BIOACCUMULATION OF HEAVY METALS IN COMMERCIALLY IMPORTANT MARINE FISH SPECIES FROM THE COASTAL WATERS OF GWADAR, BALOCHISTAN, PAKISTAN

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ABSTRACT

This study investigated the accumulation of cadmium (Cd), lead (Pb), copper (Cu), and chromium (Cr) in three commercially important fish species *Otolithes ruber*, *Rastrelliger kanagurta*, and *Epinephelus diacanthus* from the Gwadar coast, Pakistan. Fish tissues (gills, liver, and muscle) were digested using nitric-perchloric acid method and analyzed using Atomic Absorption Spectrophotometry techniques. Physicochemical parameters of seawater, including temperature, pH, salinity, dissolved oxygen, conductivity, and nutrient levels, were also estimated. Pb showed the highest accumulation across all species and tissues, followed by Cu and Cd, whereas Cr was below detection limits. *Epinephelus diacanthus* exhibited the greatest metal accumulation, particularly in liver and gills. Seawater conditions were within normal ranges, indicating a relatively healthy marine environment. Although metal levels were below FAO/WHO limits, Pb concentrations in edible tissues suggest the need for ongoing monitoring to minimize human health risks.

Keywords: Heavy metals, Gwadar coast, *Otolithes ruber*, *Rastrelliger kanagurta*, *Epinephelus diacanthus*, bioaccumulation.

INTRODUCTION

Heavy metals are considered hazardous environmental contaminants because of their severe toxicity, ability to remain in the environment for extended periods, and resistance to natural breakdown, making them a significant threat to the health and stability of marine ecosystems (Gao *et al*., 2025; Madadi *et al*., 2023). In recent years, rapid economic growth and industrialization have led to a steady release of heavy metal contaminants from human activities into the marine environment. These pollutants enter the ocean through various routes such as atmospheric deposition, surface runoff, and other transport mechanisms, causing significant harm to marine ecosystems (Avvari *et al*., 2022; Gao *et al*., 2025). A portion of the heavy metals discharged into the ocean engage in intricate physical and chemical interactions, leading to their adhesion to particles and subsequent deposition on the seabed. In contrast, other heavy metals are rapidly assimilated by marine organisms (Qiu *et al*., 2019). The processes of biological mineralization and the dynamic movement of water facilitate the reintroduction of heavy metals into the water column in a dissolved state. This phenomenon contributes to persistent contamination and presents ongoing threats to marine ecosystems and the organisms residing within them (Yue *et al*., 2024). Heavy metals enter the environment through both natural and human-related activities. Naturally, they are introduced by events such as volcanic eruptions and the breakdown of metal-rich rocks. Human activities, on the other hand, contribute significantly through processes like mining, metal smelting, industrial operations, fossil fuel combustion, and the use of phosphate-based fertilizers and metal-containing pesticides in agriculture (Ali and Khan, 2018). The most frequently encountered heavy metal and metalloid contaminants include chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As), with cadmium, lead, and mercury being of particular concern due to their high toxicity and significant health risks (Stankovic *et al*., 2014).

For centuries, marine fish and seafood have played a crucial role in providing a nutritious diet worldwide (Rajeshkumar *et al*., 2018). In many developing nations, coastal pollution has become a critical issue alongside efforts to improve livelihoods. This growing environmental threat has raised alarms among decision-makers, as traces of chemical contaminants are now detectable in nearly all food items. The swift pace of economic

development and booming population have significantly escalated the release of both organic and inorganic pollutants into aquatic ecosystems (Rajeshkumar *et al*., 2018). Understanding how heavy metals accumulate in fish is crucial for assessing the health risks associated with their consumption and for developing effective strategies to mitigate environmental pollution (Ali and Khan, 2018). Fish also serve as a pathway through which heavy metals are transferred to their consumers (Ali and Khan, 2018). Significant accumulation of heavy metals in fish can lead to toxic effects that harm their health (Li *et al*., 2015). Therefore, in addition to contaminating the human food chain, heavy metal pollution also has a detrimental impact on fish populations within aquatic ecosystems. Heavy metals have the potential to disrupt the chemical signaling processes in fish, thereby impairing their capacity to engage effectively with their surrounding environment (Ali and Khan, 2018). Heavy metal contamination can interfere with steroid hormone production in fish of both sexes, leading to decreased quality and quantity of gametes (Ebrahimi and Taherianfard, 2011). Heavy metals have been linked to deformities in fish observed both in natural habitats and laboratory studies. These abnormalities typically have adverse impacts on fish populations by reducing survival rates, inhibiting growth, affecting overall health, and altering physical appearance. As such, fish deformities can serve as valuable indicators or biomarkers of heavy metal contamination in the aquatic environment (Sfakianakis *et al*., 2015). Fish are recognized as an essential element of the human diet, primarily due to their abundant supply of high-quality proteins and essential unsaturated fatty acids, which are critical for sustaining human health. Nevertheless, the presence of toxic heavy metals in fish can render their consumption a major pathway for exposure to these hazardous substances, consequently presenting substantial health risks to consumers (Ali and Khan, 2018). Heavy metals can enter a fish's body either directly from the surrounding environment, such as water or sediments, through absorption via the gills or skin, or indirectly through the ingestion of contaminated food or prey via the digestive system. The term "bioaccumulation" in fish refers to the buildup of these contaminants originating from both environmental sources and dietary intake (Ali and Khan, 2018).

The intake of toxic metals by humans can occur when fish are eaten that have absorbed these elements from the aquatic food chain. Because many of these metals are highly resistant to microbial breakdown, they tend to accumulate progressively in marine and freshwater environments, leading to increased concentrations over time (Rani *et al*., 2021). In this context, fish and other aquatic organisms are often utilized as biological indicators, as they tend to absorb and retain heavy metals within different tissues and organs, reflecting the level of environmental contamination (Baki *et al*., 2018). In contrast, fish and other aquatic organisms residing in diverse ecosystems can directly absorb pollutants from their environment. This exposure can lead to increased mortality rates, developmental abnormalities, and, in some cases, the complete eradication of specific fish populations (Rakib *et al*., 2022).

Several studies have investigated the accumulation of heavy metals in aquatic environments in Pakistan (Ahmad *et al*., 2025; Aslam *et al*., 2020; Rind *et al*., 2024; Siddiqui and Saher, 2025). No comprehensive study has been conducted to assess the accumulation of toxic metals in *Otolithes ruber, Rastrelliger kanagurta* and *Epinephelus diacanthus* and their environment in the Gwadar region. Therefore, the present study was designed to fill this knowledge gap with the following objectives: (i) to quantitatively analyze the concentrations of hazardous heavy metals—Cadmium (Cd), Copper (Cu), Chromium (Cr), and Lead (Pb) in key commercial fish species, namely *Otolithes ruber* , *Rastrelliger kanagurta*, and *Epinephelus diacanthus*; (ii) to assess the levels of metal pollutants in nearshore and offshore waters; and (iii) to evaluate the physico-chemical properties of seawater at the sampling sites.

MATERIALS AND METHODS

STUDY AREA

This study was conducted along the Gwadar coast (25°13'06.5"N, 62°44'36.3"E) in Balochistan, Pakistan (Fig.1).

FISH SAMPLING

Fish specimens were collected from local coastal waters between May 2020 and February 2021 with the assistance of experienced local fishermen. Post-capture, the fish were placed in plastic bags and stored in ice boxes to maintain freshness. Three commercially important marine fish species were selected based on their high local consumption, ecological importance, and year-round availability in the Gwadar coastal fishery. These species represent different ecological niches and feeding habits, making them suitable for assessing heavy metal bioaccumulation in edible marine fishes. A total of eight individuals (n = 8) of each species were analyzed. The sample size was determined based on specimen availability during the sampling period. Upon arrival at the laboratory, all specimens were rinsed with freshwater to remove debris and external contaminants. Samples were

then transferred to refrigeration until further analysis. Species identification was conducted based on morphological characteristics, using scientific, local, and English names following the FAO Fish-Finder pocket guide. Total length (cm) was measured using a standard measuring scale, while body weight (g) was recorded using a calibrated digital balance.

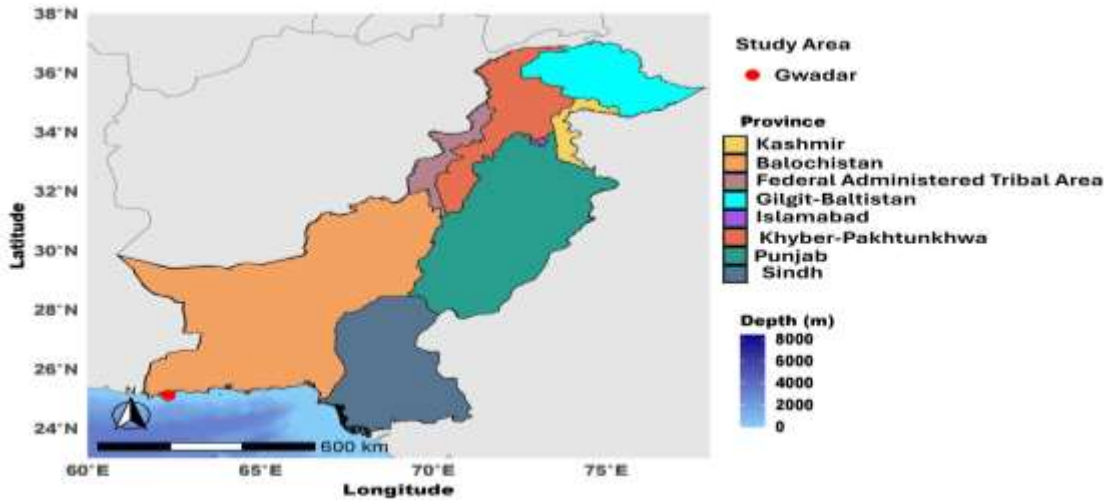

Fig. 1. Study area map with sampling site marked as red circle.

TISSUE PREPARATION AND STORAGE

All dissection tools and glassware were pre-treated with 20% hydrochloric acid and rinsed four times with deionized water to minimize contamination risk. Dissections were performed using stainless steel instruments. Approximately 1 gram of each tissue (gill, muscle, and liver) was excised and placed in labeled zip-lock bags. Samples were stored at −20 °C until further processing for heavy metal analysis.

ACID DIGESTION PROCEDURE

Tissue digestion was performed using the nitric-perchloric acid digestion method recommended by AOAC (1990). One gram of tissue sample was transferred into a 250 mL glass beaker, followed by the addition of 10 ml concentrated nitric acid (HNO_3). The mixture was heated on a hot plate at 100–120 °C for 40–45 minutes until complete oxidation. After cooling, 5 mL of 70% perchloric acid ($HClO_4$) was added dropwise, producing dense white fumes. The mixture was reheated, cooled again, and diluted with 10 mL deionized water. After a final heating phase of 10 minutes, the solution was cooled and filtered through Whatman filter paper. The filtrate was diluted to 50 mL with deionized water and stored in sterilized, labeled bottles for metal analysis. Heavy metal concentrations were determined using an Atomic Absorption Spectrophotometer (AAS) at the Centralized Scientific Laboratory, Department of Zoology, University of Karachi. Quality assurance and quality control (QA/QC) procedures were applied throughout the analytical process to minimize contamination and ensure data reliability. All glassware and laboratory equipment were acid-washed and thoroughly rinsed with deionized water prior to use. Instrument calibration was performed using standard solutions before sample analysis.

PHYSICO-CHEMICAL PROPERTIES OF SEAWATER

Key physicochemical parameters of seawater, including temperature, pH, total dissolved solids (TDS), electrical conductivity, and dissolved oxygen (DO), were measured in situ. Temperature and DO were recorded using an EZDO 7031 DO/temperature meter, while pH was measured with a Hanna HI98107 digital pH meter. TDS was quantified using a TDS meter, and conductivity was measured using a conductivity meter. For nutrient analysis, including ammonia (NH_3), nitrite (NO_2^-), nitrate (NO_3^-), and phosphate (PO_4^{3-}), water samples were collected in triplicate in pre-washed plastic bottles and tested immediately using the Nutrafin Master Test Kit.

STATISTICAL ANALYSIS

All statistical analyses and data visualizations were performed using R software (version 4.5.2; R Core Team, Vienna, Austria). Descriptive statistics are presented as mean ± standard deviation (SD). Data analysis was

performed using the dplyr and tidyr packages, while graphical visualizations were generated using the ggplot2 package.

RESULTS

The body length and weight of the three selected fish species collected from the coastline of Balochistan were recorded as follows: *Epinephelus diacanthus* ranged from 25.4 to 30.5 cm and 241 to 396 g, *Rastrelliger kanagurta* ranged from 15.2 to 25.4 cm and 54 to 184 g, and *Otolithes ruber* ranged from 30.5 to 40.6 cm and 343 to 761 g (Table 1 and Fig. 2).

Table 1. Morphometric Measurements of Selected Fish Species.

Species	N	Length (cm) (Min–Max, Mean ± SD)	Weight (g) (Min–Max, Mean ± SD)
Epinephelus diacanthus	8	25.4–30.5 (28.1 ± 1.72)	241–396 (335 ± 54.1)
Otolithes ruber	8	27.9–40.6 (34.9 ± 4.65)	343–761 (517 ± 160)
Rastrelliger kanagurta	8	15.2–25.4 (19.7 ± 3.78)	54–184 (91.6 ± 41.2)

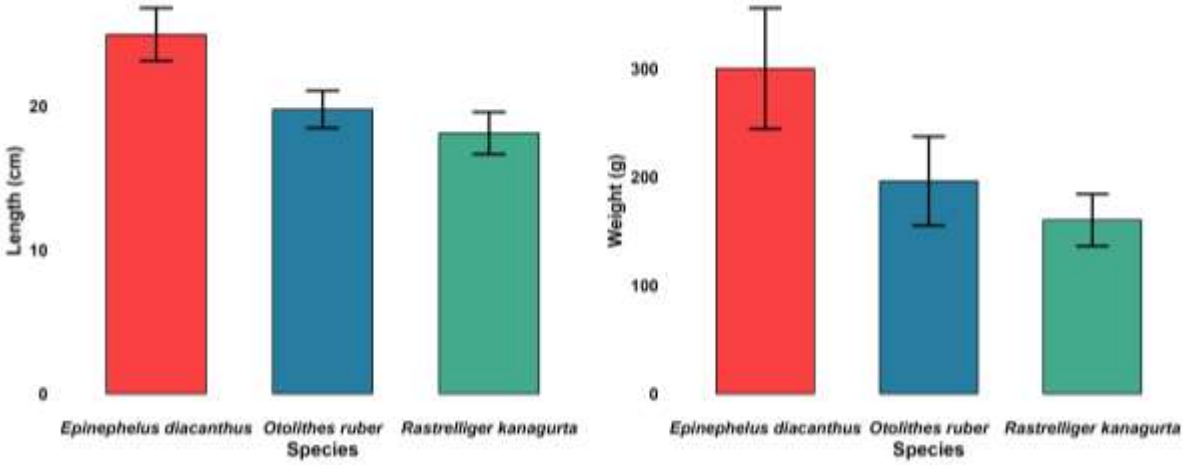

Fig. 2. Comparison of mean total length (cm) and body weight (g) ± standard deviation (SD) among three fish species: *Epinephelus diacanthus*, *Otolithes ruber*, and *Rastrelliger* kanagurta. Bar heights represent species-specific mean values, and error bars indicate standard deviation.

HEAVY METAL CONCENTRATIONS IN FISH TISSUES

The concentrations of cadmium (Cd), lead (Pb), copper (Cu), and chromium (Cr) were measured in the flesh, liver, and gills of three commercially important marine fish species: *Rastrelliger kanagurta (*Indian mackerel), *Epinephelus diacanthus* (Spinycheek grouper), and *Otolithes ruber* (Tigertooth croaker). Chromium (Cr) was below the limit of detection (LOD) in all samples across all tissues.

In *Rastrelliger kanagurta*, lead (Pb) levels were highest in the gills (0.34 ± 0.09 µg/g), followed by the liver (0.30 ± 0.07 µg/g) and flesh (0.19 ± 0.12 µg/g). Copper (Cu) concentrations were moderate, with the highest level in the liver (0.07 ± 0.04 µg/g), followed by gills (0.05 ± 0.02 µg/g) and flesh (0.03 ± 0.03 µg/g). Cadmium (Cd) was below detection limits in the flesh and gills but was recorded in the liver (0.01 ± 0.03 µg/g). Chromium (Cr) was below detection limits in all tissues (Table 2 and Fig. 3).

In *Epinephelus diacanthus*, Pb concentrations were highest in the gills (0.34 ± 0.11 µg/g), followed by the flesh (0.17 ± 0.13 µg/g) and liver (0.23 ± 0.10 µg/g). Cu levels were highest in the liver (0.36 ± 0.18 µg/g), followed by gills (0.15 ± 0.05 µg/g) and flesh (0.08 ± 0.04 µg/g). Cd was present in all tissues, with the highest concentration in the liver (0.06 ± 0.02 µg/g), and equal levels (0.03 µg/g) in both gills and flesh. Cr was below detection limits in all tissues (Table 2 and Fig. 3).

In *Otolithes ruber*, Pb levels were highest in the gills (0.36 ± 0.06 µg/g), followed by the liver (0.35 ± 0.11 µg/g) and flesh (0.23 ± 0.15 µg/g). Cu concentrations were moderate, highest in the liver (0.08 ± 0.08 µg/g), followed by the gills (0.03 ± 0.05 µg/g) and flesh (0.02 ± 0.03 µg/g). Cd and Cr both were not detected in any tissue (Table 2 and Fig. 3).

Overall, *Epinephelus diacanthus* exhibited the highest accumulation of heavy metals, particularly Cu and Cd, followed by *Rastrelliger kanagurta* and *Otolithes ruber*.

Table 2. Concentrations of heavy metals (Cd, Pb, Cu, and Cr) in different organs (flesh, liver, and gills) of selected fish species, expressed in micrograms per gram (µg/g). Values are presented as mean ± standard deviation. "LOD" indicates concentrations below the limit of detection.

Species (Scientific Name)	Tissue	Cd (µg/g)	Pb (µg/g)	Cu (µg/g)	Cr (µg/g)
Rastrelliger kanagurta	Flesh	LOD	0.19 ± 0.12	0.03 ± 0.03	LOD
	Liver	0.01 ± 0.03	0.30 ±0.07	0.07 ± 0.04	LOD
	Gills	LOD	0.34 ± 0.09	0.05 ± 0.02	LOD
Epinephelus diacanthus	Flesh	0.03 ± 0.03	0.17 ± 0.13	0.08 ± 0.04	LOD
	Liver	0.06 ± 0.02	0.23 ± 0.10	0.36 ± 0.18	LOD
	Gills	0.03 ± 0.01	0.34 ± 0.11	0.15 ± 0.05	LOD
Otolithes ruber	Flesh	LOD	0.23 ± 0.15	0.02 ± 0.03	LOD
	Liver	LOD	0.35 ± 0.11	0.08 ± 0.08	LOD
	Gills	LOD	0.36 ± 0.06	0.03 ± 0.05	LOD

PHYSICO-CHEMICAL PARAMETERS OF SEAWATER

The physio-chemical characteristics of seawater were analyzed from three sampling stations, and the results are summarized in Table 3. The temperature ranged from 22.43°C to 29.67°C, with a mean value of 26.08 ± 0.99°C. The pH values varied between 7.10 and 7.87, averaging 7.77 ± 0.03. Salinity was relatively stable, ranging from 36.30 to 36.50‰, with a mean of 36.41 ± 0.21‰. Conductivity ranged from 55.28 to 55.73 mS/cm, with an average of 55.46 ± 0.61 mS/cm. For nutrient concentrations, ammonia (NH_3) levels ranged from 0.76 to 0.90 µM/L (mean 0.82 ± 0.08 µM/L), phosphate (PO_4^{3-}) ranged from 0.79 to 0.85 µM/L (mean 0.83 ± 0.05 µM/L), nitrite (NO_2^-) ranged from 0.43 to 0.47 µM/L (mean 0.43 ± 0.07 µM/L), and nitrate (NO_3^-) varied between 2.76 and 4.50 µM/L, with a mean concentration of 3.58 ± 0.70 µM/L (Fig. 4).

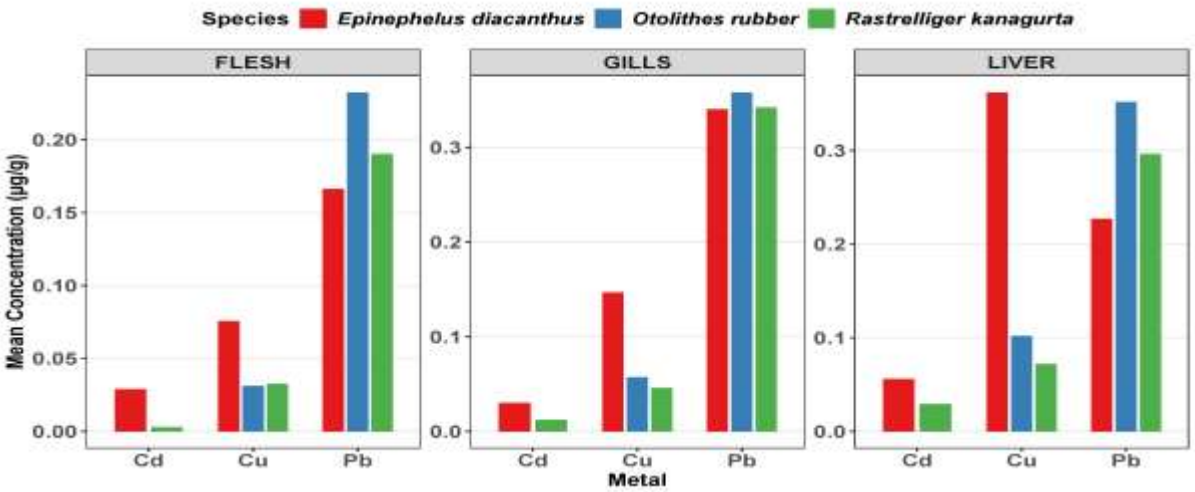

Fig. 3. Concentration (µg/g) of heavy metals (Cd, Pb, Cu) in different tissues (Flesh, Liver, Gills) of three fish species: (A) *Rastrelliger kanagurta*, (B) *Epinephelus diacanthus*, and (C) *Otolithes ruber*. Lead (Pb) shows the highest accumulation across all species and tissues, followed by Copper (Cu) and Cadmium (Cd). Values below the LOD (Limit of Detection) are considered not detected.

Table 3. Summary of physico-chemical parameters of seawater from the sampling sites. Values represent the minimum, maximum, and mean ± standard deviation (SD) for each parameter measured during the study period.

Parameter	Minimum	Maximum	Mean ± SD
Temperature (°C)	22.43	29.67	26.08 ± 0.99
pH	7.10	7.87	7.77 ± 0.03
Dissolved Oxygen (mg/L)	6.20	6.51	6.37 ± 0.15
Salinity (‰)	36.30	36.50	36.41 ± 0.21
Conductivity (mS/cm)	55.28	55.73	55.46 ± 0.61
Ammonia (NH_3, µM/L)	0.76	0.90	0.82 ± 0.08
Phosphate (PO_4^{3-}, µM/L)	0.79	0.85	0.83 ± 0.05
Nitrite (NO_2^-, µM/L)	0.40	0.47	0.43 ± 0.07
Nitrate (NO_3^-, µM/L)	2.76	4.50	3.58 ± 0.43

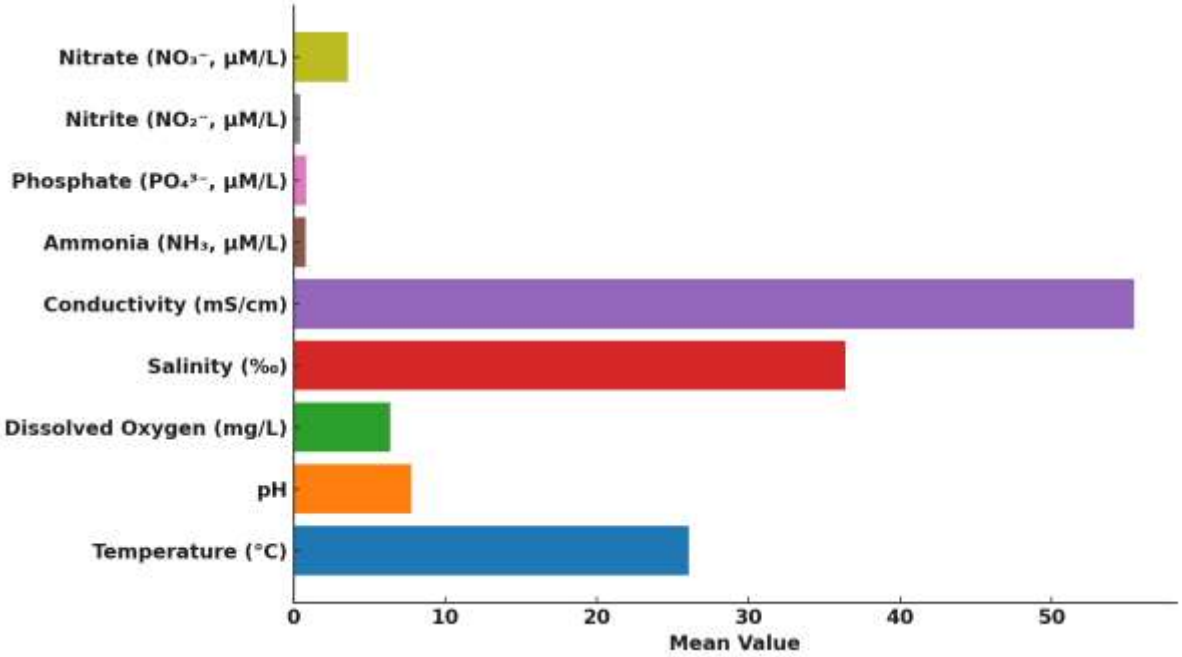

Fig. 4. Mean values of selected physicochemical parameters studied area.

DISCUSSION

The quality of water and sediments in marine ecosystems is influenced by heavy metal contamination and physicochemical parameters such as pH, temperature, conductivity, dissolved oxygen (DO), and total dissolved solids (Clottey, 2018). These factors are crucial for maintaining ecosystem health and sustaining fisheries. Temperature plays a key role in aquatic systems by regulating oxygen solubility, water density, and biochemical processes, thereby influencing the growth and distribution of organisms (Wetzel, 2001). The present study recorded temperature variations consistent with warm seas, suggesting that the Gwadar Coast provides favorable conditions for fish growth.

Seawater pH is an important indicator of environmental health, with lower pH values reflecting higher acidity. Anthropogenic activities and nutrient enrichment can accelerate coastal acidification, reducing carbonate availability and impairing shell and skeleton formation in marine organisms (Mai and Chen, 2024). In the current study, pH ranged from 7.1 to 7.8, which is comparable to earlier reports from the Balochistan coast i.e. 7.08–8.95 (Elahi *et al*., 2015), suggesting only minor increases in pollution levels in the study area.

Dissolved oxygen is a reliable measure of organic pollution and the self-purification capacity of aquatic systems (Camargo and Alonso, 2006). DO levels in this study (6.2–6.55 mg/L) fall within the EPA-recommended limits of 6–8 mg/L (EPA, 2002), indicating favorable conditions for fish survival. Salinity, another ecological determinant, was slightly lower than previous records for the Balochistan coast (Elahi *et al*., 2015). Conductivity, which reflects the concentration of dissolved minerals, also indicated moderate conditions.

Nutrients such as phosphates and nitrates strongly influence primary production and fish population dynamics. While phosphates enhance plankton growth and food availability, excessive enrichment can lead to eutrophication, threatening aquatic life (Rice *et al*., 2012). The present study observed phosphate levels that were slightly higher than those reported by Karl and Björkman (2015), likely due to localized nutrient inputs. Nitrate concentrations can indirectly support fish growth; however, uncontrolled algal blooms may reduce oxygen levels, causing fish mortality (Camargo and Alonso, 2006).

HEAVY METALS IN FISH

Fish represent a critical source of protein for coastal communities in the Makran Division. However, heavy metal accumulation in edible fish poses significant ecological and health risks (Dural *et al*., 2007; Jaishankar *et al*., 2014). In this study, cadmium (Cd), copper (Cu), lead (Pb), and chromium (Cr) were analyzed in the gills, liver, and muscles of three commercially important species: Tigertooth croaker (*Otolithes ruber*), Indian mackerel (*Rastrelliger kanagurta*), and Spinycheek grouper (*Epinephelus diacanthus*).

Metal concentrations varied among species and organs, with the liver showing the highest accumulation, followed by gills and muscles (Table 2). This distribution aligns with earlier findings indicating that the liver, due to its central role in metabolism, tends to accumulate higher metal concentrations (Al-Ghanim *et al*., 2015). Among the species studied, *E. diacanthus* exhibited the highest overall metal concentrations, followed by *R. kanagurta*, while *O. ruber* showed the lowest levels.

Pb and Cd were the most abundant toxic metals, particularly in the liver and gills, while Cr was more prominent in the muscles, although within permissible limits. These patterns are consistent with reports highlighting the role of gills as the primary site of metal entry and the tendency of muscles to accumulate relatively lower concentrations due to lower metabolic activity (Yılmaz *et al*., 2010).

When comparing species, demersal fish (*E. diacanthus*) exhibited higher levels of metal accumulation compared to bentho-pelagic (*O. ruber*) and epipelagic (*R. kanagurta*) species. This pattern supports the view that demersal fish, due to their benthic feeding strategies and direct exposure to sediment-associated metals, are more prone to heavy metal accumulation (Anandkumar *et al*., 2018). However, some studies contradict this generalization, reporting low metal loads in benthic species (Bustamante *et al*., 2003; Zhao *et al*., 2012).

Inter-species and intra-species differences were evident, with metal concentrations varying across species and sampling sites. The decreasing order of metal concentration in the studied species was Pb > Cu > Cd > Cr. Pb, categorized as a Group 2 human carcinogen by IARC (2012), was consistently the most abundant element across organs and species. Although concentrations of all metals remained below FAO/WHO (2018) permissible limits, Pb levels approached critical thresholds (0.24–0.31 mg/kg, against a limit of 0.5 mg/kg) (Table 4), warranting continued monitoring.

Comparisons with national and international studies revealed that metal concentrations in Balochistan's fish species are broadly similar to, or in some cases lower than, those reported elsewhere (Table 4) (Baloch *et al*., 2018; El-Moselhy *et al*., 2014).

Nonetheless, the presence of Pb and Cd in edible tissues highlights emerging risks to food safety and public health.

Lead (Pb) accumulation in edible fish tissues represents an important environmental and public health concern because seafood consumption is a major pathway of human exposure to this toxic metal. Although Pb concentrations detected in the present study were within the permissible limits established by FAO/WHO, continuous consumption of Pb-containing fish may contribute to chronic exposure due to the persistence, toxicity, and bioaccumulative nature of Pb (Nag *et al*., 2022). Following absorption, Pb can accumulate in soft tissues and bones, where it induces toxicity through reactive oxygen species (ROS) generation, oxidative stress, lipid peroxidation, and disruption of antioxidant defense mechanisms (Engwa *et al*., 2019; Flora, 2011). Long-term Pb exposure has been associated with neurological impairment, developmental disorders, renal dysfunction, cardiovascular diseases, hematological abnormalities, and reproductive problems (Tchounwou *et al*., 2012; Pourrut *et al*., 2011). Therefore, continuous monitoring of Pb levels in commercially important fish species is essential to ensure seafood safety and minimize potential health risks for coastal communities dependent on fish consumption.

Table 4. Comparison of mean concentrations of heavy metals (Cd, Pb, Cu, Cr; µg/g) in the tissues of *Otolithes ruber*, *Rastrelliger kanagurta*, and *Epinephelus diacanthus* from the Gwadar coast with values reported in previous regional and international studies.

Species	Cd	Pb	Cu	Cr	Study area	Source
Rastrelliger kanagurta	-0.002 ± 0.002	0.28 ± 0.01	0.05 ± 0.002	-2.87 ± 0.03	Pakistan, Gwadar Balochistan	This study.
Rastrelliger kanagurta	1.03 ± 0.46	0.82 ± 0.19	_	0.15 ± 0.15	India, Andhra Pradesh,	(Chaitanya *et al*., 2017)
Rastrelliger kanagurta	6.88 ± 0.34	11.6 ± 0.77	6.20 ± 0.24	3.44 ± 0.18	Kerala, fish market, Palakkad,	(Rini *et al*., 2020)
Rastrelliger kanagurta	_	2.554 ± 0.53	1.27 ± 0.42	0.27 ± 0.07	India, Visakhapatnam	(Bhavani *et al*., 2016)
Epinephelus diacanthus	0.04 ± 0.01	0.25 ± 0.01	0.19 ± 0.01	-1.42 ± 0.03	Pakistan, Gwadar Balochistan	This study
Epinephelus diacanthus	0.97 ± 0.78	0.49 ± 0.16	45.12 ± 28.84	26.53 ± 5.27	Red Sea, Egypt	(Al-Ghanim *et al*., 2015)
Epinephelus diacanthus	3.92 ± 0.90	2.94 ± 0.19	0.58 ± 0.17	_	Red Sea, Egypt	(El-Moselhy *et al*., 2014)
Epinephelus diacanthus	_	ND	0.84 ± 0.23	0.74 ± 0.08	India, west coast	(Molla *et al*., 2021)
Otolithes ruber	-0.04 ± 0.004	0.31±0.01	0.04 ± 0.004	-0.04 ± 0.022	Pakistan, Gwadar Balochistan	This study
Otolithes ruber	0.46 ± 0.06	0.02 ± 0.01	0.33 ± 1.14	_	Pakistan, Sonmiani, Balochistan	(Baloch *et al*., 2018)
Otolithes ruber	0.0064 ± 0.0017	0.014 ± 0.0025	_	0.146 ± 0.0052	Iran, Persian Gulf	(Norouzi, 2020)
Otolithes ruber	0.3	1.6	12	_	Sarawak, Malaysia	(Anandkumar *et al*., 2018)

CONCLUSION

This study demonstrates that the physicochemical properties of seawater along the Balochistan coast remain within acceptable limits (EPA, 2002), suggesting minimal immediate impact on fish growth and development. However, heavy metals (Cd, Pb, Cu, Cr) were detected in all examined tissues of *O. ruber*, *R. kanagurta*, and *E. diacanthus*. Although concentrations were below FAO/WHO (2018) permissible limits (Table 5), the relatively high Pb levels across species suggest increasing anthropogenic pressure on the marine environment.

Table 5. Comparison of mean concentrations of heavy metals (Cd, Pb, Cu, Cr; µg/g) in the tissues of the studied fish species with the maximum permissible limits established by FAO/WHO (2018) guidelines for human consumption. Values represented as "LOD" indicate concentrations below the limit of detection.

Heavy Metals	*Epinephelus diacanthus*	*Rastrelliger kanagurta*	*Otolithes ruber*	(FAO and WHO, (2018) Limits (µg/g)
Cadmium	0.04	LOD	LO	2
Lead	0.24	0.28	0.31	0.5
Copper	0.19	0.05	0.04	10
Chromium	LOD	LOD	LOD	1

RECOMMENDATIONS

- Continuous monitoring of heavy metals in Balochistan's coastal waters is essential to minimize human exposure through seafood consumption.
- Industrial and municipal waste discharge should be strictly regulated, as heavy metals are non-biodegradable and bioaccumulative.
- Overfishing and destructive trawling practices should be curtailed to protect fish stocks and livelihoods.
- Fisheries authorities should allocate resources for long-term pollutant surveillance programs to safeguard ecosystem health and food security.

AUTHORS CONTRIBUTIONS

Gulafroz Saeed: Writing–original draft, Writing–review and editing, Methodology, Data collection, Formal analysis.
Kareem Gabool: Supervision, Validation, Writing–review and editing and approval of the final manuscript.
Samroz Majeed: Writing–original draft, Writing–review and editing, Visualization, Software, Data curation.
Amjad Ali: Contributed to Data interpretation, Critical feedback, and editing of the manuscript.
Seema Shafique: Facilitated laboratory resources, technical guidance, and project support.

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DATA AVAILABILITY

The data used in this study are available from the corresponding author upon reasonable request.

ETHICAL APPROVAL

Not applicable.

COMPETING INTERESTS

The authors declare no competing interests.

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