



Seasonal and Site Variations in Heavy Metals Contaminations in Seawater and Fish Organs and Health Risks Assessment

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Abstract: Coastal ecosystems are increasingly exposed to land-based pollution from tourism, agriculture, and mining, resulting in heavy metal contamination of seawater and marine organisms. This study quantifies cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), and zinc (Zn) concentrations in seawater and in the organs of the commonly consumed fish *Auxis thazard* and *Selar crumenophthalmus* in the Tañon Strait, Cebu, Philippines. This research further assesses associated health risks and significant differences in metal levels across organs, seasons, sites, and between species. Fish and seawater samples were collected from three sites, Moalboal, Barili, and Toledo, during wet and dry seasons and prepared following the sampling protocols outlined in previous studies. Health risk assessment was based on the calculated Target Hazard Quotient (THQ), Hazard Index (HI), and Estimated Weekly Intake (EWI). Results revealed that Cd exceeded FAO limits in all fish organs, while Cr exceeded only in the gills, and Pb also exceeded limits and was only discovered in the gills. Cu and Zn were within acceptable levels in both species. Metal concentrations were lowest in muscles and highest in the GIT, and were generally higher during the wet season, except for Zn in the gills and GIT. Metal accumulation between species differed significantly only during the dry season ($p < 0.05$), while across organs at the three sites, metal concentrations did not differ significantly ($p < 0.05$). Only Zn and Cu were detected in low amounts in seawater. Also, results showed no significant health risk. Continued monitoring is suggested, particularly during wet seasons, to support food safety.

Keywords: Coastal pollution; fish organs; heavy metals; seasonal variation; site variation

1. Introduction

Heavy metal contamination of aquatic environments is an emerging global problem due to the persistence, bioaccumulation, and toxicity of these metals [1, 2]. Unlike other pollutants, heavy metals such as Cd, Cr, Cu, Pb, and Zn are non-biodegradable substances that can accumulate in aquatic ecosystems and provide chronic risks to the environment and human health [3]. Various natural and anthropogenic processes contribute to the accumulation of heavy metals in aquatic environments, including agricultural, industrial, and waste-disposal activities [4]. Another contributor is the tourism activities. They have negative impacts on beaches, including physical and ecological degradation [5],

untreated discharges from watercraft [6], and densification of areas along aquatic niches. Fish is a well-known staple food [7, 8], especially in the Philippines, where fish is a crucial component of Filipino diets. It is regarded as an important component of a nutritious diet due to its high-quality properties, vitamins, and essential omega-3 fatty acids [2, 8, 9]. Nonetheless, the health benefits of fish are lost when heavy metals accumulate, as the consumption of contaminated fish and seafood can cause adverse health effects [10], including kidney, liver, brain, muscle, and lung damage [1, 2].

Tañon Strait in Cebu, Philippines, is a nationally protected seascape and is considered one of the most ecologically significant marine corridors in the Philippines [11]. The Tañon Strait, despite its protected status, faces various anthropogenic activities, including mining, agriculture, and tourism, that may introduce heavy metals into aquatic ecosystems. Three coastal areas of Cebu Province, Moalboal, Barili, and Toledo City, represent distinct anthropogenic activities that are potential sources of heavy metals. Moalboal is a tourist destination in the southern province of Cebu, known for its diving and coastal recreation [12]. Infrastructure development, wastewater generation, and boating activities in the area may accelerate degradation of its marine environment [5, 6]. On the other hand, Barili is a major agricultural municipality [13], and in an agricultural context, the use of fertilizers and pesticides is widely documented to prevent post-harvest diseases and improve crop production [14]. Given Barili's agricultural characteristics, such utilization may also be practiced in the area, leading to potential heavy metal runoff into coastal zones, especially during heavy rainfall. Toledo City is linked to mining operations [15], which are perceived as major contributors of metal-rich effluents. Collectively, these activities can lead to heavy metal accumulation in seawater, which may then be transferred to fish consumed by local communities. Since fish readily absorb heavy metals through their gills, digestive tracts, and muscle tissues [16], it is important to assess their levels of contamination. Seasonal factors have a greater impact on metal concentrations, as rainfall and hydrological variations alter pollutant transport and accumulation [17].

Despite the ecological and economic importance of the Tañon Strait, studies about heavy metal pollution in the aquatic environment of Cebu Province are scarce, particularly on human health risks.

While several studies in Philippine regions and abroad have reported heavy metal contamination in aquatic environments (e.g., [1, 2, 18]), they have not collectively examined the sources of heavy metal pollution, such as tourism, agriculture, and mining. No published reports have quantified heavy metal concentrations in locally consumed fresh fish in this area, nor have hazard index approaches been used to assess potential health risks to consumers. This knowledge gap is critical, given local communities' dependence on fish as a staple food. Thus, the current study aims to assess heavy metal levels in two commonly consumed fresh fish, *Auxis thazard* (*A. thazard*) and *Selar crumenophthalmus* (*S. crumenophthalmus*), and seawater across three identified sites and two seasons (dry and wet). The findings could help evaluate food safety for local communities and serve as a scientific basis for environmental monitoring, public health protection, and policymaking.

2. Materials and Methods

2.1 Study Sites and Sample Collection

The study was conducted at the three municipalities along the Tañon Strait, a nationally protected seascape and one of the most ecologically significant marine corridors in the Philippines [11]. The Tañon Strait is still exposed to increasing anthropogenic pressures, despite its protected status, including tourism, agricultural practice, and mining, which are potential sources of heavy metal accumulation in the marine environment. Three municipalities in Southern Cebu were selected to represent the said anthropogenic activities: Toledo City, Barili, and Moalboal (Figure 1). Fish and seawater samples were collected at the three identified sites during two seasons: the dry season (April and May) and the wet season (October and November). These samples were collected concurrently at each site to allow seasonal and site comparisons.

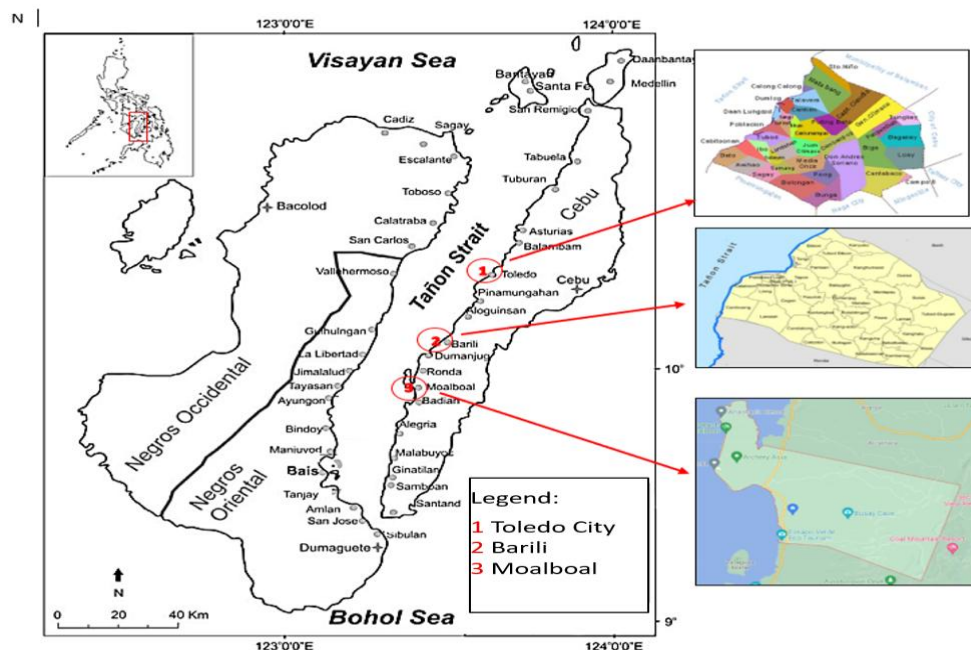


Figure 1. Map of the three study sites along the Tañon Strait in Southern Cebu, Philippines, Toledo City, Barili, and Moalboal, selected to represent areas exposed to mining, agricultural, and tourism activities, respectively.

2.2 Fish Sampling

Two fish species, *Selar crumenophthalmus* and *Auxis thazard*, which are commonly consumed by local communities and abundant in the Tañon Strait, were selected for analysis. Fish samples were obtained directly from small-scale fishermen operating at each identified site. Approximately 2 kg of each fish species was collected during the sampling period at each site, placed in pre-cleaned polyethylene bags properly labeled with the species, site, and season, and transported in containers with ice. Total length and body weight were recorded (mean $\pm$ SD total length: *A. thazard*: 24.3 ± 3.1 cm; *S. crumenophthalmus*: 19.8 ± 2.7 cm; mean $\pm$ SD body weight: *A. thazard*: 142 ± 22 g; *S. crumenophthalmus*: 98 ± 17 g), and samples were stored at -20 °C until further processing [10]. Before analysis, frozen samples were thawed and dissected using stainless-steel instruments [19]. Gills, muscle tissues, and GIT were removed and pooled to obtain 250g composite samples per organ, species, and site. A total of 18 composite organ samples were prepared. Fish organ digestion followed the perchloric acid method described by [20]. Each composite sample was placed in a 500 mL Teflon beaker, treated with 50 mL of concentrated nitric acid (HNO_3 , 65%), and heated for 45 min to remove oxidizable material. After cooling, 25 mL of perchloric acid (HClO_4) was added, and heating was continued until white fumes appeared. Then, 100 mL of distilled water was added, and the solution was reheated to eliminate residual gases. Thereafter, the solution was filtered with Whatman No. 2 filter paper and set aside for heavy metal analysis.

2.3 Seawater Sampling

Seawater samples were collected using the procedure of [13]. Polyethylene sampling bottles were pre-cleaned with 10% (v/v) HNO_3 and rinsed thoroughly with deionized water before sampling. At each site, seawater was collected from the three identified sampling points approximately 10 cm below the surface, then combined to form a composite sample from which a 500 mL sample was obtained for analysis during each sampling period. Samples were transported in an ice-filled container to the university's laboratory and stored in a freezer at -20 °C until laboratory analysis [21].

2.4 Heavy Metal Analysis

Concentrations of Cd, Cr, Cu, Zn, and Pb in fish organs and seawater were determined using atomic absorption spectrophotometry (AAS) at the FAST Laboratory. Metal quantification was performed using metal-specific hollow cathode lamps under optimized operating conditions, following standard analytical procedures [22].

2.5 Human Health Risk Assessment

Risk assessment was performed using the THQ, HI, and TWI. The THQ was calculated using Equation 1 based on Salam (2019):

$$THQ = \frac{EF * ED * FIR * C}{RfD * WAB * TA} \times 10^{-3} \quad (1)$$

where: EF (exposure frequency) = 365 days/year, ED refers to exposure duration = 71 years, the average lifetime of the Filipino population, FIR (fish ingestion rate) of an adult Filipino = 93.85 g/day [23], C represents HMs content in fish muscle tissue (mg/kg wet weight), particularly the higher value between the wet and dry season for each metals to ensure a conservative estimation of non-carcinogenic health risk, RfD (oral reference dose) based on [24]: Cd (0.001), Cr (1.5), Cu (0.040), Pb (0.0035), Zn (0.300), in mg/kg/day, WAB (average weight) = 65 kg for Filipino adults [25], and TA (average period of exposure for non-carcinogens) = 365 days/year $\times$ ED. For metal concentrations below the level of detection, half the detection limit would be used for calculation [26].

The hazard index (HI) is calculated using Equation 2, based on the study of [27], to assess the possible risk of adverse health effects from a combination of toxic metals:

$$HI = \sum_i (THQ_i) = THQ_{Cd} + THQ_{Cr} + THQ_{Cu} + THQ_{Pb} + THQ_{Zn} \quad (2)$$

The estimated daily intake of heavy metals was calculated using Eq. 3, used by [22]. Estimated daily intake (EDI) with modification in the units:

$$EDI_{HM} = \frac{HM \text{ concentration } \left(\frac{mg}{kg}\right) \times \text{consumption rate } \left(\frac{kg}{d}\right)}{\text{body weight (kg)}} \quad (3)$$

The estimated weekly intake of heavy metals for a 65 kg person was calculated using Eq. 4 below:

$$EWI_{HM} / 65 \text{ kg bw} = \frac{HM \text{ concentration } \left(\frac{mg}{kg}\right) \times \text{consumption rate } \left(\frac{kg}{d}\right) \times 7}{65 \text{ kg body weight}} \quad (4)$$

Similarly, the heavy metal concentration used in the calculations was based on the higher median values between the wet and dry seasons. The daily fish consumption rate was set at 93.85 g/day [23], while the reference body weight for Filipino adults was 65 kg [25]. Using the EDI, the EWI for heavy metals for a 65 kg body weight was computed and compared with the corresponding TWI values derived from the recommended intake. The recommended intake values applied in this study were sourced from [22] for Cd, Pb, and Zn; from the European Food Safety Authority [28] for Cu; and from [29] for Cr.

2.6 Data Analysis

A series of Kruskal-Wallis H-tests was conducted to assess significant differences in heavy metal levels in fish tissues across sampling sites, and a Mann-Whitney U-test was used to compare species and seasons. Differences in organs per species were determined using the Friedman test, with pairwise comparisons for significant results. Analysis was done using SPSS 22. The Wilcoxon Signed Rank Test was used to analyze the difference in Cr levels between the gills and the GIT. It should be noted that the statistical comparisons are performed on composite-level data: each composite sample was prepared by pooling tissues from approximately 10–15 individual fish of the same species collected at each site per sampling event, yielding one

composite value per organ, per species, per site, per season. Each composite was subjected to duplicate analytical runs, and the mean of the two determinations was used for analysis. The *n* for the statistical tests (Kruskal-Wallis, Mann-Whitney, Friedman) therefore refers to the number of composite samples per group (*n* = 3 per site comparison; *n* = 6 per species or season comparison across all sites and seasons), which limits the inferential power of the tests and precludes true biological replication. Results should therefore be interpreted as site- and season-level trends rather than population-level estimates.

3. Results and Discussion

3.1 Heavy Metal Concentrations in Fish Organs According to Species during Wet and Dry Seasons

The concentrations of Cd, Cr, Cu, Pb, and Zn in the gills, GIT, and muscle tissues of *A. thazard* and *S. crumenophthalmus* during the wet and dry seasons are presented in Table 1. Cadmium concentrations in all analyzed tissues of both fish species exceeded the FAO permissible limit of 0.05 mg/kg wet weight, indicating widespread Cd contamination in the study area. Cadmium is of particular concern due to its slow excretion rate and strong bioaccumulative potential [30]. Although Cd concentrations exceeded permissible limits, the levels observed in this study were lower than those reported in other regions of the Philippines. For example, Cd concentrations in marine fish from Manila Bay ranged from 38.262 to 56.924 mg/kg during the wet season and from 1.828 to 2.425 mg/kg during the dry season [31]. Similarly, Cd concentrations of 9.5–17 mg/kg were reported in marine fish collected from Agusan and Butuan [32]. Chromium concentrations also exceeded the allowable limit of 1.0 mg/kg in the gills of both species and in the GIT of *S. crumenophthalmus*.

In contrast, Cu and Zn concentrations in all organs of both species remained within the FAO/WHO-recommended limits during both sampling seasons. Cu and Zn are essential trace elements; their accumulation patterns vary among organs and seasons, reflecting both physiological regulation and environmental availability. Chromium showed preferential accumulation in gill tissues, suggesting waterborne exposure, consistent with the studies by [33] and [34]. Cr's affinity for gill epithelia stems from their large surface area and permeability [28]. Lead (Pb) was detected only in the GIT of *A. thazard* and only during the dry season, with concentrations exceeding the permissible limit of 0.3 mg/kg wet weight. Pb concentrations in all other tissues and sampling periods were below the limit of detection. Across both *Auxis thazard* and *Selar crumenophthalmus*, the GIT and gills consistently exhibited higher metal concentrations than muscle tissues. Such a pattern is widely documented in marine fish and is attributed to direct gill exposure to contaminated water and dietary exposure through ingestion of sediment and prey [39; 40]. In contrast, muscle tissue generally had the lowest metal concentrations, likely because of its limited role in metal sequestration. This pattern of reduced accumulation in muscle tissues aligns with the findings of [22], [35], and [36], while heavy metal accumulation in the GIT suggests dietary exposure through ingestion of contaminated prey or sediments [30].

Table 1. Heavy metal concentrations in fish organs of *A. thazard* and *S. crumenophthalmus* during wet and dry seasons

Season	Fish species	Cd			Cr			Cu			Pb			Zn		
		G	M	GIT	G	M	GIT	G	M	GIT	G	M	GIT	G	M	GIT
Wet	<i>A. Thazard</i>	Med	0.2 ^a	0.069 ^b	0.43 ^a	1.86	*	.510	1.02 ^a	0.5 ^b	2.61 ^a	*	*	10.29 ^b	5.64 ^c	11.57 ^a
		Min	0.15	0.05	0.23	.040	*	*	0.86	*	*	*	*	7.76	4.52	9.11
		Max	0.24	0.09	0.73	2.41	*	0.51	2.41	0.73	8.10	*	*	13.45	6.89	16.69
	<i>S. crumenophthalmus</i>	Med	0.22 ^a	0.06 ^b	0.34 ^a	2.50	*	*	0.95 ^{ab}	0.42 ^b	1.2 ^a	*	*	10.24 ^a	6.21 ^b	9.5 ^a
		Min	0.15	0.03	0.25	0.28	*	*	0.83	0.18	*	*	*	5.73	5.73	7.41
		Max	0.28	0.25	0.61	3.09	*	*	1.13	0.52	7.79	*	*	13.92	6.95	14.98
Dry	<i>A. thazard</i>	Med	0.07 ^b	0.05 ^b	0.24 ^a	1.62	*	1.02	0.63 ^b	0.64 ^b	1.55 ^a	*	*	0.88	24.31 ^a	4.88 ^b
		Min	0.01	0.01	0.02	1.18	*	0.64	0.03	0.05	0.08	*	*	0.88	4.11	1.69
		Max	0.23	0.09	0.58	1.84	*	1.51	1.34	1.64	3.16	*	*	0.88	55.84	9.21
	<i>S. crumenophthalmus</i>	Med	0.10 ^{ab}	0.04 ^b	0.33 ^a	0.787	*	0.23	0.36 ^b	0.49 ^{ab}	1.83 ^a	*	*	11.37 ^a	7.06 ^b	21.58 ^a
		Min	0.01	0.014	0.01	0.04	*	0.02	0.019	0.034	0.02	*	*	4.289	2.628	4.24
		Max	0.09	0.09	0.746	2.15	*	1.18	1.151	1.184	4.102	*	*	27.3	11.62	42.84
Permissible Limit		0.05			1.0			30			0.3 mg/kg			30		
		FAO (1983)			WHO/FAO (2011)			FAO (1983)			WHO/FAO (2022)			FAO (1983)		

Note: * - Less than detection level; Median values within the metal across the different organs under the same species, followed by the same letters are not significantly different from each other.

3.2 Results of Significant Differences in Metal Concentrations Across Organs, Between Species per Season, and Between Seasons

The results of significant differences in metal concentrations when compared among organs per species, between species per season, and between seasons in each species are reflected in Table 2. Concerning organ-specific distribution, metal concentrations differ significantly among fish organs for all analyzed metals in both species ($p < 0.05$). In general, the GIT had the highest metal concentrations, significantly higher than those in the gills ($p < 0.05$), while muscle tissues consistently showed the lowest concentrations. An exception was observed for Cr, which accumulated at significantly higher levels in the gills compared to other organs. This is consistent with the findings of [36] and [37], who similarly demonstrated variations in metal accumulation across different fish anatomical components. For species-based differences, metal concentrations between *A. thazard* and *S. crumenophthalmus* did not differ significantly ($p < 0.05$) across all analyzed organs during the wet season ($p > 0.05$). However, during the dry season, significant differences were observed ($p < 0.05$). *A. thazard* exhibited significantly higher Cu concentrations in the gills and muscle tissues. These interspecific differences may be partly influenced by body size, as *A. thazard* was consistently larger than *S. crumenophthalmus*, which could contribute to higher metal accumulation in certain tissues, consistent with well-documented size-dependent bioaccumulation in marine teleosts [16]. However, the contrasting pattern observed for Zn, in which *S. crumenophthalmus* showed significantly higher concentrations in muscle tissues, suggests that size alone does not fully explain metal uptake, and that species-specific differences in feeding behavior, habitat use, and metal regulation may also play important roles. Species differences, particularly during the dry season, suggest that physiological differences in feeding behavior, habitat use, and metabolic capacity may influence metal uptake under lower-dilution conditions. The absence of significant differences across species during the wet season may indicate increased metal dispersion and a more uniform exposure, driven by enhanced freshwater input and hydrodynamic mixing. Regarding seasonal variation within species, for *A. thazard*, Cd concentrations in the gills and GIT, as well as Cr concentrations in the gills, were significantly higher during the wet season ($p < 0.05$). Zinc concentrations in the gills and GIT were significantly higher during the dry season. For *S. crumenophthalmus*, significant seasonal differences were observed in gill Cd, Cr, and Cu concentrations, with higher levels during the wet season ($p < 0.05$). No significant seasonal differences were observed for muscle tissues. Each species showed significantly higher metal levels during the wet season, likely due to increased runoff, sediment resuspension, and metal mobilization from terrestrial sources during heavy rainfall [38, 39], while Zn levels were unexpectedly higher during the dry season. These results support the findings of [40], who documented seasonal peaks in Zn levels during warmer months.

3.3 Heavy Metal Concentrations in Fish Organs Across Sampling Sites

The site distribution of heavy metals in fish organs from Moalboal, Barili, and Toledo is presented in Table 3. Among the three sampling sites, Moalboal consistently exhibited the highest concentrations of Cd, Cr, and Zn in gill tissues. Moalboal also showed the highest Cu concentrations in muscle tissues and was the only site where Pb was detected in the GIT of fish. Moalboal, a tourism-dominated area, showed the highest levels of Cd, Cr, and Zn in gills, and Cu in muscle tissue, including the only site detected with Pb in the GIT. This localized Pb presence may reflect ingestion of contaminated particles or prey, consistent with findings that Pb tends to accumulate in digestive tissues due to its affinity for mucosal surfaces and limited systemic distribution [36, 41]. Also, wastewater discharge, boating activities, fuel combustion, and sediment disturbance in coastal tourism, like in Moalboal, likely contribute to heavy metal pollution [6, 42]. Furthermore, the corrosion of metallic vessel components and coastal infrastructure in chloride-rich marine environments may constitute an additional diffuse source of heavy metal inputs in high-traffic tourist areas [43]. At the same time, Cu toxicity to aquatic biota has been demonstrated at concentrations well below those reported here [39].

Table 2. Results of significant differences in metal concentrations when compared among organs per species, between species per season, and between seasons in each species.

Comparison of Heavy Metal Concentrations among organs in each species					
	Cd (Wet; Dry)	Cr (Wet; Dry)	Cu (Wet; Dry)	Pb (Wet; Dry)	Zn (Wet; Dry)
Comparison among organs of <i>A. thazard</i>					
P-value	<0.001; 0.001;	<0.001;<0.001	<0.001;<0.001	—	<0.001;<0.001
Comparison among organs of <i>S. crumenophthalmus</i>					
P-value	<0.001; 0.001	—; 0.008	<0.001; 0.001	—	<0.001; <0.001
Comparison of Heavy Metal Concentrations between species during wet and dry seasons per organ					
	Cd (G; M; GIT)	Cr (G; M; GIT)	Cu (G; M; GIT)	Pb (G; M; GIT)	Zn (G; M; GIT)
Comparison between <i>A. thazard</i> & <i>S. crumenophthalmus</i> during the wet season per organ					
P-values	0.242; 0.180; 0.270	0.319; ---	0.160; 0.266; 0.590	—	0.671; 0.068; 0.068
Comparison between <i>A. thazard</i> & <i>S. crumenophthalmus</i> during the dry season per organ					
P-values	0.521; 0.628; 0.584	0.696; ---; 0.542	0.012; 0.220; 1.00	—	0.389; 0.016; 0.696
Comparison of Heavy Metal Concentrations between seasons in each species per organ					
Comparison between wet and dry seasons of <i>A. thazard</i> per organ					
P-values	<0.001; .215; 0.010	0.048; ---; 0.325	0.134; 0.185; 0.692	—	<0.001 ; 0.755; <0.001
Comparison between wet and dry seasons of <i>S. crumenophthalmus</i> per organ					
P-values	0.013; 0.368; 1.0	0.06; ---; ---	0.031; 0.267; 0.723	—	0.465; 0.99; 0.465

Note: G-Gills, M-Muscles; Bold p-values indicate statistically significant differences at $\alpha = 0.05$, while p-values ≥ 0.05 are not statistically significant. Dashes (—) denote tests not performed due to data below the detection limit.

Table 3. Heavy metals concentration (median; mg/kg) across sites and the results of significant differences

Site	Cd			Cr			Cu			Pb			Zn		
	G	M	GIT	G	M	GIT	G	M	GIT	G	M	GIT	G	M	GIT
Moalboal	Med	0.2	0.06	0.4	0.3	0.1	0.91	0.22	0.74	*	*	0.88	13.11	6.82	13
	Min	0.01	0.01	0	0.04	*	0.02	0.03	0.02	*	*	0.88	1.7	2.66	2.27
	Max	0.23	0.09	0.6	2.22	*	1.86	1.64	3.93	*	*	0.88	38.2	55.8	37.63
Barili	Med	0.15	0.07	0.3	1.55	*	1.0	0.1	1.62	*	*	*	12.52	6.92	13.25
	Min	0.01	0.01	0	0.04	*	0.02	0.06	0.08	*	*	*	0.24	2.78	2.33
	Max	0.24	0.09	0.7	3.07	*	2.41	1.57	7.79	*	*	*	36.4	55.5	42.84
Toledo	Med	0.08	0.06	0.4	1.5	*	0.73	0.1	0.33	*	*	*	12.13	7.83	11.05
	Min	0.01	0.01	0	0.04	*	0.02	0.05	0.08	*	*	*	0.24	4.29	2.63
	Max	0.28	0.25	0.8	3.09	*	1.34	1.44	3.58	*	*	*	37.02	34.9	42.04
<i>P-value</i>	0.823	0.9	0.9	0.9	0.81	---	0.48	0.539	0.64	0.6	---	---	0.881	0.97	0.731
Permissible Limit	0.05			1			30			0.3 mg/kg			30		
	FAO (1983)			WHO/FAO (2011)			FAO (1983)			WHO/FAO (2022)			FAO (1983)		

Conversely, higher concentrations of Cr, Cu, and Zn were found in the GIT of samples from Barili than in the other sites. This result suggests dietary exposure associated with agricultural runoff. Agrochemicals are known to contain trace metals that can enter aquatic systems through erosion and leaching, particularly during the wet season [14]. Similarly, the highest Cd concentration in the GIT and the highest Zn levels in muscle tissues were observed in the Toledo samples, whereas Cu concentrations across all organs were comparatively lower at this site. This finding points to the complexity of metal sources and transport mechanisms, as contaminants from mining activities depend on waste management practices, hydrodynamics, and sediment characteristics. Despite these site-specific variations in metal concentrations, statistical analysis showed no significant differences in heavy metal levels among the three sampling sites across all fish organs ($p > 0.05$). The observed trends provide valuable insight into localized contamination patterns and emphasize the need for site-specific monitoring and management strategies.

3.4 Heavy Metal Concentrations in Seawater

Heavy metal concentrations in seawater across the three sampling sites and two seasons are presented in Table 4. Among the analyzed metals, only Zn and Cu were detected, and only during the dry season. Cr, Cd, and Pb were below detection limits in both wet and dry seasons across sites. Zinc concentrations ranged from 0.008 to 0.160 mg/L, with the highest recorded in Barili (0.160 mg/L), followed by Toledo (0.154 mg/L), and the lowest in Moalboal (0.008 mg/L). Copper concentrations were relatively low, ranging from 0.008 to 0.010 mg/L, with the highest value in Toledo and slightly lower concentrations in Barili, while Cu was not detected in Moalboal. All detected concentrations of Zn and Cu were substantially below the permissible limits for coastal waters established by FAO/WHO guidelines. No metals were detected in seawater during the wet season at any of the sampling sites. This suggests relatively good ambient water quality in the Tañon Strait during the study period. The results below detection limits of Cd, Cr, and Pb in seawater during both seasons are consistent with recent studies reporting low dissolved metal concentrations in coastal waters, particularly in areas with strong hydrodynamic mixing and dilution [48; 49; 50]. The absence of detectable Cd, Cr, and Pb in seawater, despite exceeding FAO limits in fish tissues, reflects bioaccumulation processes and multiple exposure pathways; even when dissolved concentrations are below detection limits (0.001–0.005 mg/L), heavy metals may still accumulate in fish, as high bioconcentration factors (BCF) enable uptake over time. For instance, Biota-sediment accumulation factors (BSAF; 10^3 – 10^5) for Cd in benthic-feeding fish typically range from 0.1 to 10 [44], and dietary exposure through ingestion of sediment particles and contaminated prey is a primary route of Cd and Pb accumulation in the GIT.

Table 4. Heavy metal concentrations in seawater (mg/L) across three sites during the wet and dry seasons

Sites	Cd		Cr		Cu		Pb		Zn	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Moalboal	<0.001	<0.001	<0.005	<0.005	<0.003	0.006	<0.005	<0.005	<0.005	0.008
Barili	<0.001	<0.001	<0.005	<0.005	<0.003	0.008	<0.005	<0.005	<0.005	0.160
Toledo	<0.001	<0.001	<0.005	<0.005	<0.003	0.01	<0.005	<0.005	<0.005	0.154
Permissible Limit	0.003mg/L		0.05 mg/L		0.5 mg/L		0.01mg/L		5 mg/L	
WHO (2020-2026)										

Zn and Cu were detected only during the dry season. This may be attributed to reduced water volume, increased contaminants, and lower dilution capacity, which can enhance the detectability of dissolved trace metals [20; 45]. Barili showed a higher Zn concentration than other sites, which may reflect inputs from agricultural runoff, since fertilizers containing Zn are commonly used in farming [14]. Similarly, Toledo showed slightly higher Cu levels than other sites. Recent research on coastal pollution attenuation suggests that biosurfactant-producing bacteria can enhance bioremediation of organic co-pollutants in marine coastal

zones [45], indicating that the natural microbial community may partly modulate metal bioavailability through interactions with organic matter. Comprehensive contaminant monitoring frameworks, including radiological parameters, are also essential for full characterization of aquatic environmental health [45]. Despite the detection of some metals in seawater, these metal concentrations did not directly link to fish organs' heavy metal accumulations. For example, although Cu was detected at the Toledo site, fish collected there showed lower Cu levels than those from Moalboal. This discrepancy shows that metal bioaccumulation in fish is not only dependent on dissolved metal concentrations in seawater but is strongly influenced by additional exposure pathways, including dietary intake, sediment-associated metals, and species-specific physiological regulation [39; 33]. Furthermore, the detection limits of the seawater analysis (0.001–0.005 mg/L) may not be sufficiently sensitive to detect chronically low but biologically meaningful dissolved metal concentrations. Bioconcentration factors (BCF) and biota-sediment accumulation factors (BSAF) reported in the literature indicate that fish can accumulate metals from both water and sediment at levels several orders of magnitude higher than ambient dissolved concentrations [40; 33]. The absence of sediment metal data in this study constitutes a limitation, as sediment serves as a primary reservoir and secondary source of heavy metals in coastal systems; future studies should incorporate sediment analysis to enable source attribution and more robust interpretation of tissue burdens [45].

3.5 Health Risk Assessment

3.5.1 Target Hazard Quotient (THQ) and Hazard Index (HI)

The calculated THQ values for Cd, Cr, Cu, Pb, and Zn in *A. thazard* and *S. crumenophthalmus* are presented in Table 5. All THQ values for the identified metals were below the critical threshold of 1.0, indicating consumption of the two species considered in this study is safe with respect to non-carcinogenic health risks. As shown in the results, Cd exhibited the highest THQ values in both species, indicating relatively higher concentrations in fish tissues. Pb and Cr concentrations in muscle tissues of both species were below the detection limit of 0.1 mg/kg. To avoid underestimating exposure, a conservative proxy value equal to half the detection limit (0.05 mg/kg) was used in THQ and HI calculations. Using this approach, Pb and Cr yielded THQ values of 0.0206 and 4.81×10^{-5} , respectively, for both species. While these values indicate negligible non-carcinogenic risk, using proxy concentrations ensures that potential exposure is accounted for even when metals are below the detection limit. Although health risk assessments based on THQ and HI indicate safe intake levels, continuous and excessive consumption of essential metals may still cause adverse effects, such as gastrointestinal disturbances or interference with the absorption of other micronutrients [46]. Chromium obtained the lowest THQ among all metals assessed. However, this analysis did not distinguish between trivalent chromium [Cr(III)], which is an essential nutrient, and hexavalent chromium [Cr(VI)], which is highly toxic and carcinogenic [48]. As such, this raises uncertainty and suggests that health risks could be underestimated in environments affected by industrial or mining activities. As a conservative sensitivity analysis, if all detected Cr were assumed to be Cr(VI) (worst-case scenario), the oral reference dose for Cr(VI) is substantially lower (0.003 mg/kg/day, USEPA) than the value used here for total Cr (1.5 mg/kg/day). Under this assumption, the THQ for Cr (VI) would be approximately 0.048, which remains below 1.0 and still does not indicate a significant non-carcinogenic health risk from muscle tissue consumption. Nevertheless, communities near Toledo City's mining operations face a higher potential for Cr(VI) exposure through gill and GIT ingestion, and future studies should perform Cr speciation analysis to refine risk estimates. The present results based on the calculated HI, which represents the combined non-carcinogenic risk from simultaneous exposure to all assessed metals, are similar to those reported by [22]. Despite exceeding permissible limits for Cd and Cr in certain fish organs, the calculated THQ and HI values remained below the threshold value. However, Cd and Pb contributed most to cumulative exposure, consistent with their high toxicity and bioaccumulative nature. Chronic exposure to Cd has been linked to nephrotoxicity, bone demineralization, and carcinogenic effects, while Pb exposure poses significant risks to neurological development, particularly in children [48].

Table 5. The THQ of each heavy metal and HI per species.

Heavy Metals	THQ	
	<i>A. thazard</i>	<i>S. crumenophthalmus</i>
Cd	0.1011	0.0866
Cr	4.81E-05	4.81E-05
Cu	0.0231	0.0177
Pb	0.0206	0.0206
Zn	0.0271	0.0340
HI	0.1927	0.1796

3.5.2 Estimated Daily Intake (EDI), Estimated Weekly Intake (EWI), and comparison with Tolerable Weekly Intake (TWI)

The EDI, EWI, and corresponding comparisons with TWI values for Cd, Cr, Cu, Pb, and Zn in *A. thazard* and *S. crumenophthalmus* are presented in Table 6. As shown in the Table, EDI values for *A. thazard* ranged from 0.0047 to 0.5293 mg/kg body weight/day. Similarly, EDI values for *S. crumenophthalmus* ranged from 0.0047 to 0.6626 mg/kg body weight/day, following the same trend: lowest for Pb and Cr and highest for Zn. The similarity in Pb and Cr EDIs between species may be due to concentrations that are below detection limits in muscle tissue. Furthermore, the calculated EWIs in this study for both fish species, based on a 65-kg adult body weight, were substantially below the corresponding TWI or PTWI values for all assessed metals. This indicates that weekly exposure to heavy metals from consuming either species is unlikely to cause adverse health effects.

Table 6. Results of EDI, EWI, and TWI of selected heavy metals in fish muscles.

Heavy Metals	Fish Species	Fish Muscles Conc. (mg/kg)	EDI (mg/day /kg)	EDI (mg/day/65kg bw)	EWI (mg/week/ 65kg bw)	PTWI (mg/ week/kg bw	PTWI (mg/ week 65 kg bw)
Cd	<i>Auxis thazard</i>	0.069	0.0065	0.0001	0.0007	0.007	0.455
	<i>Selar</i>	0.060	0.0056	0.0001	0.0006		
	<i>crumenophthalmus</i>						
Cr	<i>Auxis thazard</i>	0.050	0.0047	0.0001	0.0005	0.0233	1.5145
	<i>Selar</i>	0.050	0.0047	0.0001	0.0005		
	<i>crumenophthalmus</i>						
Cu	<i>Auxis thazard</i>	0.640	0.0601	0.0009	0.0065	3.5	227.5
	<i>Selar</i>	0.490	0.0460	0.0007	0.0050		
	<i>crumenophthalmus</i>						
Pb	<i>Auxis thazard</i>	0.050	0.0047	0.0001	0.0005	0.025	1.625
	<i>Selar</i>	0.050	0.0047	0.0001	0.0005		
	<i>crumenophthalmus</i>						
Zn	<i>Auxis thazard</i>	5.640	0.5293	0.0081	0.0570	7	455
	<i>Selar</i>	7.060	0.6626	0.0102	0.0714		
	<i>crumenophthalmus</i>						

The low EWI values compared to TWI thresholds suggest that fish muscle consumption may not pose adverse health risks. However, it must be emphasized that the health risk calculations above are based exclusively on muscle tissue concentrations, which is standard practice for dietary exposure assessment. Since Cd exceeded FAO permissible limits in all organs of both species and Cr exceeded limits in the gills and GIT, consumers who regularly ingest whole fish, including viscera and gills, face substantially higher metal

exposures than estimated by the THQ and HI presented. Although a full quantitative risk estimate for whole-fish consumption is beyond the scope of the current dataset, the exceedances of Cd (up to 0.43 mg/kg in GIT, 8.6× the limit) and Cr (up to 2.50 mg/kg in gills, 2.5× the limit) in organ tissues indicate that the public health advisory language of “no significant risk” applies only to muscle tissue consumption and should not be generalized. The metal contents detected in gills and GIT indicate potential risks to consuming whole fish or viscera, as some locals in some coastal communities practice. These findings underscore the importance of advisories and information dissemination for organ-specific consumption and targeted public health interventions.

4. Conclusions

This study demonstrates the accumulation of the identified metals, Cd, Cr, Cu, Pb, and Zn, which vary by organ, species, and season. Although results showed no significant health risk, and metal accumulation showed site-specific patterns but was not significant, there is still a need for site-specific, seasonally responsive monitoring programs. Local government units (LGUs), in coordination with other government agencies, should implement annual fish organ testing in high-risk zones, with sampling intensified during peak runoff periods. Public health advisories must be issued to discourage the consumption of high-risk organs, such as viscera, especially among vulnerable populations, and to remove gills and GIT during cooking to reduce heavy metal contamination. Community education campaigns should be launched to empower fisherfolk and consumers with knowledge about contamination risks and safe preparation practices. Emerging colorimetric and machine-learning-based detection technologies offer cost-effective, rapid approaches for routine heavy metal surveillance that could complement conventional AAS analysis in future monitoring programs [38]. These actions will not only mitigate exposure to toxic metals but also enhance environmental resilience in coastal communities. Moreover, the absence of sediment metal data limits the attribution of fish tissue contamination to specific land-based anthropogenic sources (mining, agriculture, or tourism). Future studies in the Tañon Strait should incorporate concurrent sediment sampling to enable robust source apportionment and to quantify biota-sediment accumulation factors (BSAF).

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