Wan, O., Zhou, Y., 2020. Fish consumption and multiple health outcomes: umbrella review. Trends Food Sci. Technol. 99, 273–283. https://doi.org/10.1016/j.tifs.2020.02.033.

Lofstedt, A., de Roos, B., Fernandes, P.G., 2021. Less than half of the European dietary recommendations for fish consumption are satisfied by national seafood supplies. Eur. J. Nutr. 60 (8), 4219–4228. https://doi.org/10.1007/s00394-021-02580-6.

Lowery, T., Garrett, E.S., 2005. Synoptic Survey of THg in Recreational Finfish of the Gulf of Mexico. NOAA Fisheries, Office of Sustainable Fisheries. National Seafood Inspection Laboratory, Silver Spring, MD.

Lozano-Bilbao, E., Lozano, G., Gutierrez, Á.J., Rubio, C., Hardisson, A., 2018. Mercury, cadmium, and lead content in demersal sharks from the Macaronesian islands. Environ. Sci. Pollut. Res. 25, 21251–21256. https://doi.org/10.1007/s11356-018-2550-9.

Lozano-Bilbao, E., Adern, N., Hardisson, A., González-Weller, D., Rubio, C., Paz, S., Pérez, J.A., Zupa, R., Gutiérrez, Á.J., 2021. Differences in macroelements, trace elements and toxic metals between wild and captive-reared greater amberjack (*Seriola dumerili*) from the Mediterranean Sea. Mar. Pollut. Bull. 170, 112637. https://doi.org/10.1016/j.marpolbul.2021.112637.

Lozano-Bilbao, E., Lozano, G., Jurado-Ruzafa, A., Hardisson, A., Rubio, C., Paz, S., Martí, V., Gutierrez, Á.J., 2023. Interdecadal variations of the mercury content in *Scomber colias* in Canary Islands. Environ. Sci. Pollut. Res. 30, 8347–8353. https://doi.org/10.1007/s11356-022-24378-7.

Lozano-Bilbao, E., Hardisson, A., Paz, S., Rubio, C., Gutierrez, Á.J., 2024. Review of metal concentrations in marine organisms in the Canary Islands: Insights from twenty-three years of research. Reg. Stud. Mar. Sci. 71, 103415. https://doi.org/10.1016/j.rsma.2024.103415.

Luckenbach, T., Fischer, S., Sturm, A., 2014. Current advances on ABC drug transporters in fish. Comp. Biochem. Physiol. C Toxicol. Pharmacol. 165, 28–52.

Malinowski, C., R., Stacyc, N., Colemana, F.C., Cusick, J.A., Duganb, C., M., Koeniga . C., C., Ragbeerb .K., N., Justin R, 2021. Perrault Mercury offloading in gametes and potential adverse effects of high mercury concentrations in blood and tissues of Atlantic Goliath Grouper *Epinephelus itajara* in the southeastern United States. Sci. Total Environ. 779, 146437. https://doi.org/10.1016/j.scitotenv.2021.146437.

Marí, J.T., Alías, M.S., de la Cruz, J.N., Ibáñez, M.V., 2010. Healthy Diet for All—A Guide of the Spanish Agency for Food Safety and Nutrition. Available online: https://www.aesan.gob.es/AECOSAN/docs/documentos/nutricion/alimentacion_sana_para_todos.pdf.

MOH (Ministry of Health, PRC), 2013. National standard of food safety-limits of food pollution MOH. Peking, China.

Moore, J.L., Hohman, W.L., Stark, T.M., Weisbrich, G.A., 1998. Shot prevalences and diets of diving ducks five years after ban on use of lead shotshells at Catahoula Lake, Louisiana. J. Wildl. Manag. 62, 564–569. https://doi.org/10.2307/3802330.

Mylonas, C.C., Katharios, P., Grigorakis, K., Papandroulakis, N., Robles, R., Corriero, A., Pousis, C., Zupa, R., Fernandez-Palacios, H., Montero, D., Izquierdo, M.S., Roo, J., Hernandez-Cruz, C.M., Rodriguez, C., Pérez, J.A., Jerez, S., Secombes, C., Guerrero, L., 2016. Greater amberjack (*Seriola dumerili*): A candidate species for the expansion of Mediterranean aquaculture. Aquac. Eur. 41 (1), 12–19.

Newth, J.L., Cromie, R.L., Brown, M.J., Delahay, R.J., Meharg, A.A., Deacon, C., Norton, G.J., O'Brien, M.F., Pain, D.J., 2013. Poisoning from lead gunshot: still a threat to wild waterbirds in Britain. Eur. J. Wildl. Res. 59 (2), 195–204. https://doi.org/10.1007/s10344-012-0666-7.

Polak-Juszczak, L., 2018. Distribution of organic and inorganic mercury in the tissues and organs of fish from the southern Baltic Sea. Environ. Sci. Pollut. Res. 25, 34181–34189. https://doi.org/10.1007/s11356-018-3336-9.

Prabakaran, K., Sompongchaiyakul, P., Bureekul, S., Wang, X., Charoenpong, C., 2024. Heavy metal bioaccumulation and risk assessment in fishery resources from the Gulf of Thailand. Mar. Pollut. Bull. 198, 115864.

Prabakaran, K., Charoenpong, C., Bureekul, S., Wang, X., Sompongchaiyakul, P., 2025. Heavy metal contamination in marine fish from the Andaman Sea: Influence of habitat and health risk assessment. Mar. Pollut. Bull. 210, 117299.

Ramos-Sosa, M.J., García-Álvarez, N., Sanchez-Henao, A., Silva Sergent, F., Padilla, D., Estévez, P., Caballero, M.J., Martín-Barrasa, J.L., Gago-Martínez, A., Diogène, J., Real, F., 2022. Ciguatoxin detection in flesh and liver of relevant fish species from the Canary Islands. Toxins 14 (1), 46. https://doi.org/10.3390/toxins14010046.

Sanchez-Henao, J.A., García-Álvarez, N., Fernández, A., Saavedra, P., Silva Sergent, F., Padilla, D., Acosta-Hernández, B., Martel Suárez, M., Diogène, J., Real, F., 2019. Predictive score and probability of CTX-like toxicity in fish samples from the official control of ciguatera in the Canary Islands. Sci. Total Environ. 673, 576–584. https://doi.org/10.1016/j.scitotenv.2019.03.445.

Satarug, S., Vesey, D.A., Gobe, G.C., 2017. Current health risk assessment practice for dietary cadmium: Data from different countries. Food Chem. Toxicol. 106, 430–445. https://doi.org/10.1016/j.fct.2017.06.013.

Sinkus, W., Shervette, V., Ballenger, J., Reed, L.A., Plante, C., Byron White, B., 2017. Mercury bioaccumulation in offshore reef fishes from waters of the Southeastern USA. Environ. Pollut. 228, 222e233. https://doi.org/10.1016/j.envpol.2017.04.057.

Smith-Vaniz, W.F., 2003. Carangidae: jacks and scads (bumpers, pompanos, leatherjacks, amberjacks, pilotfishes, rudderfishes). In: Carpenter, K.E. (Ed.), The living marine resources of the Western Central Atlantic. Vol. 3. Bony fishes part 2 (Opistognathidae to Molidae), sea turtles and marine mammals, FAO species identification guide for fishery purposes and American Society of Ichthyology and Herpetology Special Publication 5. FAO, Rome, pp. 1426–1468.

Soliño, L., Reis, P.R., 2020. Global impact of ciguatoxins and ciguatera fish poisoning on fish, fisheries and consumers. Environ. Res. 182, 1–16. https://doi.org/10.1016/j.envres.2020.109111.

Stevenson, A.L., Scheuhammer, A.M., Chan, H.M., 2005. Effects of nontoxic shot regulations on lead accumulation in ducks and American woodcock in Canada. Arch. Environ. Con. Tox. 48, 405–413. https://doi.org/10.1007/s00244-004-0044-x.

Swart, B.L., von der Heyden, S., Bester-van der Merwe, A., Roodt-Wilding, R., 2015. Molecular systematics and biogeography of the circumglobally distributed genus *Seriola* (Pisces: Carangidae). Mol. Phylogenet. Evol. 93, 274–280. https://doi.org/10.1016/j.ympev.2015.08.002.
Thera, J.C., Rumbold, D.G., 2014. Biomagnification of mercury through a subtropical coastal food web off southwest Florida. Environ. Toxicol. Chem. 33 (1), 65e73.
Tlusty, M.F., 2021. Food-based dietary guidelines for seafood do not translate into increased long-chain omega-3 levels in the diet for U.S. consumers. Foods 2021 10, 1816. https://doi.org/10.3390/foods10081816.
U.S. EPA, 1995. Mercury Study Report to Congress. Office of Research and Development, Washington, DC (External Review Draft. EPA/600/P-94/002Ab).
U.S. EPA, 2001. Water Quality Criterion for the Protection of Human Health: Methylmercury Chapter 4: Risk Assessment for Methylmercury. Office of Science and Technology, Office of Water, Washington, DC.
Uno, T., Ishizuka, M., Itakura, T., 2012. Cytochrome P450 (CYP) in fish. Environ. Toxicol. Pharmacol. 34 (1), 1–13.
USEPA, 1989. Risk assessment guidance for superfund. In: Human Health Evaluation Manual Part A, Interim Final, vol. I. United States Environmental Protection Agency, Washington (DC). EPA/540/1–89/002.
Valdés, L., Déniz-González, I. (Eds.), 2015. Oceanographic and biological features in the Canary Current Large Marine Ecosystem. IOC Technical Series, 115. IOC-UNESCO, Paris (383 pp).
Van den Broek, W.L.F., Tracey, D.M., Solly, S.R.B., Avrahami, M., 1981. Mercury levels in some New Zealand sea fishes. N. Z. J. Mar. Freshw. Res. 15 (2), 137–146. https://doi.org/10.1080/00288330.1981.9515906.
Vieira, H.C., Bordalo, M.D., Morgado, F., Soares, A.M.V.M., Abreu, S.N., 2017. Mercury content in the white and dark muscle of Skipjack tuna (*Katsuwonus pelamis*) along the canning process: implications to the consumers. J. Food Compos. Anal. 56, 67–72. https://doi.org/10.1016/j.jfca.2016.11.011.
Visseren, F.L.J., Mach, F., Smulders, Y.M., Carballo, D., Koskinas, K.C., Bäck, M., Benetos, A., Biffi, A., Boavida, J.M., Capodanno, D., Cosyns, B., Crawford, C., Davos, C.H., Desormais, I., Di Angelantonio, E., Franco, O.H., Halvorsen, S., Hobbs, F.D.R., Hollander, M., Jankowska, E.A., ESC Scientific Document Group, 2021. 2021 ESC guidelines on cardiovascular disease prevention in clinical practice. Eur. Heart J. 42 (34), 3227–3337. https://doi.org/10.1093/eurheartj/ehab484.
Wood, K.A., Brown, M.J., Cromie, R.L., MacKenzie, C., Newth, J.L., Pain, D.J., Perrins, C. M., Rees, E.C., 2019. Regulation of lead fishing weights results in mute swan population recovery. Biol. Conserv. 230, 67–74. https://doi.org/10.1016/j.biocon.2018.12.010.
Zillioux, E.J., 2015. Mercury in fish: history, sources, pathways, effects, and indicator usage. Environ. Indic. 743–766. https://doi.org/10.1007/978-94-017-9499-2_42.
Zupo, V., Graber, G., Kamel, S., Plichta, V., Granitzer, S., Gundacker, C., Wittmann, K.J., 2019. Mercury accumulation in freshwater and marine fish from the wild and from aquaculture ponds. Environ. Pollut. 255, 112975. https://doi.org/10.1016/j.envpol.2019.112975.