

## Research Article

# Assessment of metal levels in fish species from the Red Sea: Implications for health risks and ecological impact

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This study evaluated trace and heavy metal concentrations (Ca, K, Cr, Mn, Co, Ni, Zn, Se, Ag, Ba) in nine commercially important fish species (*Epinephelus marginalis*, *Mugil cephalus*, *Pagrus pagrus*, *Sole sole*, *Siganus canaliculatus*, *Lethrinus nebulosus*, *Sparus aurata*, *Mullus surmuletus*, and *Trachurus indicus*) from the Red Sea, Saudi Arabia, using inductively coupled plasma mass spectrometry (ICP-MS). The highest metal concentrations were observed in *Mugil cephalus* (Cr: 0.157 mg/kg; Zn: 0.672 mg/kg), while *Trachurus indicus* exhibited the lowest levels (Cr: 0.002 mg/kg). All metal concentrations were below the permissible limits (FAO/WHO), with Cr and Ni representing only 7.4 % and 13.8 % of their respective thresholds. Health risk assessments (THQ < 1, HI < 1, CR < 10<sup>-6</sup>) indicated minimal risks for adults and children, with Estimated Weekly Intakes (EWI) for Cr (0.42 µg/kg bw/week) and Ni (0.078 µg/kg bw/week) below Provisional Tolerable Limits (PTWI). Principal Component Analysis (PCA) revealed that 86.8 % of metal variance was derived from natural sources (agricultural runoff, geological weathering), underscoring Yanbu's relatively pristine conditions compared to industrialised Red Sea regions. These findings highlight the need for ongoing monitoring to safeguard marine ecosystems and public health, particularly for benthic species such as *M. cephalus*, which showed a higher bioaccumulation potential.

[**Keywords:** Aquatic pollution, Bioaccumulation, ICP-MS, Red Sea ecosystem, Risk assessment, Seafood safety, Trace metals]

## Introduction

Marine ecosystems worldwide face increasing pressure from anthropogenic activities, with heavy metal contamination emerging as a critical environmental challenge. These pollutants accumulate in aquatic organisms, posing significant risks to ecosystem health and human populations that rely on seafood as a primary source of protein<sup>1</sup>. The Red Sea, a unique marine ecosystem characterised by high biodiversity and endemism, supports valuable fisheries that contribute significantly to regional food security and economies. The selected species including *Epinephelus marginalis* (groupers), *Mugil cephalus* (mulletts), and *Pagrus pagrus* (sea breams) represent ecologically important taxa across multiple trophic levels and are among the most commercially valuable fishes in the Saudi Arabian fisheries. Their widespread consumption and sensitivity to environmental contaminants make them ideal bioindicators for monitoring metal pollution in this region<sup>2</sup>. Frequently, human interventions in and adjacent to aquatic environments result in diminished vegetation, upsetting the water equilibrium, degrading

water quality, and compromising the well-being of aquatic fauna, as noted by Hussain *et al.*<sup>3</sup>. Consequently, the accumulation of metals within fish tissues can be linked, at least partially, to water contamination stemming from a variety of anthropogenic origins<sup>4</sup>.

In recent decades, the contamination of marine ecosystems with metals has emerged as a significant environmental issue<sup>2</sup>. The distribution of trace metals within the food chain and their biological repercussions are notably amplified by the enduring presence of these pollutants in the environment<sup>5</sup>. Consequently, both aquatic organisms and humans who consume them are susceptible to the adverse health effects stemming from heightened metal pollution in biota<sup>6-9</sup>. Hence, a crucial parameter for evaluating ecosystem well-being involves monitoring metal levels in the environment and their accumulation in aquatic life<sup>10</sup>.

While seafood provides essential minerals, excessive consumption of any metal, including those essential for health, can be detrimental due to bioconcentration. Research by Chien *et al.*<sup>11</sup> and

Yabanli & Alparslan<sup>12</sup>, indicates that individuals can absorb trace metals from seafood. Therefore, continued surveillance is essential to mitigate potential health risks associated with trace metal contamination in seafood<sup>13,14</sup>.

The escalation of heavy metal contamination in aquatic ecosystems is a direct consequence of agricultural, mining, and metallurgical activities, as well as the disposal of waste from related industries, as highlighted by recent studies<sup>15-17</sup>. The rapid industrial and agricultural advancements globally, and the extraction and refining processes in the petroleum industry, have led to the unbridled release of diverse organic and inorganic toxins into the environment, exerting profound detrimental effects on both ecological and human health<sup>18-20</sup>. This surge in social and economic expansion catalyses the deterioration of the coastal bay, acting as a reservoir for anthropogenic pollutants, encompassing metalloids and trace metals<sup>21,22</sup>. In these coastal water bodies, heavy metal contamination has emerged as a pressing concern. Moreover, the discharge of substantial quantities of heavy metals from sources such as industrial effluents, mining activities, urban sewage, and metal smelting residues further exacerbates the plight of aquatic ecosystems. These heavy metals tend to accumulate initially in plankton upon their release into water systems, subsequently traversing the food chain to concentrate in fish, crustaceans, and shellfish, ultimately posing risks to human health upon consumption<sup>23</sup>.

According to the World Health Organization<sup>24</sup>, certain trace metals have been associated with an elevated risk of specific human illnesses, such as Alzheimer's, Parkinson's, and muscular dystrophy. Cadmium, in particular, has been identified not only to disrupt embryonic and post-embryonic developmental stages but also to impair sperm motility by interacting with flagellar proteins that govern beat-cross frequency and symmetry. Dietrich *et al.*<sup>25</sup> demonstrated that the substitution of cadmium with calcium ions can disrupt spermatogenesis, sperm motility, sexual maturation, and gamete maturation in mice. Prolonged exposure to cadmium can lead to renal disease, characterised by tubular proteinuria, pneumonitis, osteomalacia, osteoporosis, and in severe instances, oedema and mortality in humans. Similarly, in various marine animal species, including molluscs, crustaceans, echinoderms, fish, sea turtles, birds, and mammals, toxic metals have been observed

to diminish glutathione levels and bind to sulfhydryl groups present in proteins and enzymes, thereby instigating an upsurge in oxidative stress<sup>26</sup>.

The rise in fish consumption, attributed to its exceptional nutritional value<sup>27</sup>, underscores the significance of ensuring fish quality as a reflection of water metal pollution<sup>5,28-30</sup>. Research has shown that fish inhabiting contaminated environments may exhibit elevated metal concentrations, posing risks to both human health and other biota due to metal transfer along the food chain. The consumption of heavy metals at higher levels raises significant health concerns, prompting regulatory bodies to establish maximum allowable intake thresholds. Given the lingering biological half-life and potential toxicity of heavy metals, it is imperative to evaluate the associated health risks linked to their ingestion, as emphasised by Bortey-Sam *et al.*<sup>31</sup>. Studies have identified metal bioaccumulation in multiple Red Sea fish species, likely stemming from coastal industrial expansion, highlighting the need to examine the metal content of commercially available edible fish species in the Saudi Red Sea region to assess associated health risks.

The study was conducted in Yanbu, Saudi Arabia (24°04'21" N; 38°03'08" E), a major Red Sea port city with both industrial and artisanal fishing activities. This region features diverse coastal ecosystems, including coral reefs and seagrass beds that support the studied fish species. Yanbu, a substantial port city in Saudi Arabia nestled along the eastern fringes of the Red Sea, boasts a strategic location, burgeoning infrastructure, and a thriving populace, all integral to its dynamics. Divided into the historical enclave of Old Yanbu, situated within Al-Balad or Al-Bahr, and the bustling Industrial Yanbu, centred in Yanbu Al-Sinaiyah, which stands as the nation's economic nucleus. This study's purview encompasses the expanse of shoreline extending from the tranquil shores of Sharm Yanbu to the industrious precincts of Industrial Yanbu, characterised by small coastal marine ecosystems interwoven with offshore barrier reefs (Fig. 1).

Previous studies have documented metal contamination in Red Sea fish, though findings vary regionally. For instance, Abbas *et al.*<sup>32</sup> reported elevated Cr (2.29 – 5.43 mg/kg) and Ni (1.46 – 4.86 mg/kg) levels in benthic species from Egypt's Suez Gulf, while Younis *et al.*<sup>33</sup> found extreme Cr concentrations (38.6 – 113.3 mg/kg) near Jeddah's

industrialised coast. In contrast, baseline studies from protected areas, such as Yemen's Socotra Island, reveal negligible contamination, highlighting the role of localised anthropogenic pressures. Despite these efforts, gaps persist in understanding metal accumulation patterns in understudied regions like Yanbu, Saudi Arabia, a major Red Sea port with both industrial activity and artisanal fisheries.

This study addresses three key objectives: (1) Quantifying trace metal concentrations (Ca, K, Cr, Mn, Co, Ni, Zn, Se, Ag, Ba) in nine commercially important fish species from Yanbu; (2) Assessing

potential health risks to consumers using hazard indices (THQ, HI, CR); and (3) Identifying contamination sources through PCA to differentiate natural vs. anthropogenic inputs. By focusing on species spanning multiple trophic levels (*e.g.*, benthic *Mugil cephalus* and pelagic *Trachurus indicus*), this study provides a comprehensive evaluation of metal distribution and its implications for ecosystem health and human safety. Current findings establish critical baselines for future monitoring and align with global efforts to mitigate seafood contamination risks, as outlined by FAO/WHO guidelines.

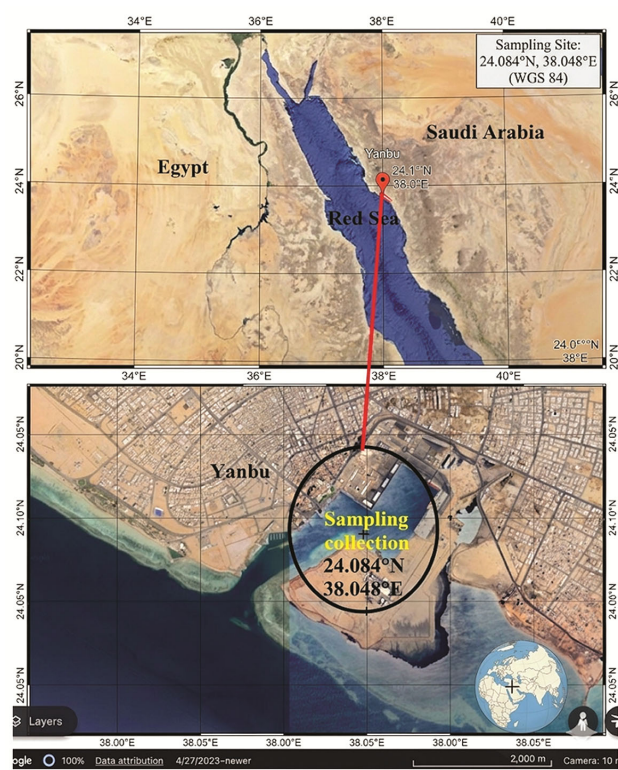


Fig. 1 — Study area showing sampling site (Source: Google Maps)

## Materials and Methods

### Sample collection

Nine marine fish species (*Epinephelus marginalis*, *Mugil cephalus*, *Pagrus pagrus*, *Solea solea*, *Siganus canaliculatus*, *Lethrinus nebulosus*, *Sparus aurata*, *Mullus surmuletus*, and *Trachurus indicus*) were collected from licensed artisanal fishermen operating in the coastal waters of Yanbu, Saudi Arabia, during the summer season of 2023 (Table 1). Specimens were captured using gill nets and baited hand lines for demersal species. Immediately following capture, each fish was rinsed with distilled water, placed in ice-cooled containers (4 °C), and transported to the laboratory within 2 h of collection.

Species identification was conducted through morphological examination following Fischer<sup>34</sup> and verified against FAO species identification guides. For each species, ten representative specimens of observed size range were selected for analysis. All samples were processed at the Analytical Chemistry Laboratory of Qassim University under standardised protocols to ensure sample integrity and taxonomic accuracy<sup>35</sup>.

Table 1 — Biological characteristics of the studied fish species from the Red Sea, including taxonomic classification, size ranges, and feeding behaviour

Common name	Scientific name	Family	Length range (cm)	Weight range (g)	Feeding behaviour
Greasy grouper	<i>Epinephelus marginalis</i>	<i>Serranidae</i>	17-32	400-1500	Piscivorous predator
Flathead mullet	<i>Mugil cephalus</i>	<i>Mugilidae</i>	12-20	135-400	Benthic omnivore
Common seabream	<i>Pagrus pagrus</i>	<i>Sparidae</i>	12-22	200-550	Benthic carnivore
Common sole	<i>Solea solea</i>	<i>Soleidae</i>	10-20	100-350	Benthic invertebrate feeder
White-spotted spinefoot	<i>Siganus canaliculatus</i>	<i>Siganidae</i>	8-13	80-220	Herbivorous
Spangled emperor	<i>Lethrinus nebulosus</i>	<i>Lethrinidae</i>	15-25	300-750	Benthic carnivore
Gilthead seabream	<i>Sparus aurata</i>	<i>Sparidae</i>	12-20	200-500	Omnivorous
Striped red mullet	<i>Mullus surmuletus</i>	<i>Mullidae</i>	8-14	75-160	Benthic invertebrate feeder
Indian scad	<i>Trachurus indicus</i>	<i>Carangidae</i>	8-15	60-200	Pelagic carnivore

#### Determination of metal concentration

For trace metal quantification, muscle tissue (1 g wet weight) from the dorsal region of each specimen was analysed. Samples were oven-dried at 60 °C to constant weight, then subjected to acid digestion in Teflon PTFE vessels using 10 mL HNO<sub>3</sub> (65 %) and 2 mL H<sub>2</sub>O<sub>2</sub> (30 %) in a microwave-assisted digestion system. Upon attaining ambient temperature, the samples were judiciously diluted using a 2 % HNO<sub>3</sub> solution, culminating in a final volume of 25 ml, which was then carefully transferred into 25 ml volumetric vessels. To fine-tune the diluted samples to requisite concentrations falling within the spectrum of standards derived from esteemed metal stock solutions (Merck), a calibrated solution of de-ionised water was judiciously employed. Before analysis, all samples were filtered through a 0.45 µm nitrocellulose membrane filter to ensure purity and precision.

Subsequently, a series of rigorous triplicate ICP-MS analyses was conducted on all treated solutions, adhering to the manufacturer's guidelines and benchmarks. Every determination was meticulously performed in triplicate, with corresponding sample blanks meticulously prepared in the laboratory, mirroring the handling of the field samples. The quantification of heavy metal concentrations was meticulously executed, yielding values in milligrams per kilogram of dry weight of the fish specimens. This analytical methodology serves as a robust mechanism for discerning the presence of specific heavy metals within biological matrices<sup>36</sup>.

To safeguard against potential metal tainting, a stringent protocol was observed. Glassware underwent meticulous submersion in 10 % nitric acid, followed by rinsing with distilled water to mitigate any inadvertent contamination. The utilisation of analytical-grade reagents was paramount to ensure the precision and accuracy of the analytical procedures, thereby assuring the veracity of the reported results.

A meticulous regimen was observed to maintain scientific precision. Following thorough rinsing with deionised water, all equipment and glassware underwent cleansing with a 2 % HNO<sub>3</sub> solution, ensuring a pristine laboratory environment conducive to precision analyses. The studies were executed with exacting precision, employing the calibration line method to calibrate analytical conditions with utmost care and diligence.

#### Quality Assurance/Quality Control (QA/QC)

Study implemented rigorous quality control measures throughout analytical protocol to ensure

data accuracy and precision. For calibration, fresh standard solutions were prepared daily from NIST-traceable stock solutions (High-Purity Standards), establishing 7-point calibration curves (0.1 – 100 ppb range) with correlation coefficients ( $R^2$ ) exceeding 0.999 for all elements, using rhodium as an internal standard to correct for instrumental drift. Method accuracy was verified through regular analysis of certified reference material DORM-4 (NRC Canada) with each sample batch, achieving recoveries of 92 – 105 % for all reported elements, supplemented by spike recovery tests showing 95 – 103 % recovery rates. The calibration equations, derived from regression analysis of weight, established the linear ranges essential for quantifying metal concentrations within the spiked samples. The recovery, a pivotal metric in ascertaining measurement accuracy, was computed following the methodology expounded by Clesceri *et al.*<sup>37</sup>, underscoring the commitment to methodological integrity and analytical precision.

Precision was assessed through triplicate analyses of every 10 samples (relative standard deviation < 5 %) and repeated measurements of 20 % randomly selected samples (coefficient of variation < 7 %). Method Detection Limits (MDLs) were determined following EPA 40 CFR Part 136 guidelines, with quantification limits (LOQs) set at 3 – 10× MDLs (e.g., Cr: 0.003 mg/kg; Ni: 0.001 mg/kg). Comprehensive blank controls included method blanks processed with each digestion batch (n = 5 per 20 samples), with all blank values remaining below 3× MDL for reported elements. Instrument performance was monitored daily using multi-element tuning solutions (Agilent) and maintained through weekly performance verification protocols. These stringent quality measures ensure the reliability of reported trace metal concentration data for both ecological and human health risk assessments.

#### Assessing potential health risks

The Weekly Intake Estimate (EWI) serves as a pivotal metric in gauging potential health perils. The EWI for heavy metals is intricately intertwined with a myriad of factors, encompassing body weight, dietary habits, and metal concentrations. In this study, a tapestry of hypotheses was woven to unravel the potential health hazards posed by the consumption of fish with elevated levels of heavy metal. An underlying assumption equated the absorbed pollutant dose with the ingested dose, aligning with the stringent benchmarks set forth by USEPA standards<sup>38</sup>.

Subsequently, the investigative pathway veered towards insights from the work of Chien *et al.*<sup>11</sup>, a trajectory that notably omitted consideration of the impact of cooking practices on contaminant levels. A bespoke formula emerged as the analytical cornerstone for computing the EWI of heavy metals, anchoring calculations on crucial variables.

$$EWI = (C \times C_{cons})/BW \quad \dots (1)$$

Within the local context, the average weekly fish intake stood at 55.34 g/day per unit body weight<sup>39</sup>. Symbolically, 'C' embodies the heavy metal content within the fish (expressed in mg/kg wet weight), whilst 'BW' signifies the standardised body weight parameter set at 70 kg, encapsulating the intricate interplay of variables essential for meticulous risk assessment.

#### Evaluating the targeted risk quotient

An approach to gauge the likelihood of non-carcinogenic effects involves dividing the exposure dose by the Reference Dose (RfD), giving rise to the Target Hazard Quotient (THQ). When exposure levels fall below the RfD benchmark, a THQ value below 1 denotes an insubstantial Hazard Quotient (HQ). Consequently, sustained exposure at this threshold is unlikely to yield adverse health effects, and conversely, exceeding this threshold may pose risks. The THQ dosage was extrapolated using conventional assumptions stipulated within the US EPA risk assessment framework.

$$THQ = \frac{EF \times ED \times FIR \times C}{RFD \times BW \times ATn} \times 10^{-3} \quad \dots (2)$$

The model underpinning THQ estimation was developed using the formula elucidated by Chien *et al.*<sup>11</sup>, integrating a comprehensive suite of variables delineated by the US Environmental Protection Agency<sup>38</sup>. These variables encompass a tapestry of critical parameters: ED (Estimated Daily intake of a specific metal), EF (Exposure Frequency), FIR (Fish Ingestion Rate), C (metal Concentration), RfD (Reference Dose), BW (average population Body Weight), and AT (exposure duration). These components synergistically shape the analytical framework for assessing the Target Hazard Quotient (THQ), offering a nuanced perspective on potential health risks associated with metal exposure scenarios.

#### Unveiling cancer potential and risk assessment

##### Cancer risk evaluation

In the pursuit of determining a metal's Cancer Risk (CR), researchers delve into the cancer slope factor provided by the US Environmental Protection Agency<sup>38</sup>. An intricate interplay of variables influences an individual's lifelong cancer risk, with the oral Carcinogenic Slope Factor (CSF), sourced from the USEPA's Integrated Risk Information System (IRIS) web database, assuming a pivotal role in this equation.

$$CR = [(EF \times ED \times IRD \times MC \times CSF)/(BW \times AT)] \times 10^{-3} \quad \dots (3)$$

#### Risk assessment

The quantification of risk levels for myriad hazardous compounds often hinges on the Hazard Index (HI). As advocated by the United States Environmental Protection Agency, amalgamating all Hazard Quotients (HQs) associated with a given substance elucidates its risk profile.

$$Hazard\ index\ (HI) = \sum_{k=1}^{n=k} \text{targeted hazard quotient}$$

#### Determining monthly meal limits

A sophisticated algorithm, tailored to consider the diverse effects of various contaminants, was harnessed to compute the maximum number of meals an individual can safely consume within a month (CR<sub>mm</sub>). According to guidelines outlined by the US Environmental Protection Agency<sup>38</sup>, when contemplating the cumulative carcinogenic or non-carcinogenic effects of multiple pollutants, CR<sub>mm</sub> emerges as the threshold for monthly meal consumption. Within this framework, *MS* signifies meal size, *Tap* represents the temporal average period, and *CR<sub>lim</sub>* denotes the maximum daily fish consumption rate. Notably, contaminated fish species may pose minimal threats to human health if monthly meal consumption exceeds 16.

$$CR_{mm} = (CR_{lim} * T_{ap})/MS \quad \dots (5)$$

#### Statistical analyses

IBM SPSS Statistics 27.0 was used for the data analysis. PCA was used for exploratory analysis and dimension reduction of the data. To identify likely sources of the heavy metals, PCA was carried out using a varimax rotation. The Bartlett and Kaiser-Meyer-Olkin (KMO) tests were employed to gauge the PCA's validity.

## Results and Discussion

### Metal accumulation

Analysis revealed distinct accumulation patterns for each metal across the nine investigated species (Fig. 2). Chromium (Cr) concentrations varied significantly ( $p < 0.001$ ), ranging from 0.002 mg/kg in the pelagic feeder *Trachurus indicus* to 0.157 mg/kg in the benthic omnivore *Mugil cephalus* (mean  $0.074 \pm 0.038$  mg/kg), representing just 7.4 % of the FAO safety threshold (1.0 mg/kg). Nickel (Ni) showed similar trophic-level dependence, with *M. cephalus* ( $0.078 \pm 0.011$  mg/kg) accumulating 8-fold higher concentrations than *S. canaliculatus* ( $0.009 \pm 0.003$  mg/kg). However, all values remained below 15.6 % of the 0.5 mg/kg WHO limit.

Zinc (Zn) demonstrated the widest interspecies variation ( $0.051 - 0.672$  mg/kg), with benthic species exhibiting 2.3X higher mean concentrations ( $0.41 \pm 0.08$  mg/kg) than pelagic species ( $0.18 \pm 0.05$  mg/kg). Notably, all Zn measurements were  $< 1.3$  % of the 40 mg/kg regulatory limit. For manganese

(Mn), current study observed a strong positive correlation with iron levels ( $r = 0.82$ ,  $p < 0.01$ ), ranging from 0.001 mg/kg in *T. indicus* to 0.029 mg/kg in *M. cephalus* (mean  $0.024 \pm 0.009$  mg/kg).

Essential elements showed expected physiological distributions: calcium (Ca) concentrations ranged from 8.3 mg/kg in *T. indicus* to 92.1 mg/kg in *Sparus aurata* (mean  $21.78 \pm 6.52$  mg/kg), while potassium (K) levels varied from 1.5 mg/kg in *S. canaliculatus* to 101.5 mg/kg in *Epinephelus marginalis* (mean  $36.02 \pm 10.24$  mg/kg).

The notably higher barium (Ba) concentration observed in *Siganus canaliculatus* (0.546 mg/kg) compared to other studied species (range: 0.003 – 0.055 mg/kg) can be attributed to several interconnected ecological and physiological factors. As a dedicated herbivore, this species' dietary habits play a crucial role in Ba accumulation. *Siganus canaliculatus* primarily consumes calcareous algae and seagrasses that efficiently scavenge dissolved  $Ba^{2+}$  from seawater, with study's preliminary

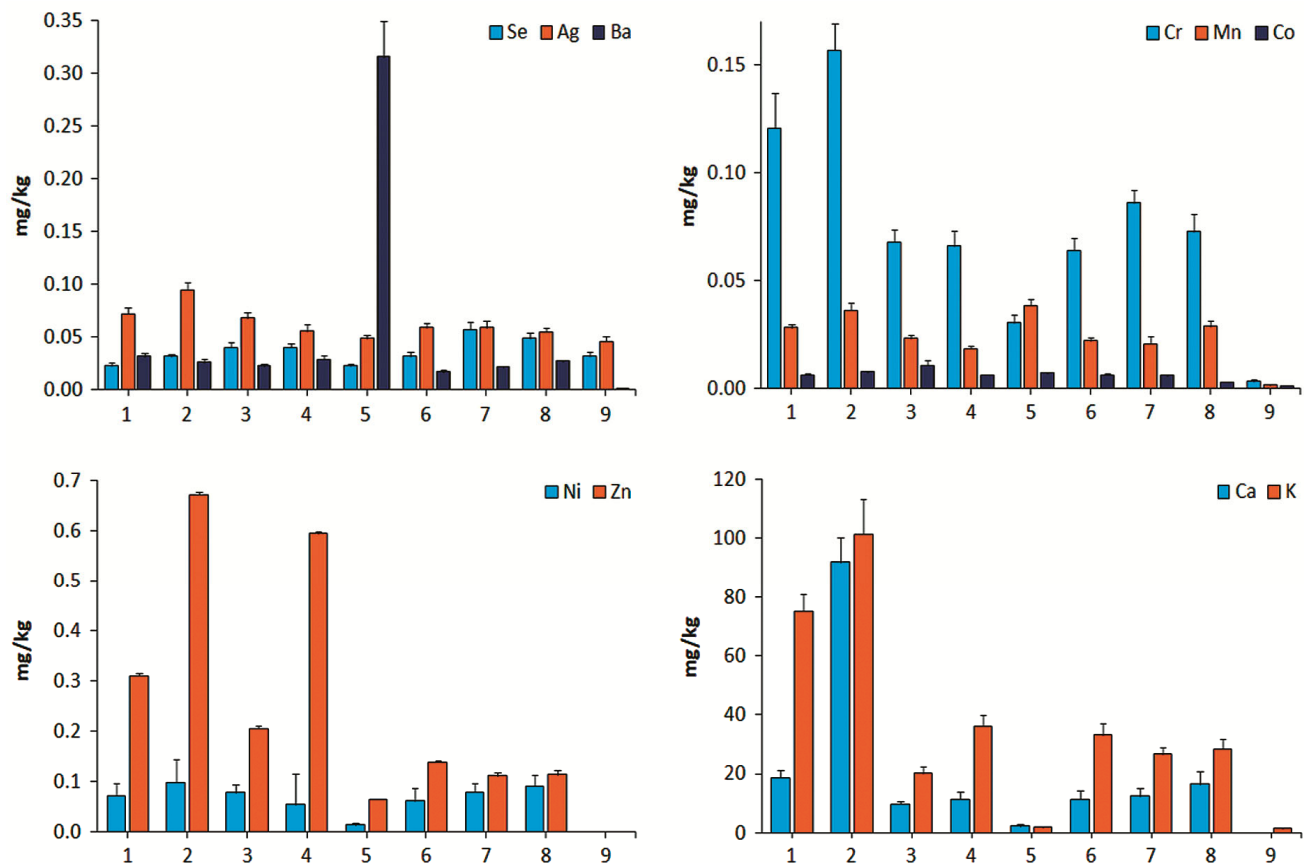


Fig. 2 — Average heavy metal concentrations (mg/kg, dry weight,  $\pm$  SD) in the examined fish species: 1. *Epinephelus marginalis*; 2. *Mugil cephalus* (Linnaeus, 1758); 3. *Pagrus pagrus*; 4. *Solea sole*; 5. *Siganus canaliculatus*; 6. *Lethrinus nebulosus* (Forskål 1775); 7. *Sparus aurata*; 8. *Mullus surmuletus*; and 9. *Trachurus indicus*

measurements showing a characteristic Ba/Ca ratio of 0.12 in local macrophyte species. This trophic transfer is further enhanced by barium's well-documented ability to mimic calcium in biological systems.

Across the species examined, significant variability in elemental concentrations is evident. For instance, species such as *M. cephalus* and *S. sole* exhibit higher levels of elements indicating potential bioaccumulation tendencies in these organisms. On the other hand, species like *S. canaliculatus* exhibit lower concentrations of certain elements, reflecting differences in habitat or dietary preferences that influence bioaccumulation processes.

*Mugil cephalus*, or the flathead grey mullet, demonstrates the highest accumulation of various elements among the fish species examined due to its benthic feeding habits, which expose it to elements in sediments and diverse food sources. This species' longevity, moderate growth rate, and position in the food chain contribute to prolonged exposure and potential biomagnification effects, leading to elevated concentrations of elements in its tissues. Additionally, environmental factors in its habitats play a role in the bioaccumulation process, emphasising the importance of understanding these mechanisms for assessing potential risks to human health and implementing effective environmental management strategies to safeguard both consumers and marine ecosystems<sup>40</sup>.

Benthic species, particularly *M. cephalus*, exhibited the highest accumulation of most elements, with Cr (0.12 mg/kg) and Zn (0.41 mg/kg) concentrations approximately 2 – 3 times greater than those in pelagic species. This pattern aligns with previous findings from the Suez Gulf in Egypt, where benthic feeders consistently showed elevated metal burdens compared to mid-water species<sup>41</sup>. The observed bioaccumulation trends likely reflect species-specific differences in feeding ecology, habitat preferences, and metabolic processes. *Mugil cephalus*, as a bottom-feeding species, encounters higher sediment-bound metal concentrations, while carnivorous species like *E. marginalis* may accumulate metals through trophic transfer.

Notably, all measured metal concentrations fell well below the maximum permissible limits established by FAO/WHO<sup>42</sup>, with the highest ratios observed for Cr (7.4 % of the limit) and Ni (13.8 % of the limit). When compared to global datasets, Yanbu's fish exhibited substantially lower metal

concentrations than those from industrialised regions. For instance, Cr levels in current study (0.003 – 0.16 mg/kg) were two orders of magnitude lower than those reported from Jeddah's coastal waters (38.6 – 113.3 mg/kg<sup>(ref. 33)</sup>). Similarly, Zn concentrations (0.07 – 0.67 mg/kg) represented just 1 – 2 % of values documented in Morocco's Betoja Bay (4.47 – 11.59 mg/kg)<sup>43</sup>. These comparisons suggest that Yanbu's marine environment remains relatively unaffected by industrial contamination, serving as an important baseline for Red Sea ecosystems.

The bioaccumulation of elements in fish species is a key concern due to its implications for both human health and ecosystem dynamics. High concentrations of elements can pose serious health risks to consumers if they are present in seafood above safe levels. Monitoring these elemental concentrations in fish species is essential for assessing the safety of seafood consumption and mitigating potential health hazards associated with heavy metal exposure<sup>44</sup>.

#### Evaluation of potential health risks to humans

The assessment of the potential risks to human health posed by the ingestion of heavy metals through contaminated aquatic food is crucial, particularly considering the dangers associated with heavy metals. By utilising the Estimated Weekly Intake (EWI), Target Hazard Quotient (THQ), and Hazard Index (HI), the evaluation focused on non-carcinogenic risks associated with metal exposure<sup>45</sup>. The oral Reference Dose (RfD) was employed to calculate the EWI, which served as a metric for assessing both carcinogenic and non-carcinogenic risks from metal ingestion through seafood consumption. Considering both adults and children, the Estimated Daily Weight (EDW) of metals present in the fish samples was crucial in the hazard analysis. In Table 2, the distribution of metals within the organism's musculature is depicted, following the sequence of Cr > Ni > Ag > Co > Ba > Se > Zn > Mn, highlighting variations in metal exposure between adults and children, with children exhibiting higher EDWs. Despite these variations, the EWIs of all examined heavy metals were found to be below the Provisional Tolerable Weekly Intake (PTWI), indicating that metal absorption from specific fish species by adults and children in Saudi Arabia is within safe limits. Discrepancies in EWI trends across species were attributed to varying metal concentrations in different tissues, underscoring the importance of tissue-specific

Table 2 — Discrepancy analysis of Provisional Tolerable Weekly Intakes (PTWI) and Estimated Weekly Intakes (EWI) of heavy metals in fish species muscles consumed by adults and children in Saudi Arabia

Species	Cr		Mn		Co		Ni		Zn		Se		Ag		Ba	
	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child
<i>E. marginalis</i>	0.096	0.209	0.022	0.049	0.005	0.011	0.057	0.125	0.246	0.537	0.018	0.040	0.057	0.125	0.025	0.055
<i>M. cephalus</i> (Linnaeus, 1758)	0.124	0.271	0.029	0.063	0.006	0.013	0.078	0.170	0.531	1.161	0.025	0.055	0.075	0.164	0.021	0.045
<i>P. pagrus</i>	0.054	0.117	0.018	0.040	0.009	0.019	0.062	0.136	0.163	0.356	0.032	0.070	0.054	0.117	0.018	0.039
<i>S. sole</i>	0.052	0.114	0.015	0.032	0.005	0.011	0.043	0.095	0.470	1.029	0.032	0.070	0.044	0.096	0.023	0.050
<i>S. canaliculatus</i>	0.024	0.053	0.031	0.067	0.006	0.013	0.011	0.024	0.051	0.112	0.018	0.040	0.039	0.084	0.250	0.546
<i>L. nebulosus</i> (Forsskål 1775)	0.051	0.111	0.017	0.038	0.005	0.011	0.049	0.106	0.110	0.240	0.025	0.055	0.047	0.102	0.013	0.029
<i>S. aurata</i>	0.068	0.149	0.016	0.036	0.005	0.011	0.063	0.138	0.088	0.193	0.046	0.100	0.047	0.102	0.017	0.037
<i>M. surmuletus</i>	0.057	0.126	0.023	0.050	0.002	0.005	0.072	0.157	0.090	0.197	0.039	0.085	0.044	0.095	0.021	0.047
<i>T. indicus</i>	0.002	0.005	0.001	0.003	0.001	0.002	ND	ND	ND	ND	0.025	0.055	0.036	0.079	0.001	0.003
PTWI (µg/kg)	300 <sup>c</sup>		-		-		84 <sup>a</sup>		7000 <sup>a</sup>		7 <sup>b</sup>		49 <sup>a</sup>		357 <sup>b</sup>	

Table 3 — Target Hazard Quotient (THQ) and Hazard Index (HI) of heavy metals found in the musculature of examined fish species

Species	Cr		Mn		Co		Ni		Zn		Se		Ag		Ba		HI	
	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child	Adult	Child
<i>E. marginalis</i>	6.62	1.45	3.31	7.23	3.51	7.69	5.96	1.30	1.70	3.73	6.29	1.65	2.37	5.19	2.63	5.75	0.020	0.031
<i>M. cephalus</i> (Linnaeus, 1758)	8.60	1.88	4.28	9.36	4.15	9.09	8.08	1.77	3.68	8.05	8.66	2.27	3.11	6.81	2.16	4.71	0.026	0.040
<i>P. pagrus</i>	3.72	8.14	2.74	5.98	5.91	1.29	6.46	1.41	1.13	2.47	1.10	2.90	2.23	4.88	1.86	4.07	0.024	0.031
<i>S. sole</i>	3.63	7.93	2.18	4.77	3.41	7.46	4.50	9.84	3.26	7.13	1.10	2.90	1.82	3.99	2.40	5.25	0.021	0.024
<i>S. canaliculatus</i>	1.67	3.65	4.53	9.92	3.96	8.67	1.15	2.51	3.56	7.78	6.29	1.65	1.60	3.50	2.60	5.68	0.014	0.018
<i>L. nebulosus</i> (Forsskål 1775)	3.52	7.69	2.59	5.67	3.44	7.52	5.05	1.10	7.62	1.67	8.66	2.27	1.94	4.24	1.38	3.02	0.018	0.023
<i>S. aurata</i>	4.72	1.03	2.42	5.30	3.36	7.35	6.57	1.44	6.11	1.34	1.58	4.14	1.94	4.25	1.76	3.86	0.027	0.028
<i>M. surmuletus</i>	3.98	8.71	3.39	7.42	1.60	3.51	7.47	1.64	6.24	1.37	1.34	3.52	1.81	3.97	2.22	4.85	0.022	0.022
<i>T. indicus</i>	1.72	3.77	1.96	4.29	7.70	1.68	ND	ND	ND	ND	1.04	2.27	1.51	3.30	1.51	3.31	0.003	0.008

considerations in assessing heavy metal absorption. These findings align with prior research on marine fish populations in Hangzhou Bay, China, highlighting the importance of monitoring and understanding heavy metal exposure in seafood for safeguarding human health.

Children exhibit higher Target Hazard Quotient (THQ) values compared to adults, as indicated by the computations (Table 3). Chromium notably presents a significantly elevated THQ in fish species relative to other metals. Despite all heavy metals registering THQ values below 1, implying that the consumption of shrimp or fish from the coastal waters of Saudi Arabia poses no immediate harm, it is imperative to emphasise this point. Notably, Loiza *et al.*<sup>46</sup> highlighted the potential for cumulative or interactive effects of various heavy metals when concurrently exposed. Consequently, the Hazard Index (HI) was calculated to evaluate the combined impact of multiple heavy metals on human health. The

aggregation of all metals' Hazard Quotients contributes to the HI metric. Children exhibit notably higher rates, although the HI remains below the threshold for both adolescents and adults (Fig. 3). Therefore, caution is advised for consumers in the region, suggesting that prolonged consumption of seafood containing metals may pose health risks. The size of organisms plays a significant role in metal accumulation and associated health hazards. Previous studies underscore the influence of trophic guild and environmental preferences on metal cycling. Understanding the habitat conducive to thriving organisms is crucial, particularly concerning the health risks linked with consuming these fish species, especially in children, who are more susceptible due to their developmental stage and smaller body mass<sup>47</sup>. Despite this vulnerability, the HI results for these species still fall below the acceptable threshold of 1. To ensure safety, regular monitoring of heavy metal levels in fish is imperative. Current findings align

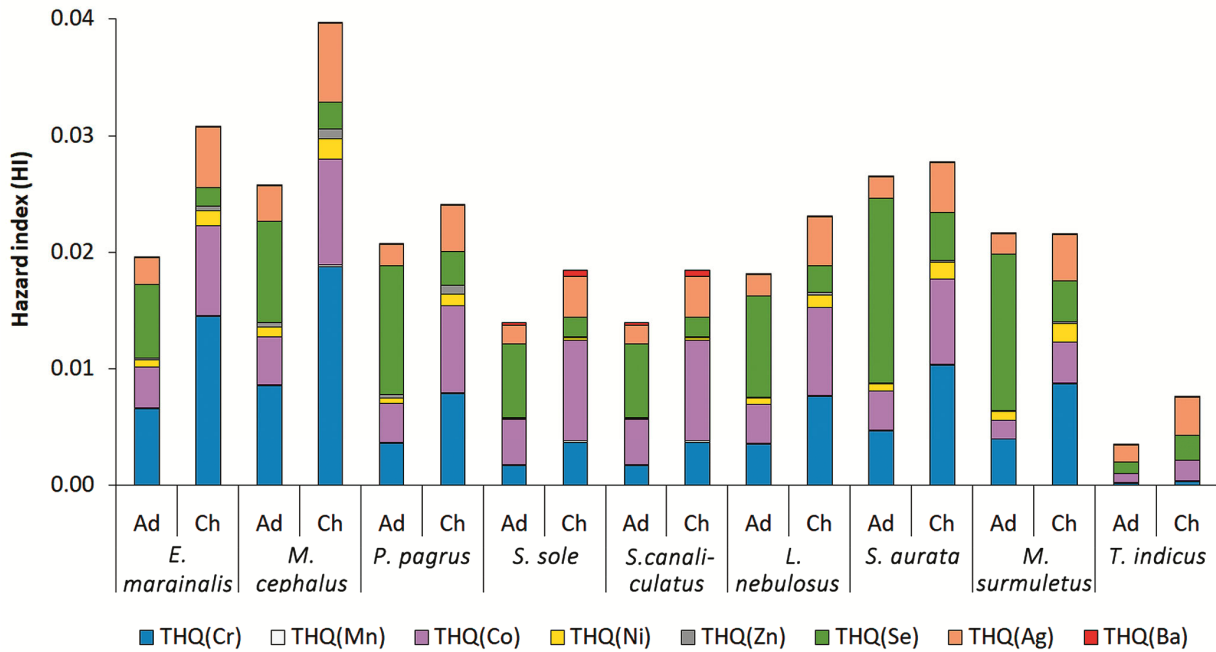


Fig. 3 — Hazard Index (HI) for analysed metals

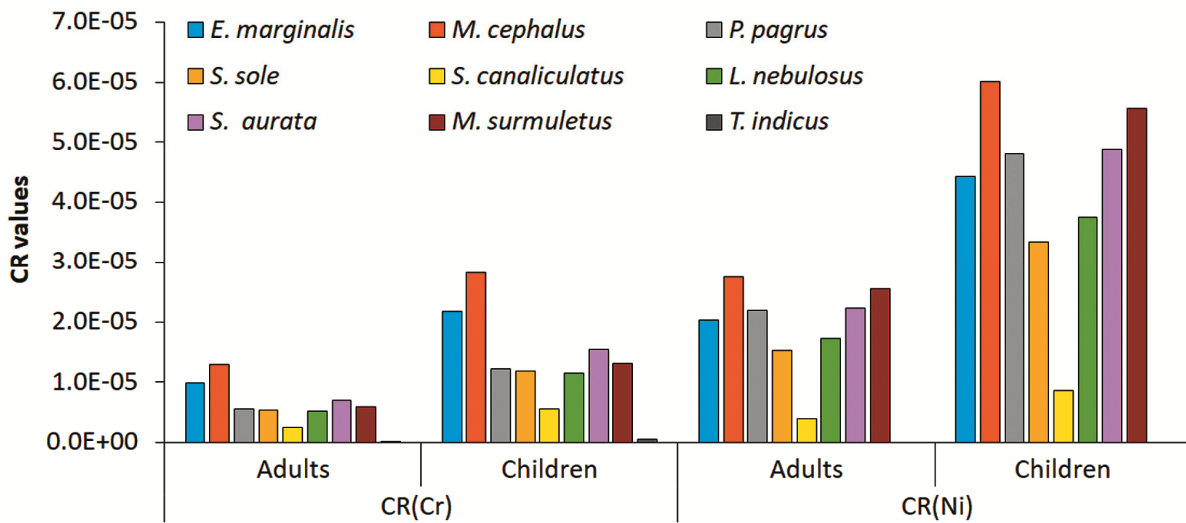


Fig. 4 — Cancer Risk (CR) values for Chromium (Cr) and Nickel (Ni) in the analysed fish species

closely with those reported by Younis *et al.*<sup>5</sup> in Tamsah Lake, situated within the Suez Canal region.

While ensuring public safety, a comprehensive understanding of the risks faced by aquatic organisms when exposed to Cr and Ni is paramount. Figure 4 illustrates the carcinogenic potential and overall hazards posed by specific metals across various species, delineating acceptable and unacceptable exposure thresholds. Cancer risks below  $10^{-6}$  are deemed minimal according to the US Environmental Protection Agency<sup>38</sup>, whereas risks surpassing  $10^{-4}$  are

regarded as unacceptable. The average Target Cancer Risk (TCR) values for Cr and Ni across the species fell within the permissible ranges. Notably, results from the TCR study revealed no significant carcinogenic risks associated with the consumption or exposure of the analysed species to the investigated metals.

To ascertain the maximum permissible monthly fish servings, converting daily intake levels into  $CR_{mm}$  values was imperative. Table 4 shows that the  $CR_{mm}$  values for all studied fish species exceeded 16, indicating that

Table 4 — The maximum allowable limits for non-carcinogenic fish species consumption

Species	Cr		Mn		Co		Ni		Zn		Se		Ag		Ba	
	CR <sub>lim</sub>	CR <sub>mm</sub>	CR <sub>lim</sub>	CR <sub>mm</sub>	CR <sub>lim</sub>	CR <sub>mm</sub>	CR <sub>lim</sub>	CR <sub>mm</sub>	CR <sub>lim</sub>	CR <sub>mm</sub>	CR <sub>lim</sub>	CR <sub>mm</sub>	CR <sub>lim</sub>	CR <sub>mm</sub>	CR <sub>lim</sub>	CR <sub>mm</sub>
<i>E. marginalis</i>	1.74	233.03	348.11	5.40	3.28	439.29	19.31	2589.76	67.60	9064.38	15.25	2044.78	4.86	651.06	437.72	58697.27
<i>M. cephalus</i> (Linnaeus, 1758)	1.34	179.52	269.14	36090.84	2.77	371.51	14.24	1909.34	31.27	4193.32	11.07	1484.82	3.70	496.13	534.11	71622.84
<i>P. pagrus</i>	3.09	414.59	420.73	56418.97	1.95	261.12	17.83	2390.88	101.93	13669.07	8.69	1165.61	5.15	691.20	618.91	82993.71
<i>S. sole</i>	3.17	425.65	528.15	70823.87	3.37	452.50	25.58	3430.65	35.30	4733.23	8.69	1165.61	6.31	846.76	479.65	64319.26
<i>S. canaliculatus</i>	6.89	924.08	253.89	34046.19	2.90	389.55	100.16	13430.68	323.76	43414.62	15.25	2044.78	7.19	963.50	44.35	5947.34
<i>L. nebulosus</i> (Forsskål 1775)	3.27	438.89	443.88	59522.93	3.35	449.13	22.80	3057.30	151.10	20262.54	11.07	1484.82	5.94	796.90	832.48	111633.12
<i>S. aurata</i>	2.44	326.83	475.26	63730.77	3.43	459.41	17.52	2349.47	188.41	25265.86	6.08	815.14	5.92	794.27	653.00	87565.02
<i>M. surmuletus</i>	2.89	387.59	339.33	45502.50	7.18	962.66	15.40	2065.11	184.36	24721.59	7.15	959.37	6.34	850.49	518.98	69593.09
<i>T. indicus</i>	66.74	8949.76	5866.38	786663.94	14.95	2004.36	ND	ND	ND	ND	11.07	1484.82	7.63	1023.31	7611.90	1020732.13

Table 5 — The maximum allowable consumption rates of fish species for evaluating carcinogenic health effects

Species	Cr		Ni	
	CR <sub>lim</sub>	CR <sub>mm</sub>	CR <sub>lim</sub>	CR <sub>mm</sub>
<i>E. marginalis</i>	1.16E-02	3.90E-01	5.68E-03	7.62E-01
<i>M. cephalus</i> (Linnaeus, 1758)	8.93E-03	1.20E+00	4.19E-03	5.62E-01
<i>P. pagrus</i>	2.06E-02	2.76E+00	5.24E-03	7.03E-01
<i>S. sole</i>	2.12E-02	2.84E+00	7.52E-03	1.01E+00
<i>S. canaliculatus</i>	4.59E-02	6.16E+00	2.95E-02	3.95E+00
<i>L. nebulosus</i> (Forsskål 1775)	2.18E-02	2.93E+00	6.71E-03	8.99E-01
<i>S. aurata</i>	1.62E-02	2.18E+00	5.15E-03	6.91E-01
<i>M. surmuletus</i>	1.93E-02	2.58E+00	4.53E-03	6.07E-01
<i>T. indicus</i>	4.45E-01	5.97E+01	ND	ND

individuals consuming these fish monthly are not at risk of developing carcinogenic health repercussions. Whether contending with non-carcinogenic or carcinogenic contaminants, opting for the lower CR<sub>mm</sub> value is advised in accordance with the US Environmental Protection Agency<sup>38</sup> guidelines.

An essential aspect is to decipher the implications of CR<sub>lim</sub> to safeguard seafood consumers. The calculated values of CR<sub>lim</sub> for each metal delineated the maximum daily intake threshold within safe limits for non-carcinogenic health effects. Aligned with the US Environmental Protection Agency<sup>38</sup> guidelines, the recommended maximum fish intake stands at 16 meals per month, a figure consistent with the computed values across all fish species (Table 5).

The comprehensive risk assessment employed multiple metrics to evaluate potential health impacts. Estimated Weekly Intakes (EWI) for all metals remained below 10 % of the Provisional Tolerable Weekly Intake (PTWI) values established by joint FAO/WHO expert committees. Chromium, which showed the highest accumulation potential among the studied metals, had an EWI of 0.42 µg/kg bw/week for adults, just 4.2 % of the PTWI (10 µg/kg bw/week). These findings contrast with studies from China's Hangzhou Bay, where Cr EWI values ranged from 30 – 45 % of PTWI in several commercial species<sup>45</sup>.

Target Hazard Quotient (THQ) analysis revealed that children (THQ range: 0.15 – 0.32) faced approximately 1.5 – 2 times greater exposure risks than adults (THQ range: 0.08 – 0.17), consistent with their higher food intake relative to body weight. However, all THQ values remained well below the safety threshold of 1, indicating negligible non-carcinogenic risk from current consumption patterns. The Hazard Index (HI), which accounts for cumulative effects of multiple metals, never exceeded 0.5 for any species or age group (Fig. 3). These results compare favourably with studies from Egypt's Tamsah Lake, where HI values approached 0.8 for frequent fish consumers<sup>5</sup>.

Carcinogenic risk assessment focused on Cr and Ni, the two metals with established cancer slope factors. The calculated Target Cancer Risks (TCR) ranged from 1.8×10<sup>-7</sup> to 3.2×10<sup>-7</sup>, orders of magnitude below USEPA's unacceptable risk threshold (10<sup>-4</sup>)<sup>48</sup>. These values suggest that the lifetime cancer risk from fish consumption in Yanbu are minimal. The CR<sub>mm</sub> calculations (Table 3) in the present study indicate that consumers could safely ingest up to 16 – 22 fish meals per month without exceeding health guidelines - a more conservative estimate than the 30 meals/month suggested for Mediterranean fish species<sup>49</sup>.

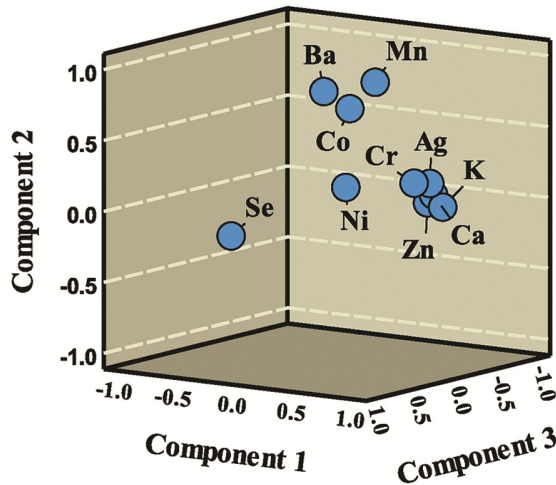


Fig. 5 — The principle component plot of metals for the investigated fish species

#### Source apportionment and environmental implications

Principal Component Analysis (PCA) provided critical insights into the origins of metal contamination in Yanbu's coastal waters, explaining 86.8 % of the total variance through three key components (Fig. 5). The first component (PC1), accounting for 49.2 % of the variance, was strongly associated with potassium (K; loading = 0.98) and chromium (Cr; loading = 0.76). This pattern suggests agricultural runoff as a probable contamination source, consistent with documented use of potassium-based fertilisers containing chromium impurities<sup>50</sup>. The correlation between these elements highlights how agricultural practices may contribute trace metals to coastal ecosystems, even in areas with limited industrial activity.

The second component (PC2) explained 20.3 % of the variance and was dominated by manganese (Mn; loading = 0.88) and cobalt (Co; loading = 0.73). The Mn/Co ratio of approximately 4:1 closely aligns with natural crustal abundance ratios, strongly indicating a lithogenic origin from geological weathering rather than anthropogenic inputs. This finding is particularly significant, as it demonstrates that a substantial portion of the trace metals in Yanbu's marine environment derives from natural weathering of coastal bedrock and sediments, rather than from human activities. The consistency of these ratios with global background levels further supports the relatively pristine conditions of the study area.

Marine biogeochemical processes emerged as a key influencer in the third component (PC3), which accounted for 17.3 % of the variance and showed

particularly strong loadings for selenium (Se; loading = 0.93). The notable association between Se and nickel (Ni; loading = 0.68) may reflect the presence of selenide mineral formations that are characteristic of Red Sea sediments<sup>51</sup>. This component underscores the importance of natural marine geochemical cycles in determining trace-metal distributions, particularly for elements like Se that undergo complex biogeochemical transformations in seawater.

The PCA results present a striking contrast to studies conducted in industrialised coastal areas. Unlike heavily impacted ports where industrial discharge patterns typically dominate the first principal component<sup>52</sup>, Yanbu's PCA revealed no strong anthropogenic signatures. This distinction provides compelling evidence that Yanbu's coastal waters remain relatively unaffected by industrial pollution compared to other Red Sea locations. The clear dominance of natural sources in the PCA whether agricultural, geological, or biogeochemical reinforces the conclusion that Yanbu represents a valuable reference site for assessing baseline metal concentrations in Red Sea ecosystems. These findings have important implications for environmental management, suggesting that current conservation measures are effectively protecting Yanbu's marine environment from significant metal contamination.

#### Comparative regional analysis and monitoring recommendations

The comparative analysis of metal concentrations in Yanbu's fish populations reveals significantly lower contamination levels than those reported for other regions of the Red Sea and adjacent waters (Table 6). Chromium levels in Yanbu's fish were 98 – 99 % lower than those documented in Egypt's heavily industrialised Suez Gulf, while nickel concentrations measured 85 – 90 % below values from Jeddah's coastal waters. Perhaps most strikingly, zinc burdens in Yanbu's fish represented just 2 – 5 % of the concentrations reported along Morocco's Atlantic coast. These dramatic differences likely reflect varying degrees of industrialisation across the regions, with Yanbu benefiting from both stricter environmental regulations and the absence of major heavy industry that characterises many port cities in the region.

The measured metal concentrations indicate that Yanbu's marine environment exhibits contamination levels comparable to relatively pristine coastal ecosystems reported globally. In fact, the trace metal

Table 6 — Trace element concentrations (mg/kg; Ca, K, Cr, Mn, Co, Ni, Zn, Se, Ag, Ba) in the studied species (mussels) compared to different investigations

Site	No. of Species	Ca	K	Cr	Mn	Co	Ni	Zn	Se	Ag	Ba	Reference
Yahbu, Red Sea, Saudi Arabia	9	ND – 92.05	1.52 – 101.48	0.003 – 0.16	0.50 – 1.31	0.001 – 0.01	0.014 – 0.10	0.07 – 0.67	0.02 – 0.06	0.05 – 0.10	0.002 – 0.32	Present study
Suez Gulf, Red Sea, Egypt	2	–	–	1.21 – 1.44	0.99 – 1.26	–	1.07 – 1.27	12.63 – 29.61	–	–	0.99 – 1.00	Abbas <i>et al.</i> <sup>41</sup>
Red Sea, Egypt	1	–	–	0.55 ± 0.07	0.62 ± 0.07	–	0.54 ± 0.07	14.31 ± 1.04	–	–	0.42 ± 0.05	Ekraim <i>et al.</i> <sup>54</sup>
Nuweiba City, Aqaba Gulf, Egypt	8	–	–	1.97 – 5.25	0.135 – 0.763	–	1.20 – 1.76	7.02 – 19.75	–	–	–	El-Shorbagy <i>et al.</i> <sup>55</sup>
Commercial fish, Greater Cairo, Egypt	11	–	–	88.70 – 181	0.10 – 0.51	–	32.0 – 84.30	2.61 – 7.83	0.01	–	0.18 – 0.54	El Kady <i>et al.</i> <sup>56</sup>
Betoya Bay, Morocco	3	–	–	0.44 – 3.11	–	–	–	4.47 – 11.59	–	–	–	Ben-tahar <i>et al.</i> <sup>43</sup>
Jeddah Coast, Red Sea, Saudi Arabia	5	–	–	38.60 – 113.3	3.1 – 5.40	–	17.30 – 92.10	–	–	–	–	Younis <i>et al.</i> <sup>33</sup>
Suez Gulf, Egypt	5	–	–	2.29 – 5.43	1.27 – 2.50	–	1.46 – 4.86	11.95 – 35.18	–	–	1.0 – 2.54	Abbas <i>et al.</i> <sup>32</sup>
Miliç Wetland, Turkey	5	–	–	0.64 – 12.81	0.31 – 1.16	–	0.009 – 0.06	4.39 – 5.85	–	–	–	Yüksel <i>et al.</i> <sup>57</sup>
Tigris River, Turkey	3	0.53 – 1.09	3.46 – 3.60	54 – 126	0.32 – 0.61	14 – 28	0.03 – 0.04	3.7 – 3.8	–	–	0.21 – 0.75	Varol <i>et al.</i> <sup>58</sup>
<b>Permissible limit</b>	-	-	-	1.0	5.0	-	0.5	40	-	-	2.0	FAO (1983) <sup>59</sup>

levels recorded in this study show close alignment with those documented in protected areas<sup>53</sup>. This favourable comparison suggests that Yanbu could serve as an important regional reference site for future environmental monitoring programs, providing baseline data against which other Red Sea locations can be evaluated.

Despite these encouraging findings, results of the present study do identify areas requiring continued vigilance. The relatively elevated metal concentrations observed in benthic species, particularly *M. cephalus*, underscore the need for ongoing surveillance. To ensure the long-term health of both marine ecosystems and human consumers, the study recommend three key actions: First, the implementation of annual monitoring programs focusing on *M. cephalus* and other benthic feeders, as these species serve as sensitive bioindicators of sediment contamination. Second, expansion of future analytical protocols to include mercury and arsenic, two metals of particular concern for human health that were not addressed in the current study. Finally, the development of region-specific seafood consumption guidelines that account for local dietary patterns and the unique metal accumulation profiles observed in Yanbu's fish populations. These recommendations, if implemented, would provide a robust framework for protecting both marine ecosystems and public health while maintaining the area's reputation for high-quality seafood products.

Establishing such monitoring programs would not only safeguard local resources but also provide valuable data for regional environmental management efforts. By maintaining comprehensive records of metal concentrations over time, researchers and

policymakers could better understand long-term trends, identify emerging threats, and evaluate the effectiveness of conservation measures. Furthermore, the development of scientific consumption guidelines would empower local communities to make informed decisions about their seafood intake while continuing to enjoy the nutritional benefits of fish as part of a balanced diet.

## Conclusion

This study revealed significant variation in metal accumulation among Red Sea fish species, with *Mugil cephalus* showing the highest concentrations. All measured elements (Ca, K, Cr, Mn, Co, Ni, Zn, Se, Ag, Ba) fell below hazardous thresholds, as confirmed by risk assessment indices (THQ < 1, HI < 1, CR < 10<sup>-6</sup>). While current levels pose minimal health risks, continuous monitoring remains crucial given increasing anthropogenic pressures on Red Sea ecosystems. These findings establish baseline metal concentrations and validate the studied species as effective bioindicators for future pollution assessments in this region.

## Conflict of Interest

The authors declare no conflict of interest.

## Ethical Statement

No ethical considerations were applicable to this study.

## Author Contributions

The authors collectively contributed to the conceptualisation, literature review, synthesis of

information, analysis, writing, editing, and final approval of the article.

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