Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(3): 1629 – 1657 (2025)
www.ejabf.journals.ekb.eg

Evaluation of Heavy Metal Concentration and Health Risk Assessment in some Marine Fish Species from Zwitina Harbor Coast (Libya), as Indicator of Petroleum Pollution

Mohamed H. Bahnasawy [1], Mohammed Ali Zeyadah[2], Mona Nawareg [1], Ahmed M. Deedah[3] Hamad M. Adress[4] and Doaa A. El-Emam[2*]

[1]Zoology Department, Faculty of Science, Demietta University, Damietta, Egypt
[2]Environmental Science Department, Faculty of Science, Damietta University, Damietta, Egypt
[3]Environmental and Natural Resource Science, Omar Al- Mukhtar University, Al Bayda, Libya
[4]Chemistry Department, Faculty of Science, Omar Al- Mukhtar University, Al Bayda, Libya

[*]Corresponding Author: doaa_alemam@du.edu.eg

ARTICLE INFO

Article History:
Received: March 5, 2025
Accepted: May 23, 2025
Online: May 29, 2025

Keywords:
Bioaccumulation,
Health risk assessment,
Serranus Scriba,
Siganus Rivulatus,
Umbrina Cirrosa,
Zwitina

ABSTRACT

As a result of industrial development, heavy metals (HMs) have become major contributors to environmental contamination worldwide. HM contamination leads to the accumulation of these metals in fish bodies. Consumption of such contaminated fish poses a serious threat to human health through the food chain. In the current study, various marine fish species were collected during the winter and summer of 2023 from four sites along the coastal region of Zwitina, Libya. The goal was to assess the levels of several heavy metals, including copper (Cu), zinc (Zn), cadmium (Cd), nickel (Ni), and lead (Pb). Additionally, health risk assessment metrics were used to evaluate potential risks to human health—particularly the carcinogenic effects associated with long-term exposure to Pb and Ni, which are known to increase the risk of cancer and other chronic illnesses. Significant seasonal and regional variations in metal concentrations were observed across different fish organs. The highest concentrations of heavy metals were found in the gills of some fish species, while in others, the liver stored the highest levels. The muscle tissues exhibited the lowest concentrations of HMs. Among the studied species, *Serranus scriba* accumulated the highest levels of Pb, Cd, and Ni. The highest concentrations of Zn were detected in *Umbrina cirrosa* and *S. scriba*, whereas *Siganus rivulatus* showed the highest Cu levels. These findings suggest that bioaccumulation of heavy metals is species-dependent. Fish species that inhabit areas near sediments tend to accumulate higher metal concentrations in their bodies. For human consumption, the data showed that Cu, Zn, and Cd levels in the muscle tissues (the edible part) of the analyzed fish were within safe limits. However, Ni and Pb levels exceeded the permissible limits, posing potential health risks. The health risk assessment indicated a moderate to high likelihood of adverse health effects from HM exposure, particularly due to Pb. The calculated Hazard Index values underscore the need for ongoing monitoring and prompt public health measures to reduce the risks associated with consuming fish from contaminated waters.

INTRODUCTION

As more people become aware of the nutritional and health benefits of fish, its popularity is growing globally. Fish is low in cholesterol, rich in vitamins, minerals and unsaturated fatty acids and include all of the essential amino acids. Additionally, fish is a source of more than 30% of animal protein for 60% of the developing world **(Magna *et al.*, 2021; Kasmi *et al.*, 2023)**. To get your recommended daily intake of omega-3 fatty acids, the American Heart Association suggests eating fish at least twice a week **(Kasmi *et al.*, 2023; Malak *et al.*, 2025)**. Although eating fish is essential for a balanced diet and general health, pollution in aquatic environments poses a serious threat to aquatic organisms and public health **(Abdein & El-Emam, 2024; Abd El-Hamid *et al.*, 2025)**. Heavy metal pollution has been considered as a significant threat to aquatic environment and aquatic organisms including fish **(Islam *et al.*, 2020)**. Numerous anthropogenic activities, including agricultural and industrial discharges, domestic waste, landfill erosion, and diverse natural processes, serve as primary sources of heavy metals in aquatic environments **(Zhang *et al.*, 2022)**. Inorganic pollutants known as heavy metals (HMs) pose a serious threat to human health and the environment worldwide. Because of their toxicity, persistence, and abundance, as well as the following bio magnification in the aquatic food chain, HM pollution of marine ecosystems has emerged as one of the most difficult issues **(Jolly *et al.*, 2023; Malak *et al.*, 2025)**.

In general, HMs are divided into two categories: biologically essential and nonessential. Although studies have not established the biological function of non-essential metals like lead (Pb), mercury (Hg), cadmium (Cd), aluminum (Al), and selenium (Sn), their effects and toxicity grow with increasing levels and concentrations. On the other hand, the essential metals such as zinc (Zn), iron (Fe), copper (Cu), cobalt (Co), nickel (Ni), chromium (Cr), and molybdenum (Mo) have a known biological function and can be harmful when present in excessive levels or when there are metabolic deficiencies **(Yousif *et al.*, 2021)**.

HMs accumulate in fish body through ingestion of food and suspended substances in water through exchange of several ions in gills. According to several studies, eating fish is the main way through which heavy metals build up in the human body **(Alam *et al.*, 2023)**.

Contamination by HMs caused several complexities including liver damages, kidney dysfunction, cardiovascular abnormalities, metabolic disturbances and in the worst situation, results in death **(El-Moselhy *et al.*, 2014)**. Furthermore, when contaminated fish are consumed, HMs accumulate in vital human organs including the liver, kidney, and bones, causing a number of neurotoxic and carcinogenic effects **(Alam *et al.*, 2023)**. The route, exposure duration, and absorbed dose all affect how harmful HMs are **(Sarker *et al.*, 2022)**.

Large cities including Benghazi, Brega, Misurata, Ras Lanouf, Zawiya, Tripoli, and Zwitina are home to the majority of Libya's industrial activities along the coast. Numerous specialized industrial complexes, including those in the steel, petrochemical, and oil and gas refinery industries, are located in these cities **(Zeyadah *et al.*, 2023)**. Previous studies have shown that oil pollution from industrial facilities and refineries can have a major negative impact on coastal communities and marine ecosystems **(Naryono, 2023; Zhuang *et al.*, 2023**; **Behnasawy *et al.*, 2024)**.

The impact of Libya's petroleum industry on heavy metal pollution has been extensively documented in local studies. **Omar *et al.* (2022)** reported elevated concentrations of heavy metals such as Pb and Ni in coastal waters near oil ports and refineries, primarily due to discharges from refinery activities. Similarly, **Elbagerma *et al.* (2021)** highlighted pollution hotspots attributable to industrial facilities, which release heavy metals into the environment. Furthermore, **Aghow and Idris (2025)** identified a significant accumulation of heavy metals in water and sediments collected from areas adjacent to the oil industry infrastructure. These studies collectively emphasize the direct link between Libya's petroleum industry and environmental heavy metal contamination, underscoring the urgent need for effective mitigation measures.

Fish's remarkable ability to rapidly metabolize, detoxify, and accumulate heavy metals within their bodies makes them valuable bio indicators for monitoring aquatic environments. Additionally, they are more sensitive to even slight changes in their surroundings. Therefore, the current study was designed to determine the heavy metals (copper, zinc, cadmium, lead, and nickel) concentration in the muscles, liver, and gills of various marine fish species in the Libyan coastal region of Zwitina. Moreover, metal pollution index (MPI), probabilistic target hazard quotient (THQ), hazard index (HI) and lifetime cancer risk (TR) were also enumerated to interpret whether fishes from the study area are safe for human consumption or not.

MATERIALS AND METHODS

1. Study area

The study area is the Zwitina region, located west of the city of Benghazi at a distance of about 140km, and northeast of the city of Ajdabiya at a distance of about 20km at coordinates 30º 54' 54.30″ N and 30º 05' 30.36″ E (Fig. 1). GPS was used to choose each of our distinct coastal locations for the fish sample collection. There were around 5 kilometers between every location. The Zwitina region is home to the largest city in Cyrenaica, a bustling seaport, a major fishing hub, and an active oil industry **(Zeyadah *et al.*, 2023)**.

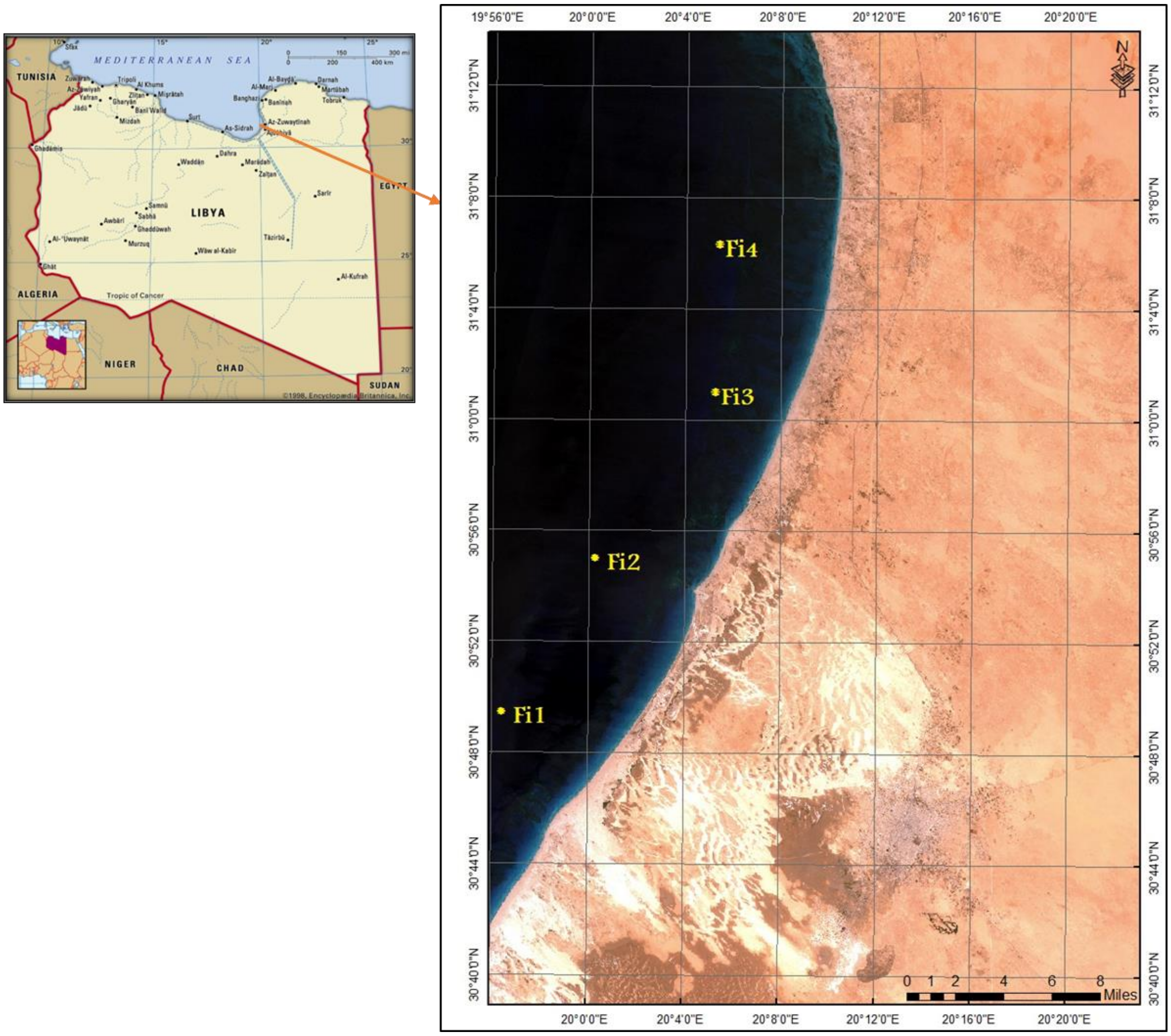

Fig. 1. Geographic map of the study area (Google earth 2024)

2. Collecting samples and assessing heavy metals

A. Sample collection

Fish samples were collected in the summer (August) and winter (December) of 2023 from the chosen locations (115 individual fish belonging to ten species where n=5 in four sites/season). Fish were caught using Seine nets. Collected samples were stored in clean plastic bags in an icebox before being transported to the Laboratory of Zoology Department, Faculty of Science, Damietta University, where they were kept deeply frozen at -20^{o} C until the samples were prepared for digestion and analysis.

B. Sample preparation and digestion

Before analysis, four fish from each species were measured, weighed, and dissected in the laboratory using sterilized stainless equipment. These fish had their liver, muscles, and gills removed to estimate the amount of studied heavy metals. Following a 48-hour oven drying process at 80°C, all samples were digested using a 2:1 ratio of concentrated nitric acid (HNO_3) (69%) and concentrated perchloric acid ($HCLO_4$) (70%) on a hot sand bath. The digestion was kept until the solution turned transparent. An atomic absorption spectrometer (PinAAcle 500, Perkin Elmer) was used to measure the amount of heavy metals present in the filtered solution. Atomic absorption spectrophotometry was performed at the Water Research Microanalysis Laboratory, Damietta University. The concentrations of metals in tissues were expressed as µg metal/ g dry weight. The heavy metal concentrations in tissues were estimated using dry weights to adjust for variability due to differences in the moisture content of organisms' interior organs (**Nawareg *et al.*, 2020**).

3. Statistical analysis

The means and standard errors (SE) of each outcome were reported. Using SPSS software (Version 22; SPSS, Chicago, IL, USA), the data were subjected to a one-way ANOVA to determine the statistical significance at a 95% confidence limit. The means were also compared using Duncan's multiple range test, with a significance level set at $P < 0.05$.

4. Health risk assessment

Risk assessment is a technique of determining the dangers to a certain population exposed to certain contaminants. It was estimated using the following equations:

$$MPI = (C_{Cu} \times C_{Ni} \times C_{Cd} \times C_{Pb} \times C_{Zn})^{1/5} \quad (1)$$

$$EDI = \frac{\mathrm{C} \times FIR}{\mathrm{BW}} \quad (2)$$

$$THQ = \frac{\mathrm{EF} \times \mathrm{ED} \times \mathrm{FIR} \times \mathrm{C}}{RfD \times WB \times AT_N} \times 10^{-3} \quad (3)$$

$$HI = \sum_{n=1}^{n=i} \mathrm{THQs} \quad (4)$$

$$TR = \frac{\mathrm{EF} \times \mathrm{ED} \times \mathrm{FIR} \times \mathrm{C} \times \mathrm{C}PSo}{BW \times AT_C} \times 10^{-3} \quad (5)$$

MPI is the Index for Metal Pollution: The (MPI) approximates fish muscle total metal content buildup. EDI is the anticipated daily intake in µg/g/day.

HI is the Target Hazard Quotient and Hazard Index: While HI is the total of the THQs to determine the likely risk of adverse health effects from a mixture of HM, the THQ assesses the non-carcinogenic health dangers presented by each metal via intake of fish. THQ's acceptable recommendation value is one; values > (1) show a likelihood of unfavorable health consequences happening. Conversely, HI more than 10 denotes a significant risk and either chronic or even acute consequence; HI < 1 implies no evident detrimental effects. Equations (3) and (4) respectively help one to determine the THQ and HI **(Hasaballah *et al.*, 2021)**.

TR is the Target Risk: TR is computed for carcinogens since an individual's incremental likelihood of developing cancer over a lifetime due to exposure to that possible carcinogen is known. Its value is derived from equation (5).

In this context, C represents the heavy metal concentration in fish muscle (μg g^{-1} d.wt); EF denotes the exposure frequency (365 days/year); ED signifies the exposure duration (30 years for non-cancer risk as per US EPA, 2011); FIR indicates the fish ingestion rate (40.33 g/person/day); BW refers to the average body weight for adults (70 kg) **(FAO, 2016; Hasaballah *et al.*, 2021)**; AT_N is the average exposure time for non-carcinogens (EF × ED) (365 days/year for 30 years as per US EPA, 2011); RfD is the reference oral dose of the metal according to the human health risk assessment. The reference doses (RfD) for cadmium (Cd), lead (Pb), copper (Cu), Nickel (Ni) and zinc (Zn) are 1×10^{-3}, 3.0×10^{-3}, 4.0×10^{-2}, 2.0×10^{-2} and 3.0×10^{-1} mg/kg/day, respectively. CPSo represents the oral carcinogenic potency slope, whereas ATc denotes the average time, with carcinogens assessed over 365 days per year for a duration of 70 years, as published by the US EPA in 2011. Given that CPSo values for Cd, Ni, and Pb were reported as 6.3, 1.7, and 0.0085 mg/kg bw-day^{-1} correspondingly, TR values were subsequently determined for the consumption of these metals **(USEPA, 2019; Rauf *et al.*, 2021; Ghani *et al.*, 2023; Rakib *et al.*, 2024)**.

RESULTS AND DISCUSSION

Fish are an important source of food for the general human population. Fish contamination with heavy metals poses one of the enormous risks to aquatic life as well as humans. Heavy metals bioaccumulate in fish organs as a result of adsorption and absorption; this accumulation is thought to occur along the gill surface, kidney, liver, and wall of the gastrointestinal tract **(Annabi *et al.*, 2013)**. In the biochemical process, metals that are not necessary for life are toxic, persistent, and regulated internally by a number of processes, such as active excretion and storage **(Raychaudhuri *et al.*, 2025)**. Our results indicated that there were great variations in heavy metal concentration across the investigated fish species. The mean lengths and weights of examined fish species are reported in Table (1).

The selected metals were copper (Cu), zinc (Zn), cadmium (Cd), nickel (Ni), and lead (Pb). This is due to their distinct environmental behaviors and sources of contamination. Lead (Pb) and nickel (Ni) are frequently utilized as industry markers, particularly in relation to petroleum-related activities, as they are intrinsic components of crude oil and are released during extraction, refining, and port operations. In contrast, cadmium (Cd), copper (Cu), and zinc (Zn) can emanate from various sources, including industrial discharges, infrastructural corrosion, and oil refining processes. These metals exhibit considerable toxicity and persistence in the environment, thereby posing substantial health risks. For instance, Pb is associated with neurotoxic effects, Cd has been identified as a carcinogen, and all five metals demonstrate potential for bioaccumulation. As such, they represent critical targets for environmental monitoring in areas impacted by oil-related activities.

In the present study, different heavy metal levels were observed between the investigated fish species. *Serranus scriba* (Linnaeus, 1758) accumulated the highest levels of Pb, Cd and Ni, as shown in Tables (4, 5, 6). The highest concentrations of Zn was found in *Umbrina cirrosa* (Linnaeus, 1758) and *S. scriba*, as shown in Table (3). The highest value of Cu was recorded in *Siganus rivulatus* (Linnaeus, 1758), as shown in Table (2).

Previous research revealed that the bioaccumulation of heavy metals varies depending on fish species **(Tanir, 2021; Guerra-Garcia *et al.*, 2023)**. The degree of accumulation is closely correlated with the eating habits (as carnivores, herbivores, omnivores, and limnivores) and animals habitats **(Kumar *et al.*, 2024)**. Factors that affect the amounts of heavy metals in different fish species include aquatic environments variations with respect to pollution kind and degree, the chemical form of metal in the water, temperature, pH level, dissolved oxygen concentration, and water transparency **(Raychaudhuri *et al.*, 2025)**. It has also been shown that, even within the same fish species, variations in metal concentrations can occur depending on the catch season and geographic location **(Bahnasawy *et al.*, 2009)**. In addition, **Shahjahan *et al.* (2022)** stated that pollution degree in sediment, water, and food, as well as water salinity and temperature, ecological needs, metabolism, all affect fish's capacity for collecting heavy metals.

According to **Gutiérrez *et al.* (2023)**, animals that have a tight association with sediment exhibit rather high metal concentrations in their bodies. Research findings indicate that sediment contains a higher concentration of metals than both water and biota **(Bahnasawy *et al.*, 2009; Priya *et al.*, 2011; Gutiérrez *et al.*, 2023)**. Furthermore, the relationship between Cu and low molecular weight proteins (metallothionein-like), which are concentrated in hepatic tissues, helps to explain the largest accumulation of Cu **(Kumar *et al.*, 2024)**. The continuous movement of fishing boats and trawlers, which employ lead acid batteries in motor boats to avoid corrosion and galvanized metal plating containing Pb, Cu, and Zn to prevent rusting, is the primary cause of the elevated levels of Cu and Pb in aquatic environments **(Priya *et al.*, 2011)**. This is in addition to the copper compounds that are used as antifouling paint on the vehicles bottom. Eventually, all of these leach into the ambient environment and accumulate in the organs of fish **(Ibrahim & Abu El-Regal, 2014)**. **Gutiérrez *et al.* (2023)** confirmed that the concentrations of toxic heavy metals, specifically cadmium (Cd) and lead (Pb), were found to be over ten times greater than those documented in recent studies. They attributed this increase to the implementation of stricter environmental regulations and controls in the North-Eastern Atlantic Ocean in recent years, in comparison to previous decades. Furthermore, they suggested that the discontinuation of leaded gasoline has likely played a significant role in mitigating Pb levels within the environment. Conversely, studies conducted in the Mediterranean Sea, particularly in regions such as Egypt and Turkey, indicate significantly higher concentrations of metals and trace elements. This phenomenon can be attributed to the unique hydrological characteristics of the Mediterranean Sea, which is a semi-enclosed body of water. Its sole connection to the Atlantic Ocean is through the Strait of Gibraltar, resulting in a notably low rate of water renewal. This limited exchange contributes to the accumulation of pollutants within marine organisms, thereby elevating the levels of contaminants observed in these studies **(Ayd *et al.*, 2017; Gutiérrez *et al.*, 2023; Orihuela-García *et al.*, 2023)**.

S. scriba gathered the highest levels of Pb, Cd, Ni, and Zn in the current study. This fish eats mostly carnivorous foods such as worms, bivalves, crabs, and cephalopods **(Vasiliki, 2016)**. Studies have shown that because cephalopods and bivalves are sedentary, they can absorb relatively larger concentrations of heavy metals from both water and sediment **(Gupta & Singh, 2011; Ibrahim & Abu El-Regal, 2014)**.

Umbrina cirrosa was recorded with the highest levels of Zn in the present study. This species inhabits inshore seas and can be found on various substrates, including rock, gravel, sand, and mud. Its primary diet consists of worms, cuttlefish, mackerels, anchovies, and mollusks. Benthic invertebrates are its primary prey **(Aydin & Sozer, 2020)**. Benthic fish have been shown to exhibit higher amounts of heavy metals in their tissues than do pelagic animals, which is consistent with the important process of sedimentation and persistence of these metals in sea depths **(Gutiérrez *et al.*, 2023)**. The accumulation of significantly higher Zn concentrations in the liver (819.8µg/ g dry weight) and gills (400.93µg/ g dry weight) of *U. cirrosa* is a noteworthy finding of this study.

In the current study, the bodies of *S. rivulatus* fish showed significant accumulations of heavy metals (Cu and Zn). This fish, a pelagic species, lives in shallow water over substrates covered in algae. It primarily feeds on zooplankton and algae **(Shakman *et al.*, 2009)**, which have a significantly higher capacity to accumulate metal than fish or water **(Bahnasawy *et al.*, 2011)**. The hypothesis of metal accumulation through diet should not be neglected. According to **Çiftçi *et al.* (2021)**, the amounts of metals in the tissues of the benthic *U. cirrosa* were consistently higher than those in the tissues of the pelagic *S. rivulatus* because of differences in feeding habits, habitats, and behaviors of species.

The mean concentrations of essential and non-essential metals in each fish species' liver, gills, and muscles varied greatly in the current investigation. Metal concentrations in each tissue from several fish species varied significantly according to a statistical analysis. The variations in each organ's physiological function are the main cause of the variations in the amounts of accumulation in the various fish organs and tissues. Additional characteristics that may impact the accumulation differences in various organs include dietary habits, behavior, and regulatory abilities **(Sharma *et al.*, 2024)**. Additionally, it was noted that the tissues' varying metal concentrations may be due to their ability to produce metal-binding proteins like metallothionein **(Kwong, 2024)**.

Table 1. Lengths and weights (Means ± SE) of fish collected from selected sites

	Season	**Summer**		**N**	**Winter**		**N**
Site	**Fish species**	**Lengths (cm)**	**Weights (g)**		**Lengths (cm)**	**Weights (g)**	
1	*U. cirrosa*	24.47±0.87	172.72±1.63	5	30.8±0.74	286.33±4.48	5
	S. rivulatus	15.9±0.44	56.05±3.93	5	-	-	-
	Lithognathus mormyrus	17.63±0.92	57.86±1.34	5	-	-	-
	Pagellus erythrinus	-	-	-	24.7±1.23	199.67±28.16	5
	Tautogolabrus adspersus	-	-	-	21.1±1.36	139.58±2.19	5
	Diplodus vulgaris	-	-	-	14.67±1.99	52.71±1.34	5
2	*Pagellus erythrinus*	25.1±1.4	214.67±1.45	5	-	-	-
	Diplodus vulgaris	16.2±0.31	70.26±1.9	5	15.53±0.03	66.65±0.8	5
	Epinephelus marginatus	-	-	-	20.67±1.45	154.97±2.49	5
	Sciaena umbra	-	-	-	34.77±3.09	550±133.64	5
3	*Tautogolabrus adspersus*	23±0.96	146.6±3.16	5	-	-	-
	S. scriba	18±0.58	71.31±10.83	5	-	-	-
	Diplodus vulgaris	14.7±0.32	57.2±3.97	5	18.07±1.75	147.65±15.61	5
	Pagellus erythrinus	-	-	-	25.4±1.76	135.51±8.70	5
4	*Siganus luridus*	16.83±0.91	110.74±5.87	5	19.8±0.12	118.81±4.98	5
	S. rivulatus	20.4±0.49	131.19±5.65	5	23.23±0.59	145.9±2.66	5
	U. cirrosa	-	-	-	25.67±2.33	163.45±7.33	5
	Sciaena umbra	-	-	-	30.37±1.19	385±8.66	5

N: number of individuals of studied species

Table 2. Copper concentration (μg/g dry wt.) in fish organs during study seasons

Sites	Season	Summer					Winter				
	Fish organs	**Muscle**	**Liver**	**Gills**	**F**	**P-value**	**Muscle**	**Liver**	**Gills**	**F**	**P-value**
	Fish species	**Concentration (Means ± SE)**					**Concentration (Means ± SE)**				
1	***U. cirrosa***	0.16^{c}±0.07	6.11^{a}±0.61	1.84^{b}±0.12	71.29	0.000	ND	7.94±0.32	ND		
	S. rivulatus	0.13^{b}±0.06	61.79^{a}±2.75	2.4^{b}±0.28	522.92	0.000	-	-	-	-	-
	Lithognathus mormyrus	ND	16.25±0.12	0.39±0.32			-	-	-	-	-
	Pagellus erythrinus	-	-	-	-	-	ND	18.7±0.67	ND		
	Tautogolabrus adspersus	-	-	-	-	-	ND	NA	ND		
	Diplodus vulgaris	-	-	-	-	-	ND	NA	ND		
2	***Pagellus erythrinus***	0.15±0.05	9.72±0.16	ND			-	-	-	-	-
	Diplodus vulgaris	ND	NA	ND			ND	NA	ND		
	Epinephelus marginatus	-	-	-	-	-	ND	14±0.59	ND		
	Sciaena umbra	-	-	-	-	-	ND	0.73±0.09	ND		
3	***Tautogolabrus adspersus***	ND	NA	ND			-	-	-	-	-
	S. scriba	ND	ND	ND			-	-	-	-	-
	Diplodus vulgaris	ND	NA	ND			ND	NA	ND		
	Pagellus erythrinus	-	-	-	-	-	ND	NA	ND		
4	***Siganus luridus***	0.16±0.03	47.12±0.62	ND			ND	126.17±1.44	7.96±0.32		
	S. rivulatus	0.15±0.01	NA	ND			0.51^{c}±0.02	171.57^{a}±0.61	50.67^{b}±0.66	28550.87	0.000
	U. cirrosa	-	-	-	-	-	ND	NA	ND		
	Sciaena umbra	-	-	-	-	-	ND	10.72±0.44	ND		

NA: not available - ND: not detected - Significant at *P< 0.05.*
(LOQ= 0.1 (mg/l), Qc = 0.3, CRM= 0.4).

Table 3. Zinc concentration (µg/g dry wt.) in fish organs during study seasons

Site	Season	Summer					Winter				
	Fish organs	**Muscle**	**Liver**	**Gills**	**F**	***P*-value**	**Muscle**	**Liver**	**Gills**	**F**	**P-value**
	Fish species	**Concentration (Means ± SE)**					**Concentration (Means ± SE)**				
1	***U. cirrosa***	22.72^{c}±1.11	181.94^{a}±2.25	152.57^{b}±1.3	2702.97	0.000	17.01^{c}±0.16	203.71^{a}±0.79	170.94^{b}±0.31	39832.09	0.000
	S. rivulatus	30.93^{c}±1.3	399.67^{b}±16.50	530.25^{a}±27.84	216.19	0.000	-	-	-	-	-
	Lithognathus mormyrus	20.07^{c}±0.79	215^{a} ±0.77	28.59^{b}±0.32	277745.74	0.000	-	-	-	-	-
	Pagellus erythrinus	-	-	-	-	-	42.19^{c}±2.94	272.29^{a}±10.66	161.44^{b}±3.48	295.42	0.000
	Tautogolabrus adspersus	-	-	-	-	-	15.81±0.16	NA	112.7±0.74		
	Diplodus vulgaris	-	-	-	-	-	31.5±0.69	NA	207.94±1.24		
2	***Pagellus erythrinus***	19.87^{c}±0.78	289.68^{a}±0.34	120.99^{b}±0.53	48514.66	0.000	-	-	-	-	-
	Diplodus vulgaris	40.17±1.39	NA	151.4± 3.45			17.19±0.7	NA	134.14±1.4		
	Epinephelus marginatus	-	-	-	-	-	12.61^{c}±0.33	185.55^{a}±0.95	36.63^{b}±0.69	17737.17	0.000
	Sciaena umbra	-	-	-	-	-	7.8^{c}±0.2	27^{b}±1.11	56.55^{a}±6.33	43.81	0.000
3	***Tautogolabrus adspersus***	50.26±1.18	NA	148.88±1.45			-	-	-	-	-
	S. scriba	20.63^{c}±0.97	801.97^{a}±5.28	214.17^{b}±1.17	16432.51	0.000	-	-	-	-	-
	Diplodus vulgaris	49.57±1.72	NA	275.91±4.01			16.24±0.15	NA	14.18±0.25		
	Pagellus erythrinus	-	-	-	-	-	15.47±1.49	NA	16.46±0.4		
4	***Siganus luridus***	50.46^{c}±1.1	512.7^{a}±1.24	140.73^{b}±0.88	51113.47	0.000	34.92±0.65	NA	143.34±1.7		
	S. rivulatus	49.34±1.65	NA	327.76±1.51			19.64^{c}±0.32	61.7^{b}±0.72	111.3^{a}±0.6	6413.63	0.000
	U. cirrosa	-	-	-	-	-	35.73^{c}±2.98	819.8^{a}±22.39	400.93^{b}±2.42	894.7	0.000
	Sciaena umbra	-	-	-	-	-	44.51^{c}±7.06	542.86^{a}±1.21	357.13^{b}±1.1	3618.67	0.000

NA: not available - Significant at $P<0.05$.
(LOQ= 0.1 (mg/l), Qc = 0.4, CRM= 0.5).

Table 4. Cadmium concentration (µg/g dry wt.) in fish organs during study seasons

Site	Season / Fish organs / Fish species	Summer: Muscle	Summer: Liver	Summer: Gills	Summer: F	Summer: P-value	Winter: Muscle	Winter: Liver	Winter: Gills	Winter: F	Winter: P-value
		Concentration (Means ± SE)					Concentration (Means ± SE)				
1	***U. cirrosa***	1.06^{c}±0.03	14.61^{a}±0.7	9.7^{b}±0.42	209.04	0.000	0.84^{b}±0.03	4.74^{a}±0.19	4.9^{a}±0.21	194.58	0.000
	S. rivulatus	1.63^{c}±0.26	9.13^{b}±0.89	16.02^{a}±0.41	226.83	0.000	-	-	-	-	-
	Lithognathus mormyrus	0.58^{b}±0.07	16.58^{a}±0.28	0.38^{b}±0.29	1546.97	0.000	-	-	-	-	-
	Pagellus erythrinus	-	-	-	-	-	0.48^{b}±0.06	6.35^{a}±0.8	5.41^{a}±0.72	25.88	0.001
	Tautogolabrus adspersus	-	-	-	-	-	1.11±0.06	NA	3.24±0.14		
	Diplodus vulgaris	-	-	-	-	-	1.17±0.1	NA	8±0.37		
2	***Pagellus erythrinus***	0.6^{c}±0.06	10.33^{a}±0.33	6.68^{b}±0.31	347.22	0.000	-	-	-	-	-
	Diplodus vulgaris	1.65±0.55	NA	11.36±0.15			1.46±0.11	NA	2.32±0.79		
	Epinephelus marginatus	-	-	-	-	-	1.32±0.11	1.71±0.08	1.29±0.13	4.62	0.061
	Sciaena umbra	-	-	-	-	-	0.64^{b}±0.08	1.61^{ab}±0.34	2.26^{a}±0.41	6.87	0.03
3	***Tautogolabrus adspersus***	1.96 ±0.16	NA	7.5±0.27			-	-	-	-	-
	S. scriba	1.7^{c}±0.1	66.33^{a}±1.33	16.84^{b}±0.17	1902.39	0.000	-	-	-	-	-
	Diplodus vulgaris	1.97±0.44	NA	14.21±1.06			0.49±0.04	NA	0.61±0.02		
	Pagellus erythrinus	-	-	-	-	-	0.63±0.12	NA	0.95±0.11		
4	***Siganus luridus***	0.93^{c}±0.19	8.6^{b}±0.29	11.02^{a}±0.39	307.1	0.000	0.91^{b}±0.08	9.36^{a}±1.27	7.47^{a}±1	22.42	0.002
	S. rivulatus	1.07±0.17	NA	10.64±0.82			0.52^{c}±0.02	11.95^{a}±0.38	8.74^{b}±0.15	608.72	0.000
	U. cirrosa	-	-	-	-	-	0.02±0.01	NA	5.87±0.19		
	Sciaena umbra	-	-	-	-	-	0.53^{b}±0.03	1.22^{a}±0.17	0.28^{b}±0.02	22.67	0.002

NA: not available - Significant at *P< 0.05* - Non significant *P>0.05.*
(LOQ= 0.025 (mg/l), Qc = 0.2, CRM= 0.3).

Table 5. Lead concentration (µg/g dry wt.) in fish organs during study seasons

Site	Season	Summer					Winter				
	Fish organs	**Muscle**	**Liver**	**Gills**	**F**	**P-value**	**Muscle**	**Liver**	**Gills**	**F**	**P-value**
	Fish species	**Concentration (Means ± SE)**					**Concentration (Means ± SE)**				
	U. cirrosa	13.59^{c}±0.64	76.14^{b}±3.24	103.6^{a}±0.89	544.78	0.000	13.34^{c}±0.68	55.47^{b}±0.4	80.68^{a}±0.33	4740.16	0.000
	S. rivulatus	24.68^{c}±0.76	118.66^{b}± 4.3	244.69^{a}±0.67	1351.3	0.000	-	-	-	-	-
	Lithognathus mormyrus	8.76^{c}±0.3	173.38^{a}±1.02	11.88^{b}±0.14	24992.09	0.000	-	-	-	-	-
1	***Pagellus erythrinus***	-	-	-	-	-	13.02^{c}±1.38	45.19^{b}±2.21	69.29^{a}±0.75	324.6	0.000
	Tautogolabrus adspersus	-	-	-	-	-	17.04±0.32	NA	61.1±0.86		
	Diplodus vulgaris	-	-	-	-	-	25.19±0.34	NA	154.9±0.33		
	Pagellus erythrinus	11.69^{c}±0.53	53.67^{b}±0.86	103.16^{a}±0.55	4775.26	0.000	-	-	-	-	-
	Diplodus vulgaris	21.76±1.1	NA	147.18±1.24			20.59±0.47	NA	91.42±1.73		
2	***Epinephelus marginatus***	-	-	-	-	-	15.65^{c}±0.22	25.98^{b}±0.2	51.99^{a}±0.44	3757.42	0.000
	Sciaena umbra	-	-	-	-	-	7.75^{b}±0.88	14.97^{b}±0.57	34.47^{a}±5.51	18.21	0.003
	Tautogolabrus adspersus	20.08±0.62	NA	87.67±0.86			-	-	-	-	-
	S. scriba	19.14^{c}±0.69	275.31^{a}±25.11	215.87^{b}±1.45	85.21	0.000	-	-	-	-	-
3	***Diplodus vulgaris***	27.41±0.28	NA	217.35±1.01			6.86±0.19	NA	11.45±0.62		
	Pagellus erythrinus	-	-	-	-	-	5.99±0.27	NA	12.1±0.44		
	Siganus luridus	12.69^{c}±0.52	76.64^{b}±0.83	149.48^{a}±0.56	11039.00	0.000	14.27^{c}±0.72	50.96^{b}±2.99	177.73^{a}±11.85	147.16	0.000
	S. rivulatus	16.7±1.17	NA	105.48±1.02			12.36^{c}±0.15	16.84^{b}±0.17	103.25^{a}±1.58	3085.76	0.000
4	***U. cirrosa***	-	-	-	-	-	24.86±0.49	NA	132.09±0.94		
	Sciaena umbra	-	-	-	-	-	12.93^{b}±0.27	6.53^{c}±0.15	73.5^{a}±0.6	8979.68	0.000

NA: not available - Significant at $P< 0.05$.
(LOQ= 0.5 (mg/l), Qc = 0.2, CRM= 0.3).

Table 6. Nickel concentration (µg/g dry wt.) in fish organs during study seasons

Site	Season / Fish organs / Fish species	Summer Muscle	Summer Liver	Summer Gills	Summer F	Summer P-value	Winter Muscle	Winter Liver	Winter Gills	Winter F	Winter P-value
		Concentration (Means ± SE)					Concentration (Means ± SE)				
1	***U. cirrosa***	8.73^{c}±0.22	18.6^{b}±0.32	38.61^{a}±0.38	2363.36	0.000	5.83^{c}±0.14	16.71^{b}±0.09	29.97^{a}±0.77	699.53	0.000
	S. rivulatus	11.39^{c}±0.47	13.84^{b}±0.43	63.53^{a}±0.79	2722.63	0.000	-	-	-	-	-
	Lithognathus mormyrus	3.04^{b}±0.37	44.75^{a}±0.75	4.69^{b}±0.09	2358.88	0.000	-	-	-	-	-
	Pagellus erythrinus	-	-	-	-	-	4.99^{c}±0.27	14.33^{b}±0.93	27.95^{a}±1.22	165.31	0.000
	Tautogolabrus adspersus	-	-	-	-	-	7.77±0.24	NA	20.55±0.37		
	Diplodus vulgaris	-	-	-	-	-	12.66±0.28	NA	50.67±0.28		
2	***Pagellus erythrinus***	4.83^{c}±0.26	17.02^{b}±0.34	29.74^{a}±0.46	1179.39	0.000	-	-	-	-	-
	Diplodus vulgaris	9.19±0.77	NA	44.65±0.74			16.43±0.69	NA	27.7±0.41		
	Epinephelus marginatus	-	-	-	-	-	7.46^{b}±0.13	8.69^{a}±0.23	9.01^{a}±0.26	14.68	0.005
	Sciaena umbra	-	-	-	-	-	4.26^{b}±0.67	7.02^{a}±0.45	7.26^{a}±0.81	6.38	0.033
3	***Tautogolabrus adspersus***	10.57±0.28	NA	35.51±0.32			-	-	-	-	-
	S. scriba	8.78^{c}±0.12	160.60^{a}±8.49	68.8^{b}±0.15	243.47	0.000	-	-	-	-	-
	Diplodus vulgaris	14.13±0.39	NA	47.97±3.78			2.24±0.13	NA	3.28±0.08		
	Pagellus erythrinus	-	-	-			2.64±0.26	NA	4.06±0.41		
4	***Siganus luridus***	6.27^{c}±0.29	24.52^{b}±0.71	46.88^{a}±0.43	1602.01	0.000	7.11^{c}±0.58	15.52^{b}±0.93	46.43^{a}±1.62	336.08	0.000
	S. rivulatus	6.97±0.55	NA	43.66±2.43			5.86^{c}±0.08	7.54^{b}±0.25	42.07^{a}±0.38	5753.57	0.000
	U. cirrosa	-	-	-	-	-	8.32±0.41	NA	0.08±0.01		
	Sciaena umbra	-	-	-	-	-	6.68^{b}±0.18	2.91^{c}±0.11	30.22^{a}±0.6	1600.45	0.000

NA: not available - Significant at $P<0.05$.
(LOQ= 0.15 (mg/l), Qc = 1, CRM= 2).

The present data indicated that the liver of some fish stored the highest concentration of metals, while the gills of some fish accumulated the highest concentrations. Muscles appeared to be the least preferred site for metal bioaccumulation, as the lowest concentrations of metals were found in this tissue in accordance with the findings of **Malak *et al.* (2025)**. Studies carried out on various fish species have demonstrated that metabolically active organs viz. the gills, liver, and kidney tend to accumulate higher levels of heavy metals in comparison with other tissues like muscle **(Bahhari *et al.*, 2017; Nawareg *et al.*, 2020)**.

Given that gills come into contact with water and suspended debris, they may be able to absorb various compounds from their surroundings, which could account for the high concentrations of metals observed in gill tissues. They also perform a number of physiological functions, including gas exchange and osmoregulation. Gills have a significant impact on the flow of harmful metals between a fish individual and its surroundings as a result of these functions **(ALkan *et al.*, 2015; Kumar *et al.*, 2024)**.

Agbugui and Abe (2022) have indicated that the elevated concentrations of metals observed in fish gills may be attributed to the presence of mucus within the elemental composition. This mucus poses challenges for complete removal from the lamellae during the tissue preparation process for analysis. They further assert that gills can serve as a depot for metals, wherein the rate of metal absorption significantly exceeds the rate of metal elimination, contributing to the accumulation observed in these tissues.

Toxic substances may directly pass through the gills because of the small distance between blood and sea water **(Alkan *et al.*, 2015)**. The increased density of chloride cells in gills, which have the ability to selectively accumulate metal ions, may be related to the increased metal accumulation in these tissues **(Alipour *et al.*, 2016)**. Since the gills are in close contact with the contaminated media and have a thin epithelium in comparison to other organs, they absorb metal ions first **(Olgunoglu *et al.*, 2015)**. According to **Agbugui and Abe (2022)** in this particular instance, metal ions precipitate the gills' mucus secretions. These precipitates occupy the intralamellar spaces, which stops the gill filaments from moving and prevents breathing. The current finding is consistent with other authors' reports postulating that gills have an intense tendency to absorb heavy metals **(Opeyemi & Olatunde, 2020; Tanir, 2021; Leonard *et al.*, 2022)**.

In the current study, liver had significantly higher concentrations of heavy metals, as it is considered metabolically active tissues like gills, gonads, and kidney that collect greater levels of heavy metals **(Khezri *et al.*, 2014; Kumar *et al.*, 2024)**. The liver of fish is the primary organ responsible for detoxification. It is also the primary site for the metabolism, accumulation, and biotransformation of pollutants in fish, as well as a significant location for the pathogenic effects of toxins **(Alijani *et al.*, 2017)**. In support to this, **El Zlitne (2022)** stated that liver is an organ where the specific metabolic and enzyme-catalyzed processes related to each heavy metals take place.

Fish exposed to high concentrations of heavy metals synthesize low molecular weight, cysteine-rich proteins known as metallothioneins. These proteins exhibit a strong affinity for heavy metals, facilitating their concentration and regulation within the liver **(Chahid *et al.*, 2014; Siraj *et al.*, 2014)**. It is well-established that fish liver tissues demonstrate a notable induction of metallothioneins in response to contamination **(Khezri *et al.*, 2014)**. **El Zlitne (2022)** provides additional support for this notion, highlighting the liver's role as the primary organ for the specific metabolic and enzymatic processes related to various heavy metals. The current findings align with existing literature indicating that fish liver accumulates significant levels of heavy metals **(Abalaka *et al.*, 2020; Al-Halani *et al.*, 2021; Kasmi *et al.*, 2023)**.

Fish muscle, in the present study, had the lowest concentrations of heavy metals. The muscles with the lowest levels of bio accumulated heavy metals may have a higher fat content, a lower fat tendency to coupling with heavy metals, or a lower muscle metabolic activity. It is well-known that muscles, with their relatively low metabolic activity, are not a good place for heavy metals to collect **(Younis *et al.*, 2024)**.

According to **Abalaka *et al.* (2020)**, the reason that fish muscles have lower metal concentrations is because they are not active detoxifying sites nor exterior boundary structures that come into contact with contaminated waters. This finding is consistent with other studies conducted on various fish species that have demonstrated that muscles can't actively accumulate heavy metals **(Islam & Mortuza, 2019; Parvin, 2019)**. Although fish muscles tend to regulate heavy metal levels, exposure to highly polluted water can cause concentrations to rise **(Younis *et al.*, 2024)**.

By dividing the dry weight of fish tissue metal concentrations by factors ranging from 4 to 6, one can translate the dry weight values into the wet weight **(Erdogrul, 2007)**. In the present study, as shown in Table (4), the lowest and highest copper levels in the muscles (edible part) of the investigated fish species were between 0.13 and 0.51µg/ g dry wt. (*S. rivulatus*). The maximum copper level permitted for fish is 20-30µg /g according to that reported by **Shaoba (2018)**. Accordingly, Cu level in the analyzed fish samples were in the safe limit for human consumption.

As shown in Table (3), the minimum and maximum zinc values measured in the fishes of the present study were 7.8µg/ g dry wt. in muscle of *S. umbra* and 50.46µg/ g dry wt. in muscle of *S. luridus.* The maximum zinc level permitted for fish is between 40-100µg /g according to that reported by **Shaoba (2018)**. Accordingly, Zn level in the analyzed fish samples were in the safe limit for human consumption.

As shown in Table (5), the concentration of lead in the muscle of fish varied from 5.99µg/ g dry wt. (*Pagellus erythrinus*) (Linnaeus, 1758) to 27.41µg/ g dry wt. (*Diplodus vulgaris*) (Linnaeus, 1758). The maximum lead level permitted for fish is 2.0µg /g according to that reported by **Shaoba (2018)**. Accordingly, Pb level in the majority of the analyzed fish samples were in the unsafe limit for human consumption.

As displayed in Table (4), cadmium levels, in the present study, ranged from 0.02µg/ g dry wt. in the muscle of *U. cirrosa* to 1.97µg/ g dry wt. in muscle of *D. vulgaris*. The maximum cadmium level permitted for fish samples is 0.5µg /g according to that reported by **Shaoba (2018)**. Thus, Cd levels in the analyzed fish samples were in the safe limit for human consumption.

Data depicted in Table (6) show that, the minimum and maximum nickel levels recorded in the present study were 2.24, and 16.43µg/ g dry wt. in the muscle of *D. vulgaris*. The maximum Ni level permitted for fish is 0.5μg /g according to that reported by **Shaoba (2018)**. Accordingly, Ni levels in the analyzed fish samples were in the unsafe limit for human consumption.

Species-specific variations in heavy metal accumulation are reflective of their ecological roles, particularly concerning their feeding habitats. Benthic species, such as *Umbrina cirrosa, Lithognathus mormyrus, Sciaena umbra, Tautogolabrus adspersus, Serranus scriba,* and *Epinephelus marginatus*, predominantly inhabit and forage on or near the seabed, primarily preying on sediment-dwelling organisms. This dietary reliance renders them highly susceptible to elevated concentrations of heavy metals found in sediments and associated biota, leading to significant bioaccumulation of these toxicants within demersal fish populations. The resultant accumulation can engender profound ecological consequences, including increased vulnerability to toxic effects and detrimental impacts on reproductive and immune system functions. Conversely, benthopelagic species, such as *Diplodus vulgaris, Pagellus erythrinus, Siganus rivulatus,* and *Siganus luridus*, inhabit the seafloor while also exhibiting swimming behaviors in the midwater column, primarily feeding on plankton and surface-dwelling prey. This feeding strategy often correlates with lower burdens of heavy metals, potentially enhancing their resilience to environmental pollution and modulating their role in trophic transfer within pelagic food webs. Understanding these interspecies disparities in metal accumulation is critical, as it underscores the importance of habitat-specific exposure pathways in the evaluation of ecological health and contamination risks. Comprehensive assessments of metal accumulation patterns in relation to habitat use are essential for predicting the ecological effects of heavy metal pollution on marine ecosystems and for informing relevant management strategies **(Ndhlovu *et al.*, 2023; Zaghloul *et al.*, 2024)**.

Health risk assessment

Metal pollution index (MPI) was used to compare the overall metal content in fish muscles. MPI of the studied HM in the investigated species ranged from 2.52 in *Pagellus erythrinus* species at site 2 to 7.31 in *Tautogolabrus adspersus* species (Table 7). The high value of MPI reflects high cumulative metal accumulations in the fish sample **(Ghani *et al.*, 2023)**. Consumption of fish with a high MPI value may pose a potential public health risk.

In the meantime, the calculated EDI values shown in Table (8) reveal that the EDI values for individual metal were below the standard reference dose in all fish species, therefore, daily intake of these metals do not cause harmful effect on public health.

Despite the observed low estimated daily intake (EDI) values for lead (Pb) and nickel (Ni), concentrations in certain biotic organisms frequently exceed established safety thresholds. This discrepancy can be attributed to several interrelated factors **(Mhungu *et al.*, 2023)**. First, prolonged bioaccumulation facilitates the concentration of these metals within biological tissues, resulting in internal levels that may surpass initial predictions based on intake rates. Chronic exposure, even at low levels, can lead to substantial accumulation, thereby posing significant ecological and biological risks **(Hashempour-Baltork *et al.*, 2023)**. Furthermore, Pb and Ni may exhibit synergistic effects; their combined toxicity can surpass the expected additive impact, elevating their ecological threat even when individual concentrations remain below safety limits. The environmental persistence of these metals, coupled with their slow elimination rates, can sustain and, in some instances, amplify internal concentrations over time. Additionally, localized hotspots of contamination or specific tissue bioaccumulation may lead to hazardous levels, despite average EDI values indicating low exposure **(Ishola *et al.*, 2023)**. These factors emphasize the limitations of relying solely on short-term exposure metrics, which may considerably underestimate actual ecological risks. Therefore, it is imperative to incorporate considerations of bioaccumulation, synergism, and environmental persistence into comprehensive environmental risk assessments to better evaluate the potential impacts of Pb and Ni on ecological systems.

The THQ values for each HM via the consumption of the investigated fish species are shown in Table (9). THQ values were < 1 for all individual HM indicating no potential non-carcinogenic health risk, except for Pb values which is > 1 showing a likelihood of unfavorable health consequences happening.

The TR values were calculated for the metals of known carcinogenic effects. The TR values for Cr, Cd and Pb are given in Table (9). According to **USEPA (2015)**, the TR values < E − 06 are classified as negligible for carcinogenic risk > E − 04 are considered unacceptable, and the values between E − 06 and E − 04 are assessed as an acceptable range. In the present study, the TR values for all fish species ranged from E − 05 to E – 03 **(Ghani *et al.*, 2023)**.

In addition, the findings of this study reveal that hazard index (HI) values range from 1 to 10, indicating a moderate to high probability of serious adverse health effects linked to the assessed exposure. Such HI values represent a critical public health concern that demands immediate attention and proactive intervention.

HI value nearing 1 signifies the onset of potential health impacts, while values approaching 10 underscore a formidable risk of serious and potentially chronic or acute health consequences. This compelling evidence necessitates urgent action to mitigate risks and protect public health. Moreover, it is vital to consider factors such as individual susceptibility, population exposure levels, and the chronicity of exposure when interpreting these HI values, as they can significantly influence health outcomes. Future research must prioritize longitudinal studies to comprehensively assess the long-term implications associated with these HI values and to formulate effective public health strategies aimed at risk reduction.

Table 7. Average concentration of heavy metals (µg/g; d.wt.) in muscles of fish species collected from the study area and the values of MPI and comparison with standard levels reported by different organizations

Site	Fish species	Ni	Pb	Cd	Zn	Cu	MPI
1	*U. cirrosa*	7.28	13.465	0.95	19.865	0.16	3.12
	S. rivulatus	11.39	24.68	1.63	30.93	0.13	4.50
	Lithognathusmormyrus	3.04	8.76	0.58	20.07	-	3.15
	Pagellus erythrinus	4.99	13.02	0.48	42.19	-	4.21
	Tautogolabrus adspersus	7.77	17.04	1.11	15.81	-	4.71
	Diplodus vulgaris	12.66	25.19	1.17	31.5	-	6.52
2	*Pagellus erythrinus*	4.83	11.69	0.6	19.87	0.15	2.52
	Diplodus vulgaris	12.81	21.175	1.555	28.68	-	6.55
	Epinephelus marginatus	7.46	15.65	1.32	12.61	-	4.55
	Sciaena umbra	4.26	7.75	0.64	7.8	-	2.78
3	*Tautogolabrus adspersus*	10.57	20.08	1.96	50.26	-	7.31
	S. scriba	8.78	19.14	1.7	20.63	-	5.68
	Diplodus vulgaris	8.185	17.135	1.23	32.905	-	5.63
	Pagellus erythrinus	2.64	5.99	0.63	15.47	-	2.74
4	*Siganus luridus*	6.69	13.48	0.92	42.69	0.16	3.55
	S. rivulatus	6.415	14.53	0.795	34.491	0.33	3.85
	U. cirrosa	8.32	24.86	0.02	35.73	-	2.72
	Sciaena umbra	6.68	12.93	0.53	44.51	-	4.59
(FAO, 2016)		0.3	0.50	0.5	40	30	
(FAO/WHO, 2011)		0.1	0.05	0.5	40	30	
(MAFF, 2000)			2	0.2	50	20	
(EC, 2005)			0.20	0.05	-	10	
(MHPRC, 2013)			0.5	0.1			

Table 8. EDI of metals in fish species caught from the study area

Site	Fish species	EDI (mg/kg/day)				
		Ni	Pb	Cd	Zn	Cu
1	*U. cirrosa*	4.19E-03	7.76E-03	5.47E-04	1.14E-02	9.22E-05
	S. rivulatus	6.56E-03	1.42E-02	9.39E-04	1.78E-02	7.49E-05
	Lithognathus mormyrus	1.75E-03	5.05E-03	3.34E-04	1.16E-02	-
	Pagellus erythrinus	2.87E-03	7.50E-03	2.77E-04	2.43E-02	-
	Tautogolabrus adspersus	4.48E-03	9.82E-03	6.40E-04	9.11E-03	-
	Diplodus vulgaris	7.29E-03	1.45E-02	6.74E-04	1.81E-02	-
2	*Pagellus erythrinus*	2.78E-03	6.74E-03	3.46E-04	1.14E-02	8.64E-05
	Diplodus vulgaris	7.38E-03	1.22E-02	8.96E-04	1.65E-02	-
	Epinephelus marginatus	4.30E-03	9.02E-03	7.61E-04	7.27E-03	-
	Sciaena umbra	2.45E-03	4.47E-03	3.69E-04	4.49E-03	-
3	*Tautogolabrus adspersus*	6.09E-03	1.16E-02	1.13E-03	2.90E-02	-
	S. scriba	5.06E-03	1.10E-02	9.79E-04	1.19E-02	-
	Diplodus vulgaris	4.72E-03	9.87E-03	7.09E-04	1.90E-02	-
	Pagellus erythrinus	1.52E-03	3.45E-03	3.63E-04	8.91E-03	-
4	*Siganus luridus*	3.85E-03	7.77E-03	5.30E-04	2.46E-02	9.22E-05
	S. rivulatus	3.70E-03	8.37E-03	4.58E-04	1.99E-02	1.90E-04
	U. cirrosa	4.79E-03	1.43E-02	1.15E-05	2.06E-02	-
	Sciaena umbra	3.85E-03	7.45E-03	3.05E-04	2.56E-02	-

Table 9. THQ, HI and TR of metals in fish species caught from the study area

site	Fish species	THQ					HI	TR		
		Ni	Pb	Cd	Zn	Cu		Ni	Pb	Cd
1	*U. cirrosa*	0.21	2.59	5.47E-01	3.82E-02	2.30E-03	3.38	3.06E-03	2.82604E-05	1.48E-03
	S. rivulatus	0.33	4.74	9.39E-01	5.94E-02	1.87E-03	6.07	4.78E-03	5.17985E-05	2.54E-03
	Lithognathus mormyrus	0.09	1.68	3.34E-01	3.85E-02	-	2.14	1.28E-03	1.83855E-05	9.02E-04
	Pagellus erythrinus	0.14	2.50	2.77E-01	8.10E-02	-	3.00	2.09E-03	2.73265E-05	7.47E-04
	Tautogolabrus adspersus	0.22	3.27	6.40E-01	3.04E-02	-	4.17	3.26E-03	3.57637E-05	1.73E-03
	Diplodus vulgaris	0.36	4.84	6.74E-01	6.05E-02	-	5.94	5.31E-03	5.28689E-05	1.82E-03
2	*Pagellus erythrinus*	0.14	2.25	3.46E-01	3.82E-02	2.16E-03	2.77	2.03E-03	2.4535E-05	9.33E-04
	Diplodus vulgaris	0.37	4.07	8.96E-01	5.51E-02	-	5.39	5.38E-03	4.44422E-05	2.42E-03
	Epinephelus marginatus	0.21	3.01	7.61E-01	2.42E-02	-	4.01	3.13E-03	3.28463E-05	2.05E-03
	Sciaena umbra	0.12	1.49	3.69E-01	1.50E-02	-	1.99	1.79E-03	1.62657E-05	9.96E-04
3	*Tautogolabrus adspersus*	0.30	3.86	1.13E+00	9.65E-02	-	5.39	4.44E-03	4.2144E-05	3.05E-03
	S. scriba	0.25	3.68	9.79E-01	3.96E-02	-	4.95	3.69E-03	4.01711E-05	2.64E-03
	Diplodus vulgaris	0.24	3.29	7.09E-01	6.32E-02	-	4.30	3.44E-03	3.5963E-05	1.91E-03
	Pagellus erythrinus	0.08	1.15	3.63E-01	2.97E-02	-	1.62	1.11E-03	1.25718E-05	9.80E-04
4	*Siganus luridus*	0.19	2.59	5.30E-01	8.20E-02	2.30E-03	3.40	2.81E-03	2.82919E-05	1.43E-03
	S. rivulatus	0.18	2.79	4.58E-01	6.62E-02	4.75E-03	3.50	2.69E-03	3.04957E-05	1.24E-03
	U. cirrosa	0.24	4.77	1.15E-02	6.86E-02	-	5.09	3.49E-03	5.21763E-05	3.11E-05
	Sciaena umbra	0.19	2.48	3.05E-01	8.55E-02	-	3.07	2.80E-03	2.71376E-05	8.24E-04

CONCLUSION

This study underscores the critical issue of heavy metal contamination in marine fish species from the coastal region of Zwitina, Libya, primarily due to industrial development and petroleum extraction activities. While copper, zinc, and cadmium levels in the muscles of the analyzed fish were within safe limits for human consumption, lead and nickel concentrations exceeded safety thresholds, posing potential health risks. Notable seasonal and regional variations in heavy metal concentrations were observed across different fish organs, with *Serranus scriba* exhibiting the highest levels of lead, cadmium, and nickel, while *Umbrina cirrosa* and *Siganus rivulatus* showed elevated zinc and copper levels, respectively. The health risk assessment metrics revealed a moderate to high probability of adverse health effects associated with heavy metal exposure, particularly concerning lead. The calculated Hazard Index values highlight the urgent need for continuous monitoring and public health interventions to mitigate risks related to fish consumption from contaminated waters. Overall, this research emphasizes the importance of monitoring heavy metal levels in marine ecosystems and the necessity for stricter environmental regulations to protect both aquatic life and human health. Future studies should focus on the long-term health implications of heavy metal exposure and effective strategies for risk reduction in affected populations.

ACKNOWLEDGMENTS

The authors would like to thank the support of the staff members and colleagues of the Environmental Sciences and Zoology Departments, Faculty of Science - Damietta University, and Environmental and Natural Resource Science and Chemistry Departments, Faculty of Science, Omar Al–Mukhtar University, Libya for their astounding part in conducting the research. The authors would also like to thank all those who took impressive parts in managing this research. The comments of the anonymous reviewers are also gratefully acknowledged.

COMPLIANCE WITH ETHICAL STANDARDS

Conflicts of interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors

Ethical approval

The methodology for this study was approved by the Ethics Committee of Damietta University **(DuRec no 35 on Sep 03, 2024)**.

Data availability

The data supporting this study's findings are available from the corresponding author, upon reasonable request.

REFERENCES

Abalaka, S.E.; Enem, S.I.; Idoko, O.S.; Sani, N.A.; Tenuche, O.Z.; Ejeh, S.A. and Sambo, W.K. (2020). Heavy metals bioaccumulation and health risks with associated histopathological changes in *Clarias gariepinus* from the Kado fish market. Abuja, Nigeria. J.Health & Poll., 10 (26):1-12. https://doi.org/10.5696/2156-9614-10.26.200602

Abd El-Hamid, H.T.; El-Emam, D.A.; Eissa, H.S. and El-Alfy, M.A. (2025). Current evaluation of radiation hazards from sediments of Manzala Lake, Egypt. J. Radioanal Nucl. Chem., 334: 927–940. https://doi.org/10.1007/s10967-024-09873-0

Abdein, R.H. and El-Emam, D.A. (2024). The Removal of Microplastics as a Source for Toxic Chemicals in Aquatic Environments: Characteristics, Occurrence and Removal Mechanisms. In: Haddout, S., Priya, K., Hoguane, A.M. (eds) Proceedings of The 2nd International Conference on Climate Change and Ocean Renewable Energy. CCORE 2022. Springer Proceedings in Earth and Environmental Sciences. Springer, Cham. https://doi.org/10.1007/978-3-031-71555-6_16

Agbugui, M. O. and Abe, G. O. (2022). Heavy metals in fish: bioaccumulation and health. Bri. J. Earth Sci. Res., 10(1), 47-66. https://doi.org/10.37745/bjesr.2013/vol10no1pp.47-66

Aghow, K. and Idris, S. (2025). Characterization and Environmental Impact of Produced Water from Oil Fields in the Sirte Basin, Libya. AlQalam Journal of Medical and Applied Sciences, 67-72.

Alam, M.; Rohani, M.F. and Hossain, M.S. (2023). Heavy metals accumulation in some important fish species cultured in commercial fish farm of Natore, Bangladesh and possible health risk evaluation. Emerg. Contamin., 9(4): 2405-6650, https://doi.org/10.1016/j.emcon.2023.100254

Al-Halani , A.; Soliman, A. and Shady, S. (2021) . The Seasonal Assessment of Heavy Metals Bioaccumulation in European Seabass (*Dicentrarchus labrax*) Inhabiting Damietta Fishing Harbor, Egypt. Egypt. J. Aquat. Biol. & Fish., 25(5): 607 – 625. https://doi.org/10.21608/ejabf.2021.205025

Alijani, R.A.; Movahedinia, A. and Rastgar, S. (2017). Fish liver biomarkers for heavy metal pollution: A review article. Amer. J. Toxicol.,1(1): 1-8. https://doi.org/10.3389/fmars.2023.1182294

Alipour, H. ; Pourkhabbaz, A. and Hassanpour, M. (2016) . Determination of metals (As, Cu, Fe, and Zn) in two fish species from the Miankaleh wetland. Arch. Pol. Fish., 24: 99-105. https://doi.org/10.1515/aopf-2016-0011

Alkan, A. F.; Koksal, E. M.; Ergun, D. D.; Karis, D.; Ozsobaci, P. N. and Barutcu, B. U. (2015). Element intoxication by marine food. Med. Sci. Discov., 2(2): 176-181. https://doi.org/10.36472/msd.v2i2.50

Annabi, A.; Said, K. and Messaoudi, I. (2013). Cadmium: bioaccumulation, histopathology and detoxifying mechanisms in fish. Am. J. Res. Commun., 1:60–79.

Ayd, S.; Öztürk, M.; Aydin-Önen, S.; Öztürk, M.; Aydın-Önen, S.; Öztürk, M.; Aydin-Önen, S. and Öztürk, M. (2017). Investigation of heavy metal pollution in eastern Aegean Sea coastal waters by using *Cystoseira barbata*, *Patella caerulea*, and *Liza aurata* as biological indicators. Environ. Sci. Pollut. Res., 24, 7310–7334. https://doi.org/10.1007/s11356-016-8226-4

Aydin, M. and Sozer, A. (2020). The length – weight relationship and maximum length of *Umbrina cirrosa* (linnaeus, 1758). Aquat. Sci. & Eng., 35(4): 7-10. https://doi.org/10.26650/ASE2020699102

Bahhari, A.H. ; Al-Switi, I.N. and Al-Rajab, A. (2017). Concentration of Heavy Metals in Tissues of *Mugil cephalus* and *Lethrinus miniatus* from Jazan Coast, Saudi Arabia. Nat. Environ. Pollut. Technol.,16(2):647-651.

Bahnasawy, M.; El-Ghobashy, A. and Abdel-Hakim,N. (2009). Culture of the Nile tilapia (*Oreochromis niloticus*) in a recirculating water system using different protein levels. Egypt.J.Aquat.Biol.&Fish.,13(2):1-15. https://doi.org/10. 21608/ EJABF. 2009.2029

Bahnasawy, M.; Khidr, A. and Dheina, N. (2011). Assessment of heavy metal concentrations in water, plankton, and fish of Lake Manzala, Egypt. Turk. J. Zool., 35:271-280. https://doi.org/10.3906/zoo-0810-6

Behnasawy, M. H.; Zeyadah, M. A.; DEEDAH, A.; Hasan, H. M. and Elemam, D. A. (2024). Soil heavy metal pollution and the associated toxicity risk assessment in Ajdabiya and Zueitina, Libya. Scientific Journal for Dami. Fac. Sci., 14(1), 16-27. https://doi.org/10.21608/sjdfs.2024.248818.1145

Chahid, A.; Hilali, M.; Benlhachemi, A.; Kadmiri, I.M. and Bouzid, T. (2014). Concentrations of heavy metals in muscle, liver and gill of *Sardina pilchardus* (Walbaum, 1792): Risk assessment for the consumers. J. Environ. Occup. Sci., 3(1):47-52. https://doi.org/10.5455/jeos.20140220085459

Çiftçi, N.; Ayas, D. and Bakan, M. (2021). The comparison of heavy metal level in surface water, sediment and biota sampled from the polluted and unpolluted sites in the northeastern Mediterranean Sea. Thalassas: *An Intern. J. Marine Sci.*, 37(1), 319-330. https://doi.org/10.1007/S41208-020-00239-3

EC. (2005). European Community, Commission regulation No. 1881/2006. Setting maximum levels for certain contaminants in foodstuffs (pp. OJ, L364/5). Official J. Eur. Union.

Elbagerma, M. A.; Alkog, M.; Alajtal, A. and Edwards, H. (2021). Assessment of the Total Petroleum Hydrocarbons and Heavy Metal Concentrations in Soils around Car Washing Stations in Misurata, Libya. International Journal of New Chemistry, 8(4), 453-473.

El Zlitne, A. (2022). Heavy metals concentration patterns in the Atlantic horse meckrel (*Trachurus trachurus*), the Round sardinella (*Sardinella aurita*) and the Common panadora (*Pagellus erythrinus*) from northwestern Egyptian coasts. Egy. J. Aqua.Bio. &Fish., 26(1), 63-81. https://doi.org/10.21608/ejabf.2022.214549

El-Moselhy, K.M.; Othman, A.I.; El-Azem, H.A. and El-Metwally, M.E.A. (2014). Bioaccumulation of heavy metals in some tissues of fish in the Red Sea, Egypt, Egypt. j. basic appl. sci. 1 (2). https://doi.org/10.1016/j.ejbas.2014.06.001

Erdogrul, O. (2007). Determination of mercury levels in edible tissues of various fish samples from Sir. Dam lake. Turk. J. Biol., 31(4):197-201. https://doi.org/10.1023/A:1014798012212

FAO. Food and Agriculture Organization (2016). Fishery Information Data and Statistics. Unit FISHSTAT, Databases and Statistics Food and Agriculture Tissueization of the United Nation, Rome Italy.

FAO/WHO, (2011). Evaluation of certain food additives and the contaminants mercury, lead and cadmium. (JECFA). International programme on chemical safety Seventy-third report of the Joint FAO/WHO Expert Committee on Food Additives WHO technical report series no. 960.

Ghani, S. A. A.; Ibrahim, M. I.; Shreadah, M. A.; El-Sayed, A. A. and Aly-Eldeen, M. A. (2023). Ecological risk assessment of selected contaminants in seawater, sediment and some fish species from Alexandria beaches, South-Eastern Mediterranean Sea, Egypt. Enviro. Nanotech., Monit. & Manag., 20, 100873. https://doi.org/10.1016/j.enmm.2023.100873

Guerra-García, J.M.; Calero-Cano, S.; Donazar-Aramendía, I.; Giraldez, I. Morales, E.; Arechavala-Lopez, P. and Cervera-Currado, L. (2023). Assessment of elemental composition in commercial fish of the Bay of C´adiz, Southern Iberian Peninsula. Mar.Poll.Bull.,187,114504. https://doi.org/10.1016/j.marpolbul.2022.114504

Gupta, S. and Singh, J. (2011). Evaluation of mollusc as sensitive indicator of heavy metal pollution in aquatic system: A review. The IIOAB J., 2 (1):49-57.

Gutiérrez, A.; Lozano-Bilbao, E.; Gutiérrez-Fernández, Á. J.; Paz-Montelongo, S.; González-Weller, D.; Rubio-Armendáriz, C., ... and Hardisson, A. (2023). Metal Levels in *Serranus Atricauda* and *Sparisoma Cretense* from the North-Eastern Atlantic Ocean—Contribution to Risk Assessment. Appl. Sci., 13(8), 5213. https://doi.org/10.3390/app13085213

Hasaballah A. F.; Hegazy T. A.; Ibrahim M. S.; El-Emam D. A. (2021). Health risk assessment of heavy metals contamination in sediments of the River Nile, Damietta Branch using Mathematical Models. Egypt. J. Aquat. Biol. Fish, 25, 947-971. 10.21608/EJABF.2021.170342.

Ibrahim, N. and Abu El-Regal, M. (2014). Heavy Metals Accumulation in Marine Edible Molluscs, Timsah Lake, Suez Canal, Egypt. ARPN J. Sci. Tech., 4 (4): 282-288.

Islam, R. and Mortuza, M.G. (2019). Heavy Metal Concentrations in Four Cultured and Captured Fishes of Rajshahi City, Bangladesh. J. Aquat.Res.Mar.Sci.,3:182-186.

Islam, S.M.M.; Rohani, M.F.; Zabed, S.A.; Islam, M.T.; Jannat, R.; Akter, Y. and Shahjahan, M. (2020). Acute effects of chromium on hemato-biochemical parameters and morphology of erythrocytes in striped catfish *Pangasianodon hypophthalmus*. Toxicol. Rep., 7, 664e670. https://doi.org/10.1016/j.toxrep.2020.04.016

Jolly, Y. N.; Rakib, M. R. J.;Kumar, R.; Islam, A. R. M. T.; Rabby, A. and Mamun, K. M., et al., (2023). Deciphering the source of heavy metals in industrially affected river sediment of Shitalakshya river, Bangladesh, and potential ecological and health implications. *J. Hazar. Mater. Advan.*, *10*, Article 100268. https://doi.org/10.1016/j.hazadv.2023.100268

Kasmi, K.; Belhaj, K.; Nasri, H.; Slimani, D.; Allai, L.; Mansouri, F.; Aissioui, S.; Abdellaoui, S.; Addi, M. and Chafi, A. (2023) .Heavy Metals Concentration in *Sardina pilchardus* (Walbaum,1792) from the Moroccan Mediterranean Coast and Potential Human Health Risk Assessment. J. Food Qual., 1-13. https://doi.org/10.1155/2023/1455410

Khezri, P.H.; Takhsha, M.; Jamshid, K.A. and Arash aghshenas, A. (2014). Assessment level of heavy metals (Pb, Cd, Hg) in four fish species of Persian Gulf (Bushehr – Iran). Int. J. Advan. Tech.Eng.Res.,4(2): 34-38.

Kumar, V.; Swain, H. S.; Upadhyay, A.; Ramteke, M. H.; Sarkar, D. J.; Roy, S. and Das, B. K. (2024). Bioaccumulation of potentially toxic elements in commercially important food fish species from lower Gangetic stretch: food security and human health risk assessment. Biolog. Trace Elem. Res., 202(3), 1235-1248. https://doi.org/10.1007/s12011-023-03743-8

Kwong, R. W. (2024). Trace metals in the teleost fish gill: biological roles, uptake regulation, and detoxification mechanisms. J. Compara. Physio. B., 194(5), 749-763. https://doi.org/10.1007/s00360-024-01565-1

Leonard, L. S.; Mahenge, A. and Mudara, N. C. (2022). Assessment of heavy metals contamination in fish cultured in selected private fishponds and associated public health risk concerns, Dar es Salaam, Tanzania. Mar. Sci. Tech. Bull., 11(2), 246-258. https://doi.org/10.33714/masteb.1108314

MAFF, (2000). Ministry of Agriculture, Fisheries and Food: Monitoring and surveillance of non-radioactive contaminants in the aquatic environment and activities regulating the disposal of wastes at sea, 1997. In: Aquatic environment monitoring report No. 52. Lowestoft,

Magna, E.K.; Koranteng, S.S.; Donkor, A. and Gordon, C. (2021). Health Risk Assessment and Levels of Heavy Metals in Farmed Nile Tilapia (*Oreochromis niloticus*) from the Volta Basin of Ghana. J. Chem., 1-10. https://doi.org/10.1155/2021/2273327

Malak, N.M.L.; Abdel-Naeem, H.H.S.; Abdelsalam, A.A. and Ezzat, G.A. (2025). A comparative study concerning the sensory, physicochemical, bacteriological, nutritional quality, heavy metal content, and health risk assessment of some low-cost fish species. Food Cont., 169. https://doi.org/10.1016/j.foodcont.2024.111023

MHPRC, (2013). (Ministry of Health of the People's Republic of China). National Food Safety Standard, Maximum Levels of Contaminants in Foods (GB2762-2012).

Naryono, E. (2023). Nickel Mine Exploitation in Indonesia, Between A Blessing and A Disaster of Environmental Damage (No. y58qe). Center for Open Science. https://doi.org/10.31219/osf.io/y58qe

Nawareg, M.M.; Bahnasawy, M.H.; El-Sisy, D.M. and Abdel-Rahim, M.M. (2020). Does the polyculture system of thinlip grey mullet, *Chelon ramada* (Risso, 1827) have positive impacts on water quality, fish performance, and hematological analyses of hybrid red tilapia, *Oreochromis mossambicus* × *O. urolepis* reared in concrete tanks with underground brackish water?. AACL Bioflux, 13(6):3360-3376.

Ndhlovu, A., Human, L. R., Adams, J. B., Rishworth, G. M., Olisah, C. and Bornman, T. G. (2023). Ecological risk assessment of metal pollutants in two agriculturally impacted estuaries. Marine Pollution Bulletin, 195, 115572.

Omar, W. A.; Busaadia, M. A.; Saleh, Y. S.; Almalki, A. S. A. and MARIE, M. S. (2022). Characterization of metal pollution in surface sediments along the northeastern coast of Libya. Applied Ecology & Environmental Research, 20(2).

Olgunoğlu, M.P.; Artar, E. and Olgunoğlu, I. A. (2015). Comparison of heavy metal levels in muscle and gills of four benthic fish species from the Northeastern Mediterranean Sea. Pol. J. Environ. Stud., 24(4):1743–1748.

Opeyemi, I.E. and Olatunde, O.O. (2020). Determination of heavy metals in water and some selected fish species in River Ofin, Ado-Ekiti. ARRB, 35(3):52-62. https://doi.org/10.9734/arrb/2020/v35i330200

Orihuela-García, M. A.; Bolado-Penagos, M.; Sala, I.; Tovar-Sánchez, A.; García, C. M.; Bruno, M.; ... and Laiz, I. (2023). Trace metals distribution between the surface waters of the Gulf of Cadiz and the Alboran Sea. Sci. of the Total Environ., 858, 159662. https://doi.org/10.1016/j.scitotenv.2022.159662

Parvin, A.; Hossain, M.; Islam, S.; Das, S.; Munshi, J.; Suchi, P.; Moniruzzaman, M.; Saha, B. and Mustafa, M. (2019). Bioaccumulation of heavy metals in different tissues of Nile tilapia (*Oreochromis niloticus*) in Bangladesh. Mal. J. Nutr., 25(2): 237-246. https://doi.org/10.31246/mjn-2018-0153

Priya, S.L.; Senthilkumar, B.; Hariharan, G.; Paneer Selvam, A.; Purvaja, R. and Ramesh, R. (2011). Bioaccumulation of heavy metals in mullet (*Mugil cephalus)* and oyster *(Crassostrea madrasensis)* from Pulicat Lake, south east coast of India. Toxicol. Indust. Health, 27(2) 117-126. https://doi.org/10.1177/0748233710381892

Rakib, M. R. J.; Miah, S.; Hossain, M. B.; Kumar, R.; Jolly, Y. N.; Akter, S.; Islam, M. S. and Idris, A. M. (2024). Delineation of trace metal level in fish feed and farmed fish, Tilapia (*Oreochromis mossumbicus*) and their consequences on human health. Regio. Stud. Marine Sci., *71*, Article 103403. https://doi.org/10.1016/j.rsma.2024.103403

Rauf, A. U.; Mallongi, A.; Lee, K.; Daud, A.; Hatta, M.;Al Madhoun, W. and Astuti, R. D. P. (2021). Potentially toxic element levels in atmospheric particulates and health risk estimation around industrial areas of Maros, Indonesia. *Toxics*, *9*(12), 328. https://doi.org/10.3390/toxics9120328

Raychaudhuri, S.; Raychaudhuri, M.; Mohanty, R.K. and Rautaray, S.K. (2025). Effect of treated wastewater on heavy metal accumulation, fish growth and associated implications on consumer health, J. Taiwan Instit. Chem. Engin.,Volume 166, Part 2,105652, https://doi.org/10.1016/j.jtice.2024.105652

Sarker, A.; Kim, J. E.; Islam, A. R. M. T.; Bilal, M.; Rakib, M. R. J.; Nandi, R.; Rahman, M. M. and Islam, T. (2022). Heavy metals contamination and associated health risks in food webs—a review focuses on food safety and environmental sustainability in Bangladesh. Environ. Sci. Pollu. Res., *29*(3), 3230–3245. https://doi.org/10.1007/s11356-021-17153-7

Shahjahan, M.; Taslima, K.;Rahman, M. S.; Al-Emran, M. D.; Alam, S. I. and Faggio, C. (2022). Effects of heavy metals on fish physiology–a review. Chemosphere, 300, 134519. https://doi.org/10.1016/j.chemosphere.2022.134519

Shakman, E.; Boedeker, C.; Bariche, M. and kinzelbach, R. (2009).Food and feeding habits of the Lessepsian migrants *Siganu sluridus* Rüppell, 1828 and *Siganus rivulatus* Forsskal, 1775 (Teleostei: Siganidae) in the southern Mediterranean (Libyan coast) . J. Biol. Res.-Thessaloniki , 12: 115 – 124.

Shaoba, S.F. (2018). Study on concentration of some heavy metals in some types of marine fish at Damietta Governorate. M.Sc. Thesis , Fac.Sci., Damietta Univ.

Sharma, M.; Kant, R.; Sharma, A. K. and Sharma, A. K. (2024). Exploring the impact of heavy metals toxicity in the aquatic ecosystem. International Journal of Energy and Water Resources, 1-14. https://doi.org/10.1007/s42108-024-00284-1

Siraj, M.; Shaheen, M.; Sthanadar, A.; Khan, A.; Chivers, D. and Yousafzai, A.M. (2014). A comparative study of bioaccumulation of heavy metals in two fresh water fishes, *Aoricthyes seenghala* and *Ompok bimaculatous* at River Kabul, Khyber Pakhtunkhwa, Pakistan. J. Bio. Environ. Sci.(JBES), 4(3): 40-54.

Tanır, O.Z. (2021). Determination of heavy metals in some tissues of four fish species from the Karasu River (Erzincan, Turkey) for public consumption. Int. J. Ocean. Hydr. 50(2):232-246. https://doi.org/10.2478/oandhs-2021-0020

USEPA. United States Environmental Protection Agency. (2015). Recommended Use of Body Weight 3/4 as the Default Method in Derivation of the Oral Reference Dose.

USEPA. United States Environmental Protection Agency. (2019). Regional screening level (RSL) summary table (TR=1E-06, HQ=1). https://support.esdat.net/Environmental%20Standards/us/region369/usepa%20rsl%20may%202019%20thq%20=%200.1.pdf.

Vasiliki, M. (2016). An Estimation of the Diet of the Species *Serranus Scriba* (Linnaeus, 1758*)* in the Area of Nisiopi, in South-West Lesvos.J. Environ. Sci. Eng. A., 5 :593-600. https://doi.org/10.17265/2162-5263/2016.12.003

Younis, A. M.; Hanafy, S.; Elkady, E. M.; Alluhayb, A. H. and Alminderej, F. M. (2024). Assessment of health risks associated with heavy metal contamination in selected fish and crustacean species from Temsah Lake, Suez Canal. Scientific Reports, 14(1), 18706. https://doi.org/10.1038/s41598-024-69561-7

Yousif, R.A.; Choudhary, M.I; Ahmed, S. and Ahmed, Q. (2021). Bioaccumulation of heavy metals in fish and other aquatic organisms from Karachi Coast, Pakistan, Rev. Nusantara Biosci.,13(1):73-84. https://doi.org/10.13057/nusbiosci/n130111

Zaghloul, G. Y., Eissa, H. A., Zaghloul, A. Y., Kelany, M. S., Hamed, M. A. and Moselhy, K. M. E. (2024). Impact of some heavy metal accumulation in different organs on fish quality from Bardawil Lake and human health risks assessment. Geochemical Transactions, 25(1), 1.

Zeyadah, M.A.; Bahnasawy, M.H.; Deedah, M.A.; El-Emam, A.D. and Adress, M.H. (2023). Evaluation of the Contents of Aliphatic and Aromatic Hydrocarbons in Sediment from Zwitina Harbor Coast (Libya), as Indicator of Petroleum Pollution. Egy. J. Aquat. Bio. Fish., 27(6), 253-265. https://doi.org/10.21608/EJABF.2023.328456

Zhang, Z.; Yu, N.; Liu, D. and Zhang, Y. (2022). Assessment and source analysis of heavy metal contamination in water and surface sediment in Dongping Lake, China. Chemosphere, 307, Article 136016.https://doi.org/10.1016/j.chemosphere.2022.136016

Zhuang, Z.; Xu, Z. and Zhou, Y. F. (2023). The Effect of Marine Oil Spill on Corporate Performance: Evidence from the Penglai: 19-3 Oil Spill. https://doi.org/10.1016/j.chemosphere.2023.138619