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Human health risk–benefit assessment of metal(loid)s in commercial fish from the Northeastern Mediterranean, Türkiye

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ORIGINAL ARTICLE

Abstract

This study investigated 13 metal(loid)s in 10 commercial fish species from the Northeastern Mediterranean. Notably, Lead (Pb) consistently exceeded the permissible limit (PL) (0.30 mg kg^{-1}). The assessment of health risks, conducted by considering the toxicologically significant inorganic fraction of arsenic (As) (10%), suggested a generally low estimated toxicological risk profile for adult consumers under the assumed intake scenario. The cumulative noncarcinogenic risk (total THQ) was found to be below the safety threshold of 1 for all studied species, suggesting that appreciable noncarcinogenic health concerns are unlikely under the assumed intake scenario. Furthermore, total carcinogenic risk values fell within acceptable ranges, with Nickel (Ni) identified as the primary contributor. From a nutritional perspective, all species exhibited a significant health benefit, characterized by positive selenium health benefit values (HBV_{Se}) and Se:Hg molar ratios exceeding 1, supporting a potential protective role against mercury toxicity. In conclusion, while the consistent exceedance of the Pb regulatory limit warrants continued environmental monitoring and a cautious approach, the integrated risk–benefit assessment suggests that these species are unlikely to pose appreciable health risks for adults under the assumed intake scenario (moderate consumption), and they remain a valuable source of dietary selenium.

Keywords: Northeastern Mediterranean, Human health, Element, Metalloid, Marine fish, Muscle tissue

Introduction

Seafood, particularly marine fish, constitutes a critical component of a healthy diet due to its high-quality protein, essential trace elements (e.g., Se and Zn), and bioavailable micronutrients, including long-chain n-3 polyunsaturated fatty acids (EPA and DHA). Regular fish consumption has been associated with cardioprotective, neurodevelopmental, and anti-inflammatory benefits across life stages (Lund, 2013; Tufail *et al.*, 2025). However, marine ecosystems are simultaneously recipients of both natural and anthropogenic inputs of metal(loid)s, including legacy contaminants (e.g., Hg, Pb, and Cd) and essential-but-potentially toxic elements (e.g., Cu, Ni, and Se), which can bioaccumulate and biomagnify along trophic webs (Hasan *et al.*, 2025; Paul *et al.*, 2024). This dual character—specifically the nutritional benefits derived from elements like Se versus the contaminant risk posed by elements like Hg—renders fish a priority matrix for comprehensive risk–benefit assessment in food safety and public health (Bautista *et al.*, 2024).

The Mediterranean Sea is a semi-enclosed, oligotrophic basin subjected to intense maritime traffic, coastal urbanization, industrial discharges, agricultural runoff, and climate-change-related stressors (e.g., warming and salinification) (Madron *et al*., 2011). These pressures can alter metal(loid) speciation, bioavailability, and trophic transfer dynamics. Türkiye's Eastern Mediterranean coastline—specifically the Northeastern sector investigated in this study—simultaneously serves as a major seafood supply node (UNEP/MAP-SPA/RAC, 2021) and a receptor of transboundary pollutants. Previous foundational studies have investigated trace element levels in commercial fish from the Turkish Mediterranean Coast (Akçay *et al*., 2026; Ateş *et al*., 2015; Canli and Atli, 2003; Can *et al*., 2020; Canli *et al*., 2001; Çiftçi *et al*., 2021a, 2021b; Çoğun *et al*., 2005, 2006; Ersoy and Çelik, 2009, 2010; Kalay *et al*., 1999; Karayakar *et al*., 2022; Kılıç *et al*., 2021; Korkmaz *et al*., 2019; Kuplulu *et al*., 2017; Olgunoglu *et al*., 2015; Özyurt *et al.,* 2021; Turan *et al*., 2009; Türkmen 2005, 2008a, 2008b, 2009, 2010; Yılmaz, 2003; Yılmaz *et al*., 2016). While these works provided initial concentration data, a comprehensive assessment integrating both contaminant risk (multielement) and nutritional benefit (Se and Zn) using contemporary risk assessment models under specific toxicological assumptions and limitations is less established for the regional species marketed in Türkiye. This necessity for a holistic, up-to-date evaluation is further amplified by current environmental and market dynamics. Moreover, the reopening of fisheries immediately following the seasonal fishing ban (post-2025) signifies a period of increased market availability and potential consumption of regionally important species. In this evolving environmental and regulatory landscape, up-to-date, species-specific data on metal(loid) burdens in edible tissues are indispensable for providing nuanced exposure assessments that account for the inherent limitations of current risk models, consumer guidance, and alignment with national and international standards (e.g., Codex, EU, and FAO/WHO). A further complexity arises from species ecology and biogeography. The studied taxa encompass benthic and pelagic niches and distinct feeding guilds, which govern contaminant uptake pathways and tissue partitioning. The significant ecological and trophic variability among these market species requires a targeted assessment of how contaminant burdens differ based on their feeding habits. Parallelly, selenium (Se)–mercury (Hg) interactions are increasingly recognized as a determinant of net health outcomes from fish consumption (Suratno and Puspitasari, 2024); Se can mitigate methylmercury toxicity via high-affinity selenoprotein binding and redox modulation, yet this protective capacity is species- and tissue-specific (Penglase *et al*., 2014; Tinggi and Perkins, 2022). Therefore, a holistic framework integrating both risk and benefit metrics is necessary to avoid overconservative advisories that may compromise nutritional status or, conversely, overly permissive guidance that neglects vulnerable populations.

Against this backdrop, the present study conducts a targeted and multidimensional risk–benefit assessment of metal(loid)s—Al, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, and Zn—in 10 commercial fish species marketed in Türkiye: Meagre (*Argyrosomus regius*), Bogue (*Boops boops*), Blackbelly rosefish (*Helicolenus dactylopterus*), Sand steenbras (*Lithognathus mormyrus*), Flathead gray mullet (*Mugil cephalus*), Salema porgy (*Sarpa salpa*), Lizardfish (*Saurida lessepsianus*), Chub mackerel (*Scomber japonicus*), Gilthead seabream (*Sparus aurata*) and European barracuda (*Sphyraena sphyraena*). Elemental concentrations in muscle tissue were quantified by inductively coupled plasma mass spectrometry (ICP-MS), enabling multi-element determination with high sensitivity suitable for dietary exposure evaluations.

While various studies have separately addressed metal(loid) concentrations in Mediterranean fish, this research distinguishes itself by simultaneously evaluating thirteen different elements across 10 taxonomically and ecologically diverse species within a unified, contemporary risk-benefit framework. To translate occurrence data into public health relevance, we calculated the estimated weekly intake (EWI), target hazard quotient (THQ), cumulative non-carcinogenic risk (ΣTHQ), and carcinogenic risk (CR) for elements with established cancer potency factors. In parallel, we applied the selenium health benefit value (HBV_{Se}) to appraise the balance between Se's protective effects and Hg's neurotoxicity and calculated the Metal Pollution Index (MPI) to synthesize overall metal(loid) contamination across species.

By quantifying element concentrations and applying standardized health risk and benefit models, this study addresses a critical gap in regional literature by providing a holistic and comprehensive assessment that accounts for both individual and cumulative exposures. The research seeks to: (i) generate contemporary baseline data for Northeastern Mediterranean seafood; (ii) compare the calculated exposure estimates with relevant toxicological reference values and regulatory limits; (iii) contextualize interspecific variability in light of ecology and market relevance; and (iv) provide evidence-based insights for risk managers, nutrition policymakers, and consumers in Türkiye. The ultimate goal is to inform balanced consumption advisories that safeguard vulnerable populations while promoting the recognized nutritional advantages of marine fish consumption, aligning with a precision public health approach for sustainable marine resource use.

Materials and Methods

Sample collection and processing

Sampling was carried out between September and October 2025, immediately following the cessation of the annual fishing prohibition in Türkiye. A total of 100 specimens (10 individuals per species) belonging to 10 commercially significant marine fish species were systematically collected directly from local fishermen operating in the Turkish Northeastern Mediterranean area. The selected species—Meagre (*A. regius*), Bogue (*B. boops*), Blackbelly rosefish (*H. dactylopterus*), Sand steenbras (*L. mormyrus*), Flathead gray mullet (*M. cephalus*), Salema porgy (*S. salpa*), Lizardfish (*S. lessepsianus*), Chub mackerel (*S. japonicus*), Gilthead seabream (*S. aurata*), and European barracuda (*S. sphyraena*)—represent diverse ecological niches and feeding guilds within the water column.

Immediately upon collection, the samples were rinsed with clean seawater on-site to remove any external contaminants. To maintain sample integrity, the specimens were placed in insulated containers with dry ice for transport, ensuring preservation during the 6-hour transit to the laboratory. Once in the laboratory, the samples were measured for total length and weight. The edible muscle tissue was then carefully removed using plastic tools to prevent metal(loid) contamination and placed in labeled polyethylene bags. All samples were subsequently stored at −20°C until further processing for element analysis.

Microwave Digestion Procedure

Sample preparation involved the acid decomposition of the fish tissue matrix utilizing a Berghof MSW-4 microwave digestion system. Approximately 250 mg (wet weight) of the homogenized tissue was precisely transferred into dedicated digestion vessels. For the breakdown of the organic material, a robust mixture was employed: Five milliliters of 65% HNO_3 (nitric acid) was combined with 1 mL of 37% HCl (hydrochloric acid). To manage initial exothermic reactions, the vessels were intentionally kept open for a period of 15–20 minutes before sealing.

The programmed thermal regimen for digestion was executed in two primary heating ramps:

1. The temperature was escalated to 160°C for over 5 minutes, followed by a 5-minute hold at this set point.

2. The temperature was rapidly pushed to 190°C for over 1 minute and maintained for 15 minutes to ensure complete decomposition. The process concluded with a final cooling stage down to 50°C.

Throughout the active heating phases, the system pressure was restricted to a maximum of 40 bar, utilizing 80% of the maximum power. Post-digestion, all samples were allowed to return to ambient temperature prior to subsequent processing steps.

Elemental Analysis by ICP-MS

Elemental concentrations were quantified using a Perkin Elmer NexION 350X ICP-MS unit. The instrument configuration included standard peripherals: a Mainhard (concentric) nebulizer, a glass cyclonic spray chamber, and a Ni triple-cone interface. Optimized gas flow rates were applied for plasma (18.0 L/min), auxiliary gas (1.2 L/min), and nebulizer gas (0.68 L/min). The instrument's RF power was set to 1500 W, operating with a sample uptake rate of 1 mL/minute.

Following the rigorous digestion process, the resulting solution volume in each vessel was meticulously brought up to 10 mL using ultrapure water. To achieve concentrations compatible with the ICP-MS detector, a 0.5 mL aliquot from this final solution was taken and subjected to further necessary dilution. To ensure data reliability and methodological precision, all sample solutions were analyzed in triplicates. Both standard (STD) and kinetic energy discrimination (KED) operating modes were employed, with helium (He) used as the collision gas for interference removal. The reported elemental concentrations are expressed as mg kg^{-1}.

Risk–Benefit Assessment

The potential human health implications arising from the consumption of potentially toxic elements (PTEs) present in the fish samples were comprehensively evaluated using a series of established toxicological risk assessment models.

Estimated Daily and Weekly Intake (EDI & EWI)

The potential intake of elements through consumption of the fish samples was assessed by calculating the estimated daily intake (EDI) for each element. The EDI was determined using Equation (1), following the approach of Sadeghi *et al.* (2020):

$$EDI = (MC \times FDC)/BW \qquad \text{(Eq. 1)}$$

Where MC represents the concentration of the element in the fish muscle (mg kg^{-1}).

FDC is the average daily consumption (14.90 g $person^{-1}$ day^{-1}) in Türkiye, according to the WPR (2022).

BW is the average consumer body weight (70 kg for adults).

The EWI of the elements was subsequently determined using Equation (2), following the methodology established by Alipour *et al.* (2015):

$$EWI\ (mg\ kg^{-1}\ week^{-1}) = EDI \times 7 \quad \text{(Eq. 2)}$$

Note: The EWI calculation facilitates comparison with regulatory benchmarks, such as the provisional tolerable weekly intake (PTWI).

THQ and Total THQ (∑THQ)

To assess the potential for noncarcinogenic health risks, the THQ for individual elements was calculated using Equation (3), as specified by Sadeghi *et al.* (2020):

$$THQ=(EF \times ED \times FIR \times C) / (RfDs \times BW \times ATn) \times 10^{-3} \quad \text{(Eq. 3)}$$

The cumulative non-CR arising from the simultaneous intake of multiple contaminants was then evaluated using the ∑THQ. This cumulative risk index was calculated with Equation (4) (Pokorska *et al.*, 2022):

$$\sum THQ=THQ\ (Al)+THQ\ (As)+\ldots\ldots\ldots\ldots+THQ\ (Zn) \quad \text{(Eq. 4)}$$

A THQ or ∑THQ value less than 1 suggests that adverse noncarcinogenic effects are unlikely under the applied exposure assumptions. Conversely, a THQ value greater than 1 indicates that chronic exposure to the elements presents a potential noncarcinogenic health risk, necessitating cautious monitoring (Kilercioglu *et al.*, 2022; Miri *et al.*, 2017). All factors, corresponding units, and numerical values utilized in the THQ calculations, including reference doses and daily intake rates, are compiled and presented in detail within Table 1 (Çiftçi *et al.*, 2021a; Dayananda and Liyanage, 2021; Javed and Usmani, 2016; Li *et al.*, 2020; Pokorska *et al.*, 2022; Sadeghi *et al.*, 2020; Tecimen *et al.*, 2023; US EPA, 2014).

Target CR

The lifetime cancer risk was assessed for the elements classified as carcinogens by the International Agency for Research on Cancer (IARC)—specifically As, Cd, Cr, Ni, and Pb —through the calculation of the Target CR. Since toxicological data indicated that inorganic As constitutes only a fraction of total As in seafood, a conversion factor of 10% was applied to estimate the inorganic As concentration, as adopted by Zhong *et al.* (2018). This conversion is a key model assumption intended to provide a more toxicologically realistic assessment of inorganic As exposure through seafood consumption

The CR was quantified based on the average concentrations of these metal(loid)s found in the samples, utilizing Equation (5), as detailed in several studies (Alam *et al.*, 2023; Islam *et al.*, 2016; Tokatlı and Ustaoglu, 2021):

$$CR=(EF \times ED \times FIR \times C \times CSF)/(BW \times ATc) \times 10^{-3} \quad \text{(Eq. 5)}$$

In this equation, CSF represents the cancer slope factor. The CSF values of As, Cd, Cr, Ni, and Pb were 1.5, 0.01, 0.5, 1.7, 0.38 $(mg/kg/day)^{-1}$, respectively. The acceptable lifetime cancer risk levels for individual and multiple carcinogenic metals are 10^{-6} and less than 10^{-4}, respectively (Alsafran *et al.*, 2021).

Se:Hg Molar Ratios and HBV_{Se}

For a comprehensive assessment of seafood safety, the relationship between Se and Hg was evaluated using two established indices: the Se:Hg molar ratio and the HBV_{Se}. This approach is based on the widely accepted premise that Se offers protective effects against the toxic properties of Hg, thus providing a more robust basis for consumer risk analysis compared to simple total concentration measurements. The calculated HBV_{Se} values

Table 1. Essential parameters and corresponding numerical values employed in the target hazard quotient (THQ) calculations.

Statement (factors; unit)	Value for adult
EF: Exposure frequency	365 days $year^{-1}$
ED: Exposure duration	26 years (US EPA, 2014)
FIR: Food ingestion rate	14.90 g $person^{-1}$ day^{-1}
C: Metal(loid) concentration	Present study (mg kg^{-1}, wet weight)
BW: Average body weight	70 kg
ATn: Averaging time for noncarcinogens	EF×ED = 9 490 days
ATc: Averaging time for carcinogens	70 years (life time) × 365 day $year^{-1}$ = 25 550 days
Rfd: Oral reference dose (mg kg^{-1} day^{-1})	Pb = 0.0035; Ni = 0.02; Cd = 0.001; Cr = 0.003; Cu = 0.04; Fe = 0.7; Mn = 0.14; Zn = 0.3; Hg = 0.0001; Se = 0.005; Al = 1; As = 0.0003

are especially critical for assessing whether the Se concentration is sufficiently high to counteract potential Hg toxicity.

Following the determination of total Se and Hg concentrations, the Se:Hg molar ratio and HBV_{Se} were computed for each sample, utilizing the average concentrations of both elements.

To calculate the Se:Hg molar ratio, the molar concentration of Se was divided by the molar concentration of Hg for each analyzed tissue. Molar concentrations were derived by dividing the measured concentration (mg kg^{-1}) of each element by its corresponding atomic weight (Se: 78.96 g/mol; Hg: 200.59 g/mol).

The HBV_{Se} was subsequently calculated to quantify the balance between the protective effects of Se and the potential harmful effects of Hg within the edible tissue, as shown in Equation (6):

$$HBV_{Se} = [(Se - Hg) / Se] \times (Se + Hg) \qquad \text{(Eq. 6)}$$

Note: [Se] and [Hg] represent the molar concentrations of Se and Hg, respectively.

A positive HBV_{Se} value suggests that the consumption of the product is unlikely to pose a risk from Hg toxicity. Conversely, negative values indicate a potential Hg-related risk to consumers (Bautista *et al.*, 2024).

MPI

For an overall evaluation of metal(loid) contamination within the fish muscle tissue, the MPI was calculated. The MPI quantifies the total level of metal contamination by determining the geometric mean of the concentrations of all detected elements (Jafiya *et al.*, 2022).

The MPI was calculated using the following formula, shown as Equation (7):

$$MPI\ (mg\ kg^{-1}) = (C_1 \times C_2 \times C_3 \times \ldots \times C_n)^{1/n} \qquad \text{(Eq. 7)}$$

Where Cn represents the concentration of each element detected in the sample, and n is the total number of metal(loid)s analyzed.

Statistical analysis

Statistical analysis was performed using SPSS for Windows (version 21.0; IBM Corp., Armonk, NY, USA). The results are expressed as mean ± standard deviation (SD). The Shapiro–Wilk test revealed that the raw data for several elements deviated from a normal distribution. To address this and satisfy the assumptions required for parametric testing, all data were subjected to logarithmic transformation (log_{10}). Following transformation, the normality of the distribution and homogeneity of variances (evaluated via Levene's test) were confirmed. One-way analysis of variance (ANOVA) was then performed on the transformed data to evaluate significant differences in metal(loid) concentrations among the species. Where significant differences were identified ($p < 0.05$), Duncan's multiple range test was employed for post-hoc comparisons.

Results

Biometric measurements and ecological characteristics

The initial findings of this study comprise the fundamental biometric measurements (total length (cm) and weight (g)) and ecological characteristics (feeding habits and habitat) for the 10 commercially important fish species sourced from the Northeastern Mediterranean. These comprehensive data are summarized as the mean ± SD in Table 2. These findings, which reflect the interspecies differences in size and ecological niche, provide the necessary contextual framework for understanding the variability in element accumulation levels that will be presented subsequently.

A preliminary descriptive review of the data in Table 2 indicates a wide range in sample size, with Meagre (*A. regius*) exhibiting the largest mean total length (47.53 ± 1.88 cm) and the heaviest mean weight (960.27 ± 38.94 g). Conversely, the Bogue (*B. boops*) had the smallest mean total length (19.50 ± 1.29 cm), while the Lizardfish (*S. lessepsianus*) had the lowest mean weight (108.89 ± 9.35 g). Ecologically, the species are distributed across multiple niches, with representatives from demersal (e.g., *L. mormyrus*), epipelagic (e.g., *S. japonicus*), and benthopelagic (e.g., S. aurata) habitats. Furthermore, a majority of the species are classified as carnivorous, while omnivorous (*S. aurata, B. boops*, and *M. cephalus*) and herbivorous (*S. salpa*) feeding habits are also represented. Overall, the biometric measurements and ecological characteristics presented in this study underscore the variability among the fish species in the Northeastern Mediterranean, laying a foundational basis for further investigations into their ecological roles and element accumulation.

Element concentrations in fish muscle tissue

Table 3 details the concentrations of the 13 analyzed metal(loid)s (Al, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb,

Table 2. Biometric and ecological characteristics of commercial fish species from the Northeastern Mediterranean.

Species	Total length (cm)	Weight (g)	Habitat	Feeding habit
Meagre (*A. regius*)	47.53 ± 1.88	960.27 ± 38.94	Benthopelagic	Carnivorous
Bogue (*B. boops*)	19.50 ± 1.29	111.61 ± 5.08	Demersal	Omnivorous
Blackbelly rosefish (*H. dactylopterus*)	20.66 ± 0.58	168.66 ± 8.15	Demersal	Carnivorous
Sand steenbras (*L. mormyrus*)	27.33 ± 1.76	247.33 ± 15.99	Demersal	Carnivorous
Flathead gray mullet (*M. cephalus*)	41.00 ± 1.83	705.68 ± 30.83	Epipelagic	Omnivorous
Salema porgy (*S. salpa*)	26.16 ± 2.36	266.00 ± 24.00	Benthopelagic	Herbivorous
Lizardfish (*S. lessepsianus*)	23.10 ± 1.95	108.89 ± 9.35	Benthopelagic/Demersal	Carnivorous
Chub mackerel (*S. japonicus*)	28.33 ± 1.04	233.33 ± 8.57	Epipelagic	Carnivorous
Gilthead seabream (*S. aurata*)	24.50 ± 1.32	235.33 ± 12.67	Benthopelagic	Omnivorous
European barracuda (*S. sphyraena*)	33.83 ± 1.61	169.33 ± 8.03	Epipelagic	Carnivorous

Se, and Zn) in the edible muscle tissue of the 10 fish species. These results are presented as the mean concentration ± SD in mg kg^{-1} (wet weight). Different superscript letters in the same column indicate statistically significant differences ($p < 0.05$) among species.

The concentrations of Co remained below the limit of detection (LOD) in all species. Among the analyzed elements, Al and Fe showed the highest concentrations. The concentration of Al was significantly highest in the Chub mackerel (*S. japonicus*), reaching 89.364 ± 11.10 mg kg^{-1} (^{f}), while the lowest Al level was recorded in the Bogue (*B. boops*) at 25.471 ± 3.84 mg kg^{-1} (^{a}). Similarly, Fe concentrations varied significantly, peaking in *M. cephalus* (21.908 ± 2.70 mg kg^{-1}, ^{e}) and showing the lowest values in *B. boops* (6.226 ± 0.78 mg kg^{-1}, ^{a}).

Regarding the PTEs, As showed the highest accumulation levels, with Lizardfish (*S. lessepsianus*) exhibiting the highest concentration (5.54 ± 0.70 mg kg^{-1}, f). A notable finding concerns the nonessential toxic metals. While Hg and Cd remained at very low levels and well below their respective PLs, Lead (Pb) concentrations (ranging from 0.477 to 0.672 mg kg^{-1}) consistently exceeded the EU's PL of 0.30 mg kg^{-1} in all 10 species (Table 3). However, no statistically significant differences were observed among species in terms of Pb concentrations ($p > 0.05$).

To determine if the observed variations in metal(loid) concentrations were statistically significant, an ANOVA was performed comparing the total mean concentrations across the 10 fish species. The ANOVA results followed by Duncan's post-hoc test indicated statistically significant differences in the mean concentrations of most metal(loid)s (Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Se, and Zn) across the species ($p < 0.05$).

EWI and comparison with PTWI

In order to evaluate the potential health risks of regular fish consumption, we calculated the EWI for the various metal(loid)s detected in fish muscle. These results, presented in Table 4, are compared against established guideline values, namely, the PTWI. The PTWI is defined as the quantity of a contaminant that a person can ingest weekly throughout their lifetime without significant risk. EWI values are normalized to body weight (70 kg) and expressed in mg kg^{-1} bw week^{-1} to allow direct comparison with the PTWI guidelines set by international organizations (e.g., JECFA and FAO/WHO). Different superscript letters in the same column of Table 4 indicate statistically significant differences ($p < 0.05$) among species.

Overall, the calculated EWI values across all fish species for all analyzed elements were below their respective PTWI benchmarks. This finding indicates that the risk from individual elements, when assessed on a weekly basis, is low.

Regarding nonessential and toxic elements, the EWI values are generally minimal despite variations among species. The highest Al intake was observed in Chub mackerel (*S. japonicus*) (1.33 × 10^{-1} mg kg^{-1} bw week^{-1}), representing only 6.65% of its PTWI limit. Risk assessment for As was performed by considering the inorganic fraction (10%), resulting in EWI values significantly below the safety limits.The peak intake for As was found in Lizardfish (*S. lessepsianus*) (8.25 × 10^{-4} mg kg^{-1} bw week^{-1}), which constitutes only 5.5% of its PTWI (0.015 mg kg^{-1} bw week^{-1}). The highest Cd intake, recorded in Bogue (*B. boops*) (4.02 × 10^{-3} mg kg^{-1} bw week^{-1}), represents a notable 57.4% of its PTWI, although still below the PTWI. For the highly toxic metals, the maximum

Table 3. Concentrations of analyzed metal(loid)s in muscle tissue of some Northeastern Mediterranean fish species (mg kg^{-1}, wet weight).

Species	Elements												
	Al	As	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Zn
A. regius	42.173 ± 5.27^{bc}	1.656 ± 0.21^{b}	0.011 ± 0.00^{a}	ND	0.275 ± 0.03^{e}	0.205 ± 0.03^{ab}	10.282 ± 1.29^{b}	0.004 ± 0.00^{a}	0.330 ± 0.04^{e}	0.426 ± 0.05^{ab}	0.547 ± 0.07^{a}	0.282 ± 0.04^{b}	4.601 ± 0.58^{ab}
B. boops	25.471 ± 3.84^{a}	2.701 ± 0.34^{d}	0.027 ± 0.03^{f}	ND	0.227 ± 0.03^{d}	0.617 ± 0.08^{d}	6.226 ± 0.78^{a}	0.002 ± 0.00^{a}	0.431 ± 0.05^{f}	2.455 ± 0.31^{e}	0.630 ± 0.08^{a}	0.604 ± 0.08^{e}	6.126 ± 0.77^{c}
H. dactylopterus	67.554 ± 8.43^{e}	5.17 ± 0.64^{f}	0.014 ± 0.00^{b}	ND	0.084 ± 0.01^{a}	0.151 ± 0.02^{a}	7.154 ± 0.91^{a}	0.110 ± 0.015^{c}	0.152 ± 0.02^{ab}	0.158 ± 0.02^{a}	0.611 ± 0.07^{a}	0.718 ± 0.09^{f}	4.295 ± 0.55^{ab}
L. mormyrus	51.34 ± 6.42^{cd}	1.972 ± 0.25^{c}	0.024 ± 0.00^{f}	ND	0.129 ± 0.02^{b}	0.187 ± 0.02^{ab}	14.71 ± 1.84^{c}	0.009 ± 0.00^{ab}	0.232 0.03^{cd}	1.118 ± 0.14^{c}	0.563 ± 0.07^{a}	0.443 ± 0.06^{d}	4.918 ± 0.62^{bc}
M. cephalus	35.257 ± 4.40^{ab}	2.480 ± 0.30^{d}	0.011 ± 0.01^{a}	ND	0.172 ± 0.02^{c}	0.195 ± 0.02^{ab}	21.908 ± 2.70^{e}	0.001 ± 0.00^{a}	0.257 ± 0.03^{cd}	2.425 ± 0.30^{e}	0.477 ± 0.06^{a}	0.269 ± 0.03^{b}	3.464 ± 0.40^{a}
S. salpa	63.896 ± 7.90^{de}	0.255 ± 0.03^{a}	0.022 ± 0.00^{e}	ND	0.233 ± 0.03^{e}	0.299 ± 0.04^{c}	12.52 ± 1.55^{bc}	0.001 ± 0.00^{a}	0.675 ± 0.05^{g}	2.028 ± 0.25^{d}	0.672 ± 0.08^{a}	0.080 ± 0.01^{a}	7.760 ± 0.95^{d}
S. lessepsianus	80.536 ± 10.00^{f}	5.540 ± 0.70^{f}	0.013 ± 0.00^{b}	ND	0.204 ± 0.03^{d}	0.209 ± 0.03^{ab}	17.825 ± 2.20^{d}	0.008 ± 0.00^{ab}	0.154 ± 0.02^{ab}	0.390 ± 0.05^{ab}	0.569 ± 0.05^{a}	0.323 ± 0.04^{bc}	3.660 ± 0.40^{a}
S. japonicus	89.364 ± 11.10^{f}	0.590 ± 0.05^{a}	0.014 ± 0.00^{b}	ND	0.223 ± 0.03^{d}	0.274 ± 0.03^{c}	10.368 ± 1.30^{b}	0.005 ± 0.001^{a}	0.131 ± 0.02^{a}	0.612 ± 0.05^{b}	0.500 ± 0.06^{a}	0.540 ± 0.05^{e}	5.523 ± 0.70^{bc}
S. aurata	43.357 ± 5.50^{bc}	3.478 ± 0.45^{e}	0.019 ± 0.00^{cd}	ND	0.154 ± 0.02^{b}	0.167 ± 0.02^{a}	14.338 ± 1.80^{c}	0.002 ± 0.00^{a}	0.277 ± 0.03^{de}	1.139 ± 0.15^{c}	0.599 ± 0.15^{a}	0.400 ± 0.05^{cd}	5.405 ± 0.70^{bc}
S. sphyraena	60.935 ± 7.60^{de}	1.970 ± 0.25^{c}	0.016 ± 0.00^{c}	ND	0.128 ± 0.02^{b}	0.242 ± 0.03^{bc}	10.488 ± 1.30^{b}	0.014 ± 0.002^{b}	0.201 ± 0.03^{bc}	0.143 ± 0.02^{a}	0.617 ± 0.08^{a}	0.408 ± 0.05^{cd}	7.568 ± 0.90^{d}
PL			0.05	–	–	30	100	0.30-1.00	1	–	0.30	–	40

The data are presented as the mean ± standard deviation (SD) of triplicate measurements; ND: not detected; PL: permissible limit (mg kg^{-1}); Arsenic (As) values represent total As concentrations; Different superscript letters (a–f) within the same column indicate statistically significant differences ($p < 0.05$) according to Duncan's post-hoc test.

Table 4. Estimated weekly intake (EWI) of metal(loid)s for adult consumers from muscle tissue of some Northeastern Mediterranean fish species (mg kg^{-1} bw week^{-1}) compared with provisional tolerable weekly intake (PTWI—mg kg^{-1} bw week^{-1}).

Species	Al	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Zn
A. regius	6.28 E-02^{bc}	2.47 E-04^{b}	1.64 E-03^{a}	4.09 E-04^{e}	3.05 E-04^{ab}	1.53 E-02^{b}	5.96 E-06^{a}	4.92 E-04^{e}	6.35 E-04^{ab}	8.15 E-04^{a}	4.20 E-04^{b}	6.85 E-03^{ab}
B. boops	3.79 E-02^{a}	4.00 E-04^{d}	4.02 E-03^{f}	3.38 E-04^{d}	9.19 E-04^{d}	9.28 E-03^{a}	2.98 E-06^{a}	6.42 E-04^{f}	3.66 E-03^{e}	9.39 E-04^{a}	8.99 E-04^{e}	9.13 E-03^{c}
H. dactylopterus	1.0 E-01^{e}	7.70 E-04^{f}	2.09 E-03^{ab}	1.25 E-04^{a}	2.25 E-04^{a}	1.06 E-02^{a}	1.64 E-04^{c}	2.26 E-04^{ab}	2.35 E-04^{a}	9.12 E-04^{a}	1.07 E-03^{f}	6.40 E-03^{ab}
L. mormyrus	7.65 E-02^{cd}	2.94 E-04^{bc}	3.58 E-03^{ef}	1.92 E-04^{b}	2.79 E-04^{ab}	2.19 E-02^{c}	1.34 E-05^{ab}	3.46 E-04^{cd}	1.66 E-03^{c}	8.39 E-04^{a}	6.60 E-04^{d}	7.33 E-03^{bc}
M. cephalus	5.25 E-02^{ab}	3.69 E-04^{cd}	1.64 E-03^{a}	2.56 E-04^{bc}	2.90 E-04^{ab}	3.26 E-02^{e}	1.49 E-06^{a}	3.82 E-04^{cd}	3.61 E-03^{e}	7.11 E-04^{a}	4.00 E-04^{b}	5.16 E-03^{a}
S. salpa	9.52 E-02de	3.80 E-05^{a}	3.28 E-03de	3.47 E-04de	4.45 E-04^{c}	1.86 E-02^{bc}	1.49 E-06^{a}	1.00 E-03^{g}	3.02 E-03^{d}	1.00 E-03^{a}	1.19 E-04^{a}	1.15 E-02^{d}
S. lessepsianus	1.20 E-01^{f}	8.25 E-04^{f}	1.94 E-03^{ab}	3.04 E-04^{cd}	3.11 E-04^{ab}	2.65 E-02^{d}	1.19 E-05^{ab}	2.29 E-04^{ab}	5.81 E-04^{ab}	8.48 E-04^{a}	4.81 E-04^{bc}	5.45 E-03^{a}
S. japonicus	1.33 E-01^{f}	8.79 E-05^{a}	2.09 E-03^{ab}	3.32 E-04^{d}	4.08 E-04^{c}	1.54 E-02^{b}	7.45 E-06^{a}	1.95 E-04^{a}	9.12 E-04^{b}	7.45 E-04^{a}	8.04 E-04^{e}	8.23 E-03^{bc}
S. aurata	6.46 E-02^{bc}	5.18 E-04^{e}	2.83 E-03^{cd}	2.29 E-04^{b}	2.48 E-04^{a}	2.14 E-02^{c}	2.98 E-06^{a}	4.13 E-04de	1.70 E-03^{c}	8.92 E-04^{a}	5.96 E-04^{cd}	8.05 E-03^{bc}
S. sphyraena	9.08 E-02de	2.93 E-04^{bc}	2.38 E-03^{bc}	1.91 E-04^{b}	3.60 E-04^{bc}	1.56 E-02^{b}	2.08 E-05^{b}	2.99 E-04^{bc}	2.13 E-04^{a}	9.19 E-04^{a}	6.08 E-04^{cd}	1.12 E-02^{d}
PTWI	2	0.015	0.007	0.0233	3.5	5.6	0.025	2.5	0.035	0.025	0.066	7

Note: Risk assessment calculations were performed assuming 10% of total As was inorganic As; PTWI: provisional tolerable weekly intake (mg kg^{-1} bw week^{-1}); Different superscript letters (a–f) in the same column indicate statistically significant differences ($p < 0.05$) according to Duncan's post-hoc test.

EWI for Hg was identified in Blackbelly rosefish (*H. dactylopterus*) (1.64×10^{-4} mg kg^{-1} bw week^{-1}), corresponding to a negligible 0.66% of its PTWI limit. Similarly, the maximum for Pb was found in Salema *(S. salpa)* (1.00×10^{-3} mg kg^{-1} bw week^{-1}), corresponding to 4.0% of its PTWI limit.

Furthermore, the intake of essential elements was well within safe limits. The maximum EWI for Fe was found in Flathead grey mullet (*M. cephalus*) (3.26×10^{-2} mg kg^{-1} bw week^{-1}), a value orders of magnitude below its PTWI. Se intake reached a maximum of 1.07×10^{-3} mg kg^{-1} bw week^{-1} in Blackbelly rosefish (*H. dactylopterus*), which remains only 1.62% of its high PTWI of 0.066 mg kg^{-1} bw week^{-1}.

While these findings indicate that individual elements are unlikely to pose an appreciable risk when evaluated separately under the assumed intake scenario, this assessment does not account for the cumulative health effects of exposure to a mixture of contaminants. Therefore, a complete evaluation of public health risk requires further analysis of their combined effects, which will be addressed in the following sections on THQ and CR.

THQ and ∑THQ

To address the limitations of the EWI analysis and evaluate the combined impact of multiple contaminants, the THQ and ∑THQ were calculated. Table 5 presents these calculated values for elements detected in the muscle tissue of the fish species caught in the Mediterranean Sea.

The assessment revealed that the calculated ∑THQ values for all 10 fish species remained significantly below the critical safety threshold of 1. This indicates that non-CR is unlikely for adult consumers under the assumed food ingestion rate (FIR).

The cumulative risk ranged from a low of 0.133 (*S. salpa*) to a high of 0.700 **(***H. dactylopterus***)**. By accounting for the inorganic fraction of arsenic As (10%), which is the toxicologically relevant form, the results suggest that the consumption of these species is unlikely to pose a collective noncarcinogenic health concern under the assumed intake scenario.

It is well-established that using total As concentrations in risk assessments often leads to a significant overestimation of potential hazards, as the majority of As in marine fish exists in organic, nontoxic forms (Zhong *et al.*, 2018). In this study, the application of the 10% inorganic fraction revealed that the individual THQ values for As were well below the safety limit of 1 in all species, ranging from 0.018 to 0.393. The contribution of other toxic metals was also minimal; for example, the highest THQ for Pb was 4.09×10^{-2} (*S. salpa*), and Hg reached a maximum 2.34×10^{-1} (*H. dactylopterus*), both of which were well below the threshold.

In summary, the THQ data indicate that the consumption of all studied fish species presents a minimal non-CR. The cumulative exposure remains within acceptable limits, supporting the conclusion that the Mediterranean fish species analyzed in this study are unlikely to pose a significant public health concern under the current intake assumptions. This study serves as an important reference for assessing the health risks and benefits of Mediterranean fish.

Carcinogenic health risk assessment

The CR values associated with exposure to As, Cd, Cr, Ni, and Pb in the muscle tissues of 10 fish species from the Northeastern Mediterranean were calculated. The results are presented in Table 6.

The acceptable range for lifetime CR is generally defined as being between 10^{-6} and 10^{-4}, where values below 10^{-4} are considered acceptable as proposed by Alsafran *et al.* (2021).

The calculated total carcinogenic risk (∑CR) values were found to vary among the studied species, ranging from a minimum of 6.62×10^{-5} for *S. sphyraena* to a maximum of 3.90×10^{-4} for *B. boops*. A key finding of this study is that for several species (*S. sphyraena, S. japonicus, H. dactylopterus*, and *A. regius*), ∑CR values were either within or very close to the permissible limit of 10^{-4} cited by Alsafran *et al.* (2021).

The cumulative risk in this assessment is primarily driven by Ni and, to a lesser extent, As. Since the inorganic fraction (10%) was applied only to As, Ni naturally emerged as the dominant contributor to the ∑CR in most species. For instance, in Bogue (*B. boops*), the individual CR for Ni (3.30×10^{-4}) accounted for approximately 85% of the total risk. Similarly, in Flathead grey mullet (*M. cephalus*), Ni was the primary driver with a CR of 3.26×10^{-4}. In contrast, the risk from As remained well within the acceptable limit, reaching its peak in Blackbelly rosefish (*H. dactylopterus*) at 6.13×10^{-5}, which represents approximately 59% of the cumulative risk for that specific species.

The CR values for the other metals—Cd, Cr, and Pb—were observed to be negligible across all species, with their values often falling into the 10^{-6} to 10^{-9} range, indicating a marginal contribution to the ∑CR. These findings reveal that the CR profile is species-specific;

Table 5. Target hazard quotient (THQ) and total THQ (∑THQ) values for metal(loid)s in muscle tissue of various Northeastern Mediterranean fish species.

Species	Al	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Zn	∑THQ
A. regius	8.98 E-03^{bc}	1.17 E-01^{b}	2.34 E-03^{a}	1.95 E-02^{e}	1.09 E-03^{ab}	3.13 E-03^{b}	8.51 E-03^{a}	5.02 E-04^{e}	4.53 E-03^{ab}	3.33 E-02^{a}	1.20 E-02^{b}	3.26 E-03^{ab}	2.14E-01
B. boops	5.42 E-03^{a}	1.92 E-01^{d}	5.75 E-03^{f}	1.61 E-02^{d}	3.28 E-03^{d}	1.89 E-03^{a}	4.26 E-03^{a}	6.55 E-04^{f}	2.61 E-02^{e}	3.83 E-02^{a}	2.57 E-02^{e}	4.35 E-03^{c}	3.24E-01
H. dactylopterus	1.44 E-02^{e}	3.67 E-01^{f}	2.98 E-03^{ab}	5.96 E-03^{a}	8.04 E-04^{a}	2.18 E-03^{a}	2.34 E-01^{c}	2.31 E-04^{ab}	1.68 E-03^{a}	3.72 E-02^{a}	3.06 E-02^{f}	3.05 E-03^{ab}	7.00E-01
L. mormyrus	1.09 E-02^{cd}	1.40 E-01^{bc}	5.11 E-03^{ef}	9.15 E-03^{b}	9.95 E-04^{ab}	4.47 E-03^{c}	1.92 E-02^{ab}	3.53 E-04^{cd}	1.19 E-02^{c}	3.42 E-02^{a}	1.89 E-02^{d}	3.49 E-03^{bc}	2.59E-01
M. cephalus	7.50 E-03^{ab}	1.76 E-01^{cd}	2.34 E-03^{a}	1.22 E-02^{bc}	1.04 E-03^{ab}	6.66 E-03^{e}	2.13 E-03^{a}	3.91 E-04^{cd}	2.58 E-02^{e}	2.90 E-02^{a}	1.15 E-02^{b}	2.46 E-03^{a}	2.77E-01
S. salpa	1.36 E-02de	1.81 E-02^{a}	4.68 E-03de	1.65 E-02de	1.59 E-03^{c}	3.81 E-03^{bc}	2.13 E-03^{a}	1.03 E-03^{g}	2.16 E-02^{d}	4.09 E-02^{a}	3.41 E-03^{a}	5.51 E-03^{d}	1.33E-01
S. lessepsianus	1.71 E-02^{f}	3.93 E-01^{f}	2.77 E-03^{ab}	1.45 E-02^{cd}	1.11 E-03^{ab}	5.42 E-03^{d}	1.70 E-02^{ab}	2.34 E-04^{ab}	4.15 E-03^{ab}	4.07 E-02^{a}	1.38 E-02^{bc}	2.60 E-03a	5.12E-01
S. japonicus	1.90 E-02^{f}	4.19 E-02^{a}	2.98 E-03^{ab}	1.58 E-02^{d}	1.46 E-03^{c}	3.15 E-03^{b}	1.06 E-02^{a}	1.99 E-04^{a}	6.51 E-03^{b}	3.04 E-02^{a}	2.30 E-02^{e}	3.92 E-03^{bc}	1.59E-01
S. aurata	9.23 E-03^{bc}	2.47 E-01^{e}	4.04 E-03^{cd}	1.09 E-02^{b}	8.89 E-04^{a}	4.36 E-03^{c}	4.26 E-03^{a}	4.21 E-04de	1.21 E-02^{c}	3.64 E-02^{a}	1.70 E-02^{cd}	3.83 E-03^{bc}	3.50E-01
S. sphyraena	1.30 E-02de	1.40 E-01^{bc}	3.41 E-03^{bc}	9.08 E-03^{b}	1.29 E-03^{bc}	3.19 E-03^{b}	2.98 E-02^{b}	3.06 E-04^{bc}	1.52 E-03^{a}	3.75 E-02^{a}	1.74 E-02^{cd}	5.37 E-03^{d}	2.62E-01

Note: Risk assessment calculations were performed assuming 10% of total As was inorganic As; Different superscript letters (a–f) in the same column indicate statistically significant differences ($p < 0.05$) according to Duncan's post-hoc test.

however, the overall risk for the majority of analyzed fish remains within or near established risk thresholds under the applied assumptions.

Se:Hg Molar Ratios and HBV$_{Se}$

The calculated Se:Hg molar ratios and the HBV$_{Se}$, used to evaluate the protective effect of Se against Hg toxicity, are presented in Table 7.

The interpretation of these metrics is straightforward: a Se:Hg molar ratio greater than 1 signifies a molar excess of Se, which is necessary to counteract Hg toxicity. Consequently, a positive HBV$_{Se}$ (HBV$_{Se}$ > 0) indicates a net health benefit, whereas a negative value suggests potential risk (Bautista *et al.*, 2024; Cabral *et al.*, 2025).

Our analysis revealed that all 10 fish species possessed Se:Hg molar ratios substantially greater than 1. As a result, the HBV$_{Se}$ was positive for every species analyzed, confirming a net protective health benefit against Hg toxicity across the sample set (Table 7).

This protective effect was evident in the Se:Hg molar ratios, which ranged from a low of 16.58 in *H. dactylopterus* to a high of 767.20 in *B. boops*. Correspondingly, all HBV$_{Se}$ values were positive, ranging from $1.01x10^{-3}$ in *S. salpa* to $9.06x10^{-3}$ in *H. dactylopterus*. Notably, *H. dactylopterus*, the species with the lowest Se:Hg molar ratio, recorded the highest HBV$_{Se}$. This highlights that the overall health benefit is strongly influenced by the total Se concentration, even when the protective molar ratio is simply met rather than exceeded by a large margin.

Table 6. The calculated CR (carcinogenic risk) levels in muscle tissue of various Northeastern Mediterranean fish species.

Species	As	Cd	Cr	Ni	Pb	∑CR
A. regius	1.97E–05^{b}	8.69E–09^{a}	1.09E–05^{e}	5.72E–05^{ab}	1.64E–05^{a}	1.04E–04
B. boops	3.20E–05^{d}	2.14E–08^{f}	8.99E–06^{d}	3.30E–04^{e}	1.89E–05^{a}	3.90E–04
H. dactylopterus	6.13E–05^{f}	1.11E–08^{ab}	3.32E–06^{a}	2.12E–05^{a}	1.84E–05^{a}	1.04E–04
L. mormyrus	2.34E–05^{bc}	1.90E–08^{ef}	5.09E–06^{b}	1.50E–04^{c}	1.69E–05^{a}	1.96E–04
M. cephalus	2.94E–05^{cd}	8.69E–09^{a}	6.80E–06^{bc}	3.26E–04^{e}	1.43E–05^{a}	3.77E–04
S. salpa	3.02E–06^{a}	1.74E–08de	9.21E–06de	2.73E–04^{d}	2.02E–05^{a}	3.05E–04
S. lessepsianus	6.57E–05^{f}	1.03E–08^{ab}	8.06E–06^{cd}	5.24E–05^{ab}	2.01E–05^{a}	1.46E–04
S. japonicus	6.98E–06^{a}	1.11E–08^{ab}	8.80E–06^{d}	8.21E–05^{b}	1.50E–05^{a}	1.13E–04
S. aurata	4.12E–05^{e}	1.50E–08^{cd}	6.09E–06^{b}	1.53E–04^{c}	1.80E–05^{a}	2.18E–04
S. sphyraena	2.34E–05^{bc}	1.27E–08^{bc}	5.05E–06^{b}	1.92E–05^{a}	1.85E–05^{a}	6.62E–05

Note: Risk assessment calculations were performed assuming 10% of total As was inorganic As; Different superscript letters (a–f) in the same column indicate statistically significant differences ($p < 0.05$) according to Duncan's post-hoc test.

Table 7. The calculated Se:Hg molar ratios and the selenium health benefit value (HBV$_{Se}$) in muscle tissue of various Northeastern Mediterranean fish species.

Species	[Se]mol (mmol/kg)	[Hg]mol (mmol/kg)	Se:Hg molar ratio	HBV$_{Se}$
A. regius	3.57E–03	1.99 E–05	179.09	3.57 E–03
B. boops	7.65 E–03	9.97 E–06	767.20	7.65 E–03
H. dactylopterus	9.09 E–03	5.48 E–04	16.58	9.06 E–03
L. mormyrus	5.61 E–03	4.48 E–05	125.04	5.61 E–03
M. cephalus	3.41 E–03	4.98 E–06	683.37	3.41 E–03
S. salpa	1.01 E–03	4.98 E–06	203.23	1.01 E–03
S. lessepsianus	4.09 E–03	3.98 E–05	102.57	4.09 E–03
S. japonicus	6.84 E–03	2.49 E–05	274.36	6.84 E–03
S. aurata	5.06 E–03	9.97 E–06	508.08	5.06 E–03
S. sphyraena	5.17 E–03	6.98 E–05	74.03	5.17 E–03

In conclusion, the findings indicate that Hg-related risk is unlikely for adult consumers under the assumed intake scenario. On the contrary, their Se content provides nutritional benefit; from an Hg-specific perspective, these species generally represent a beneficial dietary option, provided that consumption remains moderate and consistent with the applied exposure assumptions.

MPI

The MPI was calculated as the geometric mean of the concentrations of the 12 analyzed metal(loid)s to assess the overall metal(loid) contamination load across the 10 species, as presented in Table 8.

The MPI values ranged from a minimum of 0.49 mg kg^{-1} to a maximum of 0.67 mg kg^{-1}. The highest overall contamination was found in Bogue (*B. boops*), with an MPI of 0.67 mg kg^{-1}. As a demersal omnivore that consumes a variety of organisms from near the seafloor, its feeding habits likely contribute to this higher accumulation of metals. Closely following were *S. japonicus* (0.61 mg kg^{-1}), *H. dactylopterus* and *L. mormyrus* (both 0.60 mg kg^{-1}), and *S. lessepsianus* (0.58 mg kg^{-1}). This finding is consistent with their ecology as benthopelagic/demersal or higher-trophic-level species that prey on other bottom-dwelling or pelagic organisms, leading to biomagnification of metals from the sediment and water-column food webs.

Conversely, the lowest overall metal(loid) contamination (MPI of 0.49 mg kg^{-1}) was shared by three species with varied ecologies: Meagre (*A. regius*), a benthopelagic carnivore; Flathead grey mullet (*M. cephalus*), an epipelagic omnivore; and Salema porgy (*S. salpa*), a benthopelagic herbivore. The low MPI in the epipelagic *M. cephalus* is expected, as its habitat in the upper water column minimizes exposure to sediment-associated metals. However, the finding that two benthopelagic (bottom-associated) species also exhibit the lowest levels of metal(loid) contamination is noteworthy. This strongly indicates that habitat alone does not determine the total metal(loid) load. Instead, it highlights that metal accumulation is a complex process influenced by a combination of factors, including species-specific metabolic differences and precise dietary preferences within broader feeding categories.

Table 8. Metal pollution index (MPI) values based on the concentrations of the 12 analyzed metal(loid)s.

Species	MPI (mg kg^{-1})
A. regius	0.49
B. boops	0.67
H. dactylopterus	0.60
L. mormyrus	0.60
M. cephalus	0.49
S. salpa	0.49
S. lessepsianus	0.58
S. japonicus	0.61
S. aurata	0.55
S. sphyraena	0.54

Note: Cobalt (Co) was excluded from the MPI calculation as its concentrations were below the detection limit in all analyzed species.

Discussion

The variations among fish species presented in Table 2, along with their associated biological differences—such as differences in growth, feeding behaviors, and the types of organic material present—combined with local environmental factors, may significantly affect metal(loid) bioaccumulation in these species. These factors are crucial in determining the accumulation of elements (Piórewicz *et al*., 2021).

Comparison of Metal(loid) Levels with Previous Studies from the Mediterranean Sea

Aluminum (Al): Al is the most abundant natural metallic element in the Earth's crust. It enters the environment through both natural processes and human activities, resulting in its accumulation in aquatic ecosystems (Closset *et al*., 2022). In the present study, Al concentrations in muscle tissues varied widely, ranging from a minimum of 25.471 mg kg^{-1} (*B. boops*) to a maximum of 89.364 mg kg^{-1} (*S. japonicus*), as presented in Table 3. Akçay *et al*. (2026) reported the mean Al concentration for *M. cephalus*, which is the same species as in our study, as 2.77 mg kg^{-1}, and for *M. barbatus* and *P. lascaris* as 2.28 mg kg^{-1} and 2.33 mg kg^{-1} respectively, in the Mersin Bay, Northeastern Mediterranean Sea. Kılıç *et al*. (2021) also reported mean Al accumulation ranges in various fish species from the North-Eastern Mediterranean, such as *S. rivulatus* (0.56–7.62 mg kg^{-1}), *M. barbatus* (1.63–6.46 mg kg^{-1}), and *S. solea* (1.83–7.49 mg kg^{-1}). The values in our study substantially exceed these previously reported ranges.

The consistently elevated Al concentrations across all sampled species represent a significant finding. Rather than indicating a methodological artifact, the distinct yet consistently high accumulation pattern across different species suggests a strong environmental signal. This suggests that the bioavailability of Al in our specific sampling area may be genuinely higher compared to other locations cited in the literature. Factors such as local geology, specific terrestrial runoff patterns, or unique water chemistry in the study location could lead to increased Al accumulation in the local food web. It should be noted that, unlike heavy metals such as Pb and cadmium (Cd), there are no universally adopted regulatory limits for Al concentration in fish muscle tissue.

As: As is a naturally occurring element that is found extensively in the environment (Korkmaz *et al.*, 2019). In a study by Korkmaz *et al.* (2019) on heavy metal levels in the muscle tissues of various fish species caught from the Northeastern Mediterranean Sea, As levels were reported to range between 1.08 and 15.06 mg kg^{-1}. Other Mediterranean studies have reported mean As levels ranging from 0.076 to 1.82 mg kg^{-1} (Kuplulu *et al.*, 2017) and 0.09 to 0.49 mg kg^{-1} (Karayakar *et al.*, 2022). In our study, As concentrations ranged from a minimum of 0.255 mg kg^{-1} (*S. salpa*) to a maximum of 5.540 mg kg^{-1} (*S. lessepsianus*) (Table 3), which is consistent with the higher end of regional concentrations previously reported, particularly by Korkmaz *et al.* (2019).

Cd: Cd is a nonessential and highly toxic element that, while typically found at low levels in nature, is frequently introduced into the environment as a byproduct of Zn, Cu, and Pb ore processing; it is also well-known for its tendency to bioaccumulate in aquatic organisms (Abd-Elghany *et al.* 2024; Korkmaz *et al.*, 2019). The concentrations of Cd found in the muscle tissues of the species analyzed in our study were generally low, ranging from a minimum of 0.011 mg kg^{-1} (*A. regius* and *M. cephalus*) to a maximum of 0.027 mg kg^{-1} (*B. boops*) (Table 3). These findings are highly consistent with reports suggesting low background contamination in the Northeastern Mediterranean. For instance, Korkmaz *et al.* (2019) reported that Cd was not detected (n.d.) in the muscle tissues of fish from six stations in the region. Olgunoglu *et al.* (2015) similarly found Cd to be nondetectable in the muscle tissues of *M. merluccius* and *L. budegassa*. Regional studies further corroborate this low contamination trend, with mean Cd levels in edible species typically reported at the lower end of global ranges: 0.03 to 0.20 mg kg^{-1} (Ersoy and Celik, 2010), 0.002 to 0.03 mg kg^{-1} (Karayakar, 2022), and 0.002 to 0.01 mg kg^{-1} (Kılıç *et al.*, 2021). Our measured concentrations are fully aligned with the lower boundary of these regional values. Crucially, all Cd concentrations observed in our study are significantly below the regulatory limit (PL) of 0.05 mg kg^{-1} set by the European Union. Therefore, Cd exposure from consuming the analyzed seafood species is unlikely to be of concern under the assumed intake scenario.

Cobalt (Co): Co is an essential trace element for humans and other animals, playing a crucial role in very small quantities; however, excessive doses can be harmful to human health (Genchi *et al.*, 2023). In our study, which focuses on the Northeastern Mediterranean, Co was n.d. in the muscle tissue of any of the 10 analyzed species (Table 3), indicating that concentrations were below the method's LOD. This finding is in contrast to regional studies that have consistently reported low but detectable concentrations of Co in fish muscle. For instance, Kılıç *et al.* (2021) reported mean Co concentrations in the North-Eastern Mediterranean ranging from 0.01 to 0.04 mg kg^{-1} across several species (*S. solea*, *M. barbatus*, and *S. rivulatus*). Similarly, Akçay *et al.* (2016) reported mean values for *M. cephalus*, *M. barbatus*, and *P. lascaris* as 0.012, 0.016, and 0.006 mg kg^{-1}, respectively. Other studies in the Mediterranean have reported a broad range of Co concentrations, such as 0.07 to 0.26 mg kg^{-1} (Türkmen *et al.*, 2008a) and extreme values up to 0.45 mg kg^{-1} for *Pomadasys incisus* (Türkmen *et al.*, 2009). Given the literature, the absence of Co detection in our samples likely reflects a low local bioavailability in the sampling area.

Chromium (Cr): Cr is a biologically active element that is known to exist primarily in two valence states in the environment: the trivalent form (Cr (III)), which is considered an essential trace mineral involved in lipid and protein metabolism, and the hexavalent form (Cr(VI)), which is recognized for its carcinogenic potential (Korkmaz *et al.*, 2019). In our study, Cr concentrations in muscle tissue were relatively low, ranging from a minimum of 0.084 mg kg^{-1} (*H. dactylopterus*) to a maximum of 0.275 mg kg^{-1} (*A. regius*) (Table 3). This range is comparable to most regional literature. For instance, Akçay *et al.* (2026) reported mean values for *M. cephalus*, *M. barbatus*, and *P. lascaris* as 0.39, 0.31, and 0.37 mg kg^{-1}, respectively, in the Mersin Bay. Other studies in the North-Eastern Mediterranean have reported similar ranges, such as 0.06–0.48 mg kg^{-1} (Can *et al.*, 2020), 0.03–0.07 mg kg^{-1} (Ersoy and Çelik, 2010), and 0.02–0.28 mg kg^{-1} (Karayakar *et al.*, 2022). However, a notable exception is the study by Korkmaz *et al.* (2019), which reported significantly higher mean Cr levels in muscle tissues, ranging between 2.15 and 7.10 mg kg^{-1}. Our low findings and those of the majority of recent literature contrast sharply with these high reported peak values, suggesting that the higher levels are likely attributable to highly localized contamination or pronounced biological variability in the organisms analyzed in that specific study.

Copper (Cu): Cu is an essential trace element that plays a vital role in various biological processes, acting as a cofactor for numerous enzymes; however, it can be toxic when present in excessive amounts (Hefnawy and Elkhaiat, 2015). In the present study, Cu concentrations in the muscle tissue varied between a minimum of 0.151 mg kg^{-1} (*H. dactylopterus*) and a maximum of 0.617 mg kg^{-1} (*B. boops*), as presented in Table 3. Our findings are highly consistent with recent regional studies reporting low to moderate Cu levels. For example, Akcay *et al.* (2016) reported mean concentrations in the Northeastern Mediterranean Sea as 0.29 mg kg^{-1} for *M. cephalus* and 0.25 mg kg^{-1} for *M. barbatus*. Similarly, Can *et al.* (2020) found a range of 0.24–0.57 mg kg^{-1}, and Karayakar *et al.* (2022) reported seasonal mean concentrations from 0.11 to 0.37 mg kg^{-1}. Furthermore, Korkmaz *et al.* (2019) reported mean Cu levels ranging from <0.006 to 0.74 mg kg^{-1} in fish from the North-East Mediterranean. The Cu concentrations measured in our study fit well within this established, consistent regional range, suggesting a typical background level for the Northeastern Mediterranean.

Iron (Fe): Fe is an abundant element on Earth and is a biologically essential component crucial for numerous metabolic activities and healthy development (Abbaspour *et al*., 2014). In our study, Fe concentrations in the muscle tissue exhibited a wide range of variability, from a minimum of 6.226 mg kg^{-1} (*B. boops*) to a maximum of 21.908 mg kg^{-1} (*M. cephalus*), as detailed in Table 3. The concentrations observed in our samples are generally consistent with some of the higher values reported in the region. For instance, Türkmen *et al.* (2008a) reported a broad Fe range, from 19.9 to 73.3 mg kg^{-1}, in fish muscle from two Mediterranean locations. Our highest values (~21.9 mg kg^{-1}) align closely with the lower end of this wider range. Korkmaz *et al.* (2019) also reported a significant range in the North-East Mediterranean, from <0.001 to 19.02 mg kg^{-1}. The remaining regional studies generally show lower, yet comparable, mean values: Can *et al.* (2020) found Fe concentrations between 5.47 and 11.73 mg kg^{-1}, and Akçay *et al.* (2026) reported 1.51–5.42 mg kg^{-1}. The pronounced variability in Fe levels observed both in our study and the wider literature is primarily a reflection of biological factors.

Hg: Hg is a highly toxic metal pollutant frequently released into aquatic environments as a result of industrial and agricultural discharges (Abd-Elghany *et al.,* 2024). In the present study, Hg concentrations in the muscle tissue were consistently low across all 10 species analyzed, ranging from a minimum of 0.001 mg kg^{-1} (in *M. cephalus* and *S. salpa*) up to a maximum of 0.110 mg kg^{-1} (*H. dactylopterus*) (Table 3). These findings align well with other baseline regional data, such as Kuplulu *et al.* (2017), who reported a comparable range of 0.006 to 0.203 mg kg^{-1} for Mediterranean fish. This trend of low regional Hg levels is further supported by Özyurt *et al.* (2021), who reported that Hg was not detectable in the muscle tissues of the bluefish (*Pomatomus saltatrix*). However, a comparison with top predatory species reveals markedly lower concentrations in our samples. For example, Ulusoy *et al.* (2019) documented a mean Hg level of 0.45 mg kg^{-1} for Atlantic bluefin tuna in the Eastern Mediterranean. This notable difference is expected given the significantly higher trophic position of the tuna.

Manganese (Mn): Mn is a relatively abundant metal that is widely distributed in the Earth's crust and occurs in nodules on the ocean floor (Tsuji *et al*., 2016). In the present study, Mn concentrations in the muscle tissue were low and exhibited a narrow range of variability, from a minimum of 0.131 mg kg^{-1} to a maximum of 0.675 mg kg^{-1} (Table 3). These results are highly consistent with the established baseline data for the Mediterranean region. For example, Ersoy and Çelik (2009) reported a similar low range of 0.08–0.51 mg kg^{-1}, while their subsequent study (Ersoy and Çelik, 2010) found concentrations between 0.11 and 0.64 mg kg^{-1}. Akçay *et al.* (2026) also reported low values, ranging from 0.22 to 0.68 mg kg^{-1}. The findings of Türkmen *et al.* (2009) (0.08–1.14 mg kg^{-1}) encompass our entire measured range. Even the specific seasonal study by Özyurt *et al.* (2021) only detected Mn in bluefish during winter (0.44 mg kg^{-1}). While some older studies, such as Türkmen *et al.* (2008a) and Türkmen *et al.* (2008b), reported slightly higher peak Mn values, the majority of the literature, including our current findings, strongly suggests that Mn levels in fish muscle tissue across the Mediterranean remain consistently low.

Ni: Ni is generally regarded as an essential micronutrient at trace levels but poses a toxicological risk when concentrations are elevated (Kılıç *et al*., 2021; Kumar *et al*., 2021). In the present analysis, Ni concentrations showed a considerable range, from a minimum of 0.143 mg kg^{-1} (*S. sphyraena*) to a striking maximum of 2.455 mg kg^{-1} in *B. boops* (Table 3). Other species, including *M. cephalus* (2.425 mg kg^{-1}) and *S. salpa* (2.028 mg kg^{-1}), also recorded elevated levels. These measured values are consistent with the higher end of regional contamination studies. The maximum concentration reported by Türkmen *et al.* (2008a) for Mediterranean fish, at 2.78 mg kg^{-1}, is comparable to our Ni concentration in *B. boops*. Furthermore, high Ni levels were confirmed as a regional issue by Ateş *et al.* (2015), who found concentrations reaching up to 3.43 mg kg^{-1} in Iskenderun Bay and 3.16 mg kg^{-1} in Mersin Bay. Our Ni level in *M. cephalus* (2.425 mg kg^{-1}) notably exceeds the mean of 1.22 mg kg^{-1} reported by Yılmaz (2003) from Iskenderun Bay. The pronounced disparity between these elevated Ni concentrations and the lower regional baselines (e.g., Korkmaz *et al.*, 2019) strongly indicates the influence of specific localized industrial or terrestrial discharges.

Pb: Pb is classified as a toxic, nonessential metal with no recognized biological role, entering aquatic environments predominantly through anthropogenic activities (Abd-Elghany *et al.*, 2024). Pb concentrations in fish species from the Mediterranean Sea have been reported in ranges of 0.33 to 1.05 mg kg^{-1} for Antalya Bay, 1.13 to 5.80 mg kg^{-1} for Mersin Bay, and 0.40 to 2.78 mg kg^{-1} for Iskenderun Bay (Ateş *et al.*, 2015). Similarly, Kılıç *et al.* (2021) reported maximum Pb concentrations of 0.91 mg kg^{-1} in the muscle tissue of M. barbatus from Iskenderun Bay. Other studies have shown comparable results; Türkmen *et al.* (2008b) reported maximum Pb levels of 0.86 mg kg^{-1} in Iskenderun Bay. Furthermore, Türkmen *et al.* (2009) documented a maximum Pb concentration of 0.66 mg kg^{-1} in *P. incisus* from Antalya Bay. These findings are consistent with our study, in which the minimum and maximum Pb concentrations were found to be 0.477 mg kg^{-1} (*M. cephalus*) and 0.672 mg kg^{-1} (*S. salpa*), respectively (Table 3). However, it is critical to note that the levels detected in our study consistently exceed the permissible limit of 0.30 mg kg^{-1} wet weight for seafood, as established by The Contaminants in Food (Amendment) (EU Exit) Regulations 2019. While this exceedance highlights a clear environmental concern regarding Pb contamination, the actual implications for human health depend heavily on specific dietary intake rates. Accordingly, the exceedance should be interpreted primarily as a regulatory compliance and monitoring concern, whereas the health risk indices reflect exposure under the specific consumption assumptions applied in this study.

Se: Se is an essential trace element for human health, functioning as a critical antioxidant and an enzymatic cofactor (Çelebi *et al.*, 2023). In the present study, Se concentrations ranged from a minimum of 0.080 mg kg^{-1} in *S. salpa* to a maximum of 0.718 mg kg^{-1} in *H. dactylopterus* (Table 3). To contextualize these findings, we compared them with available literature. Our maximum concentration (0.718 mg kg^{-1}) is lower than the mean level of 1.05 mg kg^{-1} reported for Atlantic bluefin tuna in the Eastern Mediterranean (Ulusoy *et al.*, 2019). Conversely, our minimum finding (0.080 mg kg^{-1}) can be situated against trace levels found in other marine contexts, such as the 0.004 mg kg^{-1} reported by Yabanli and Tay (2021). Overall, the Se levels detected are consistent with the natural, essential variability expected in marine environments.

Zinc (Zn): Zn is an essential mineral and biological trace element, critical for optimal health (Rosli *et al.*, 2018; Hefnawy and Elkhaiat, 2015). In our study, Zn concentrations in muscle tissue ranged from a minimum of 3.464 mg kg^{-1} (*M. cephalus*) to a maximum of 7.760 mg kg^{-1} (*S. salpa*) (Table 3). These findings are highly consistent with the baselines reported across the Northeastern Mediterranean Sea. Regional studies show a wide but comparable context for Zn variability. Ateş *et al.* (2015) documented high-end concentrations, reaching 8.87 mg kg^{-1} in Antalya Bay and 7.74 mg kg^{-1} in Iskenderun Bay. Our results are further supported by Can *et al.* (2020), who reported concentrations ranging from 2.81 to 4.15 mg kg^{-1}. The lower bounds of our measured Zn are consistent with findings from Akçay *et al.* (2026), who reported values between 1.53 and 3.45 mg kg^{-1} in Mersin Bay. Considering the robust homeostatic regulation of Zn in fish muscle, the observed levels fall within natural regional baselines and are unlikely to pose a toxicological concern under the assumed intake scenario.

In summary, the trace element analysis revealed a clear distinction between essential and nonessential metals concerning regulatory compliance and public health risk. Pb stands out as the primary concern, as its concentrations exceeded the mandatory 0.30 mg kg^{-1} limit in all analyzed species, indicating widespread environmental contamination. Conversely, the essential elements, Zn and Se, along with the toxic elements Cd and Hg, were found at levels significantly below their respective international regulatory thresholds. The high concentrations of Al were determined to be consistent with exogenous contamination rather than true bioaccumulation. Taken together, while most analyzed metals pose a minimal toxicological threat, the consistent exceedance of the Pb limit highlights a critical concern for public health monitoring and risk assessment regarding the consumption of fish from the study area.

Health Risk Assessment and Biological Indices

Although fish muscle tissue typically exhibits low levels of metal(loid)s, the associated health risk can fluctuate depending on the species and the amount consumed (Kilercioglu *et al.*, 2022). In the present study, the overall risk assessment indicates a low level of concern for consumers. The calculated EWI values for all analyzed elements in all species were found to be below their respective PTWI guidelines. These findings are consistent with those of Özyurt *et al.* (2021), who also reported that heavy metal concentrations in commercial fish from the Northeastern Mediterranean did not pose a significant risk to human health. Moreover, Karayakar *et al.* (2022) reported that the EWI values for three fish species sold in Karatas region were also well below PTWI levels, confirming a low baseline risk for regular fish consumption in this area. This further supports our findings, indicating that the consumption of fish from this region is unlikely to pose significant health risks under the current intake assumptions.

However, noteworthy variations were observed for specific elements. The EWI for Cd in *B. boops* reached a notable 57.4% of its PTWI limit. Although still below the PTWI, this value is considerably higher than for other toxic elements. In contrast to total As assessments, the application of the 10% inorganic fraction revealed that the EWI for As in *S. lessepsianus* constituted only 5.5% of its PTWI, posing no significant threat. This suggests that while Cd may warrant continuous monitoring in specific species like *B. boops*, the consumption of these fish contributes negligibly to the total weekly intake of individual toxic metals and, from this specific short-term intake perspective, does not pose an appreciable risk.

The calculated ∑THQ values indicated no non-CR ($\sum THQ < 1$) in any of the 10 fish species studied. This finding diverges from some regional studies, such as Korkmaz *et al.* (2019), who reported that the THQ for inorganic As exceeded the safety threshold. However, it is crucial to interpret this difference based on methodology. While assessments based on total As often suggest high risk, Kucuksezgin *et al.* (2014) highlighted that over 90% of As in seafood is typically present in less toxic organic forms. By incorporating this fact, our study presents a more realistic risk characterization, where As individual THQ values remained well below 1. Consequently, while the calculated non-CR from the investigated metal(loid) s is minimal at current intake levels ($\sum THQ < 1$), the exceedance of the EU maximum level for Pb dictates a cautious approach. Rather than classifying the fish as unequivocally safe, consumers should maintain a diversified diet and moderate consumption frequencies, particularly in light of the consistently elevated Pb concentrations; in parallel, local authorities should ensure continuous environmental monitoring.

The CR findings provide a nuanced profile. While previous regional research (e.g., Korkmaz *et al.*, 2019) often identified As as the primary risk driver based on total concentrations, our study reveals that Ni is a critical, and often dominant, contributor to the total risk (∑CR) when the toxicologically relevant inorganic fraction of As (10%) is applied. For instance, Ni accounted for approximately 86% of the ∑CR in *M. cephalus* and 85% in *B. boops*. This finding is significant, as it suggests that assessments limited to As and Pb may underestimate the specific carcinogenic burden posed by Ni. It highlights the necessity of a multimetal approach to accurately evaluate the heterogeneous and species-specific health risks associated with seafood consumption.

The findings—Se:Hg molar ratios are substantially greater than 1 and positive HBV_{Se} values for all samples—are consistent with the work of Suratno and Puspitasari (2024), who identified Se as a primary detoxifying agent typically found in excess of Hg in most fish. Our work reinforces the argument, also highlighted by Suratno and Puspitasari (2024), that assessing Hg risk based on Hg concentration alone is insufficient. The consistent positive HBV_{Se} values in our samples demonstrate a surplus of Se available to counteract Hg's toxic effects, validating the HBV_{Se} as a more reliable index for risk assessment. A notable finding was that *H. dactylopterus* exhibited the highest HBV_{Se} despite having the lowest Se:Hg molar ratio. This underscores that once the protective molar ratio (>1) is achieved, the absolute concentration of Se becomes a key driver of the overall health benefit, showcasing the nuanced utility of the HBV_{Se} metric beyond a simple molar comparison.

In conclusion, our findings suggest the Northeastern Mediterranean is a Se-replete environment for these species. This supports the conclusion from Ralston *et al.* (2006) that fish from Se-rich waters pose minimal risk. Therefore, the species studied present a minimal toxicological risk regarding Hg and serve as a valuable dietary source of Se.

The MPI for all species was below the contamination threshold of 1.0 (Yabanli and Alparslan 2015), suggesting an absence of severe metal pollution (Table 8). However, the variations in MPI, which can reflect metal uptake from diet or water (Zaghloul, *et al*. 2024), reveal noteworthy bioaccumulation dynamics. The observation that the lowest MPI values were shared by species from disparate ecological niches (epipelagic and benthopelagic) indicates that species-specific physiological factors, such as metabolic efficiency, can be more influential in determining metal load than habitat alone. These findings highlight that bioaccumulation is governed by a complex interplay of diet, habitat, and species-specific physiology rather than a single ecological factor.

Conclusions

This study provides a comprehensive assessment of metal(loid) concentrations in 10 commercial fish species from the Northeastern Mediterranean, revealing significant findings for public health. A critical finding was the concentration of Pb, which consistently surpassed the European Union's permissible limit of 0.30 mg kg^{-1} in all 10 species analyzed, signaling a persistent issue of environmental contamination that requires regulatory attention.

The health risk assessment, conducted by incorporating the toxicologically relevant inorganic fraction of As (10%), provided a realistic estimation of consumer exposure. The EWI for individual elements remained well below established guidelines. Crucially, when the inorganic fraction of As (10%) was applied, the total non-CR (ΣTHQ) remained below the safety threshold of 1 for all 10 species. This indicates that the regular consumption of these fish is unlikely to pose a significant noncarcinogenic health risk for adults under the assumed intake scenario. Furthermore, the ΣCR assessment showed that values fell generally within or near the acceptable safety range (10^{-6} to 10^{-4}), with Ni, rather than As, emerging as the primary contributor to the total risk profile.

In addition to the minimal toxicological risk indicated by the hazard indices, the study confirmed a significant health benefit. The Se:Hg molar ratios were substantially greater than 1, and HBV_{Se} were positive across all species. This demonstrates that these fish are a rich source of dietary Se and that the physiological risk from Hg is effectively mitigated.

In summary, while the calculated risk indices suggest minimal noncarcinogenic health risks, the consistent exceedance of the regulatory limit for Pb necessitates a cautious approach. These findings suggest that public health guidance should focus on the continued monitoring of industrial pollutants like Pb and Ni. To balance the nutritional benefits, such as Se intake, with potential exposure risks, it is advisable for consumers to maintain a diversified diet and practice moderate consumption of these species. Furthermore, local authorities must implement continuous environmental surveillance to ensure long-term food safety and public health protection.

Mandatory Disclosure on Use of Artificial Intelligence

During the preparation of this manuscript, the authors used artificial intelligence (AI) tools only for language editing and to improve readability. The authors subsequently reviewed and revised the text where necessary and accept full responsibility for the content and integrity of the final publication.

Author Contributions

The authors all contributed equally to this article.

Conflicts of Interest

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