QUANTIFICATION OF METALLIC TRACE ELEMENTS IN *MULLUS BARBATUS* (L., 1758) FROM THE WESTERN ALGERIAN COAST: ASSESSMENT OF HUMAN HEALTH RISKS

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Abstract. Marine pollution is a significant environmental concern. This study assesses the extent of contamination of the western Algerian coast by selected trace metals, using the benthic fish *Mullus barbatus* (L., 1758) as a bioindicator. It also evaluates the potential health risks linked to the consumption of this species. Seasonal biological sampling was conducted between March 2023 and February 2024 at two sites: Oran Bay and Ghazaouet Bay. Metal accumulation was analyzed in three target organs: gills, liver, and muscle. The concentrations of Zn, Cu, and Pb were quantified following mineralization using Flame Atomic Absorption Spectrometry. Consumer health risks were assessed through the calculation of specific toxicological indices. Statistical analysis of the spatial variation in average trace metal contents reveals a heterogeneous distribution, particularly for Pb. The results showed significant seasonal variations, with the highest concentrations observed in summer and the lowest in winter. *Mullus barbatus* bioaccumulated all metals, with zinc being the most prevalent, followed by copper and lead. In terms of health risks, estimated daily intake values were within the recommended tolerable daily intake, and both the target risk quotient and the total target risk quotient were <1. Additionally, the carcinogenic risk assessment for Pb indicates no significant cancer risk associated with long-term consumption of this fish. Therefore, while the consumption of red mullet from the Algerian west coast appears safe for consumers, continued monitoring is recommended to track potential marine pollution concerns.
Keywords: *trace metals, estimated daily intake, tolerable daily intake, target risk quotient, carcinogenic risk*

Introduction

The marine environment serves as the ultimate repository for a wide range of contaminants generated by industrial activities, exerting continuous pressure on marine and coastal ecosystems worldwide (Rao et al., 2007).

The Mediterranean Sea, due to its semi-enclosed nature, limited water exchange, and high anthropogenic activity, faces significant toxicological threats, making it particularly vulnerable to pollution (Ayas et al., 2018). Among environmental pollutants, heavy metals pose a severe risk to aquatic ecosystems, as they are persistent, non-biodegradable, and prone to bioaccumulation (Rodrigue et al., 2016).

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Heavy metal contamination in marine ecosystems originates from both natural and anthropogenic sources. Natural inputs include volcanic activity, erosion, atmospheric deposition, and geochemical weathering of bedrock (Aras et al., 2017). However, human activities such as industrial discharges, mining, agricultural runoff, and untreated domestic wastewater represent the dominant sources of heavy metal pollution in coastal waters, significantly altering their chemical composition (Aras et al., 2017).

Once released into the aquatic environment, heavy metals undergo bioaccumulation in marine organisms and may undergo biomagnification through the food chain, ultimately posing a toxicological risk to higher trophic levels, including humans (Chowdhury et al., 2018; Gwimbi et al., 2020; Sattari et al., 2020a, b). Due to their high solubility in water and affinity for biological tissues, heavy metals are rapidly absorbed by marine organisms, leading to their accumulation in various organs (Chowdhury et al., 2018).

The Algerian western coastline is particularly exposed to metallic pollutants, as numerous studies have highlighted the significant anthropogenic pressure affecting its coastal ecosystems (Bouhadiba et al., 2017; Guendouzi et al., 2017; Rouane-Hacene et al., 2018; Rouabhi et al., 2020; Tabeche et al., 2021; Kaddour et al., 2021a, 2022; Belhoucine et al., 2022; Djellouli et al., 2023). However, spatial and temporal variations in heavy metal contamination remain insufficiently documented, particularly in less-studied regions such as the Bay of Ghazaouet.

Seafood consumption represents the primary pathway for human exposure to heavy metals in marine environments. Fish is a key component of the human diet, valued for its high-quality proteins, omega-3 fatty acids, and essential vitamins (Khalili Tilami and Sampels, 2018; Peivasteh-Roudsari et al., 2020). However, the accumulation of heavy metals in edible fish tissues raises concerns regarding potential health risks for consumers. The World Health Organization (WHO) underscores the need for strict monitoring and regulation of heavy metal levels in seafood to ensure public health safety (Artar et al., 2024). The risk of human exposure through the aquatic food chain necessitates continuous surveillance and toxicological risk assessments, particularly in regions affected by intense industrial and urban pollution (Hallare et al., 2016; Igbo et al., 2018).

The red mullet (*Mullus barbatus*, L., 1758) has been widely recognized as a sentinel species in biomonitoring programs (European Commission, 2010). Due to its benthic lifestyle, limited mobility, and feeding habits, this species is highly exposed to sediment-bound contaminants, making it a reliable indicator of historical and ongoing metal contamination (Meinesz, 2011). Moreover, *M. barbatus* is widely distributed along the Algerian coastline and represents a commercially valuable species, heavily consumed by local populations. Given its ecological and economic significance, assessing its bioaccumulation patterns provides valuable insights into both environmental pollution levels and potential human health risks.

This study aims to assess the ecotoxicological status of the western Algerian coast by using *Mullus barbatus* as a bioindicator species. The specific objectives are: (1) To compare metal contamination between Oran Bay and Ghazaouet Bay to identify potential spatial variations. (2) To Assess metal contamination levels (Zn, Cu, Pb) in the biological tissues of *M. barbatus* (liver, gills, and muscle) and analyze their seasonal distribution. (3) to assess the potential health risks associated with human consumption of *M. barbatus*, based on key toxicological indices, including Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), Total Target Hazard Quotient (TTHQ), and Carcinogenic Risk (CR).

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The present work contributes to the broader effort of monitoring heavy metal pollution in the Mediterranean and provides essential data for risk assessment and the development of environmental management strategies along the western Algerian coast.

Material and methods

Study area

Algeria has a 1,622 km coastline along the Mediterranean Sea, with a population estimated at 43.9 million in 2020, the majority of whom reside in coastal areas (ONS, 2020). Due to its geographical position within the Mediterranean basin, the Algerian coastline is subject to significant anthropogenic pressures, including the continuous discharge of untreated urban and industrial wastewater into the sea, primarily due to the lack of wastewater treatment facilities (Belhabib et al., 2022). The country's industrial sector is dominated by petrochemical, steel, and agri-food industries, contributing to marine pollution (Grimes, 2010).

This study focuses on the western Algerian coastline, specifically two key sampling sites: The Bay of Oran and the Bay of Ghazaouet (*Fig. 1*). The Bay of Oran (N 35°43', W 00°38'), located in northwestern Algeria within the southwestern Mediterranean, is part of the Tel Septentrional coastal chain (Djebel Murdjadjo and Djebel Khar) (Leclaire, 1972). The Oran coastline is heavily impacted by industrial activity, intensive tourism, and rapid urbanization, leading to increasing levels of environmental pollution (Kerfouf et al., 2010). Several studies have examined the degradation of the Oran Bay ecosystem, focusing on both biological aspects and the accumulation of pollutants, particularly heavy metals and pesticides, in the tissues of commercially exploited fish species (Belhoucine et al., 2014, 2022; Bouhadiha et al., 2017; Rouabhi et al., 2020; Tabeche et al., 2021; Kaddour, 2021b; Belhabib et al., 2022).

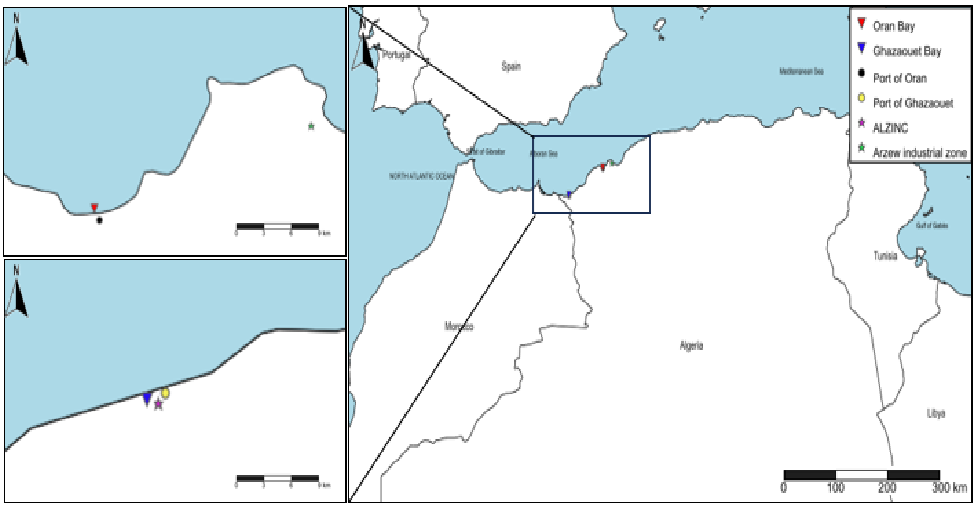

***Figure 1.** Map showing the location of the study area: Oran bay and Ghazaouet bay [Created by SimpleMappr. Accessed March 19, 2025]*

In contrast, the Bay of Ghazaouet (35°06' N - 1°52' W), located in the extreme northwest of Algeria, approximately 10 km from the Algerian-Moroccan border, is primarily affected by industrial, urban, and agricultural waste, leading to the release of

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substantial amounts of contaminants, notably zinc (Zn) and cadmium (Cd), from the ALZINC zinc electrolysis unit, a subsidiary of METANOF (Kalakhi et al., 2022). However, despite these pollution sources, very few studies have been conducted on Ghazaouet Bay, particularly regarding the biological impacts and pollutant bioaccumulation in marine organisms. Most available studies have focused on sediment and plant contamination in the harbor area, reporting heavy metal accumulation (Benguedda-Rahal, 2011; Grimes, 2012).

Despite the economic importance of fisheries in Oran and Ghazaouet, very limited data are available to evaluate the potential toxic effects of heavy metal contamination on commercial fish species, particularly red mullet (*Mullus barbatus*, L., 1758) in these regions. Given that fish consumption represents a major source of dietary exposure to heavy metals, assessing the toxic risk to consumers is a public health priority.

Sample collection and processing

The sampling campaign was conducted over a 12-month period, from March 2023 to February 2024. Samples were collected monthly from two sites, Oran Bay and Ghazaouet Bay, by professional fishermen. A total of 144 individuals of the red mullet (*Mullus barbatus*, L., 1758) were collected, with 72 individuals per site and 18 per season, regardless of sex. All individuals fell within the same length range (18 to 22 cm).

The fish specimens were rinsed with distilled water to remove surface particles, then placed in sterile polyethylene bags and transported on ice to the Toxicology, Environment, and Health Laboratory (LATES) at the University of Science and Technology Oran - Mohamed Boudiaf (USTO-MB) for further processing.

In the laboratory, the samples were subjected to various procedures, including biometry and dissection using stainless steel instruments. Three separate parts were taken from each individual: liver, gills, and muscle. The sub-samples obtained were weighed and stored in labelled pillboxes at -20°C until processed for heavy metal analysis.

Sample digestion and metal analysis

The search for a toxic mineral fixed in the organs always requires mineralization, which leads to total degradation of the organic matter (Amiard et al., 1991).

Mineralization was carried out according to the protocol described by Chiffoleau et al. (2001).

The sub-samples were oven-dried at 60°C for 24 to 72 hours to a constant weight, then ground, a mass of 0.2 g of each dried sub-sample was weighed and a volume of 4 ml of pure nitric acid HNO_3 was added and left at room temperature overnight. The resulting solutions were placed in an oven at 90°C for 3 hours. After cooling, the mineralizates were filtered through Wattman filter paper and stored in polyethylene containers at 4°C until the analysis of trace metal element concentrations which will be determined using a flame atomic absorbance spectrophotometer of the Perkin Elmer specifically AAnalyst 400.

At the same time, each series of mineralization is systematically accompanied by a digestion of a standard blank (nitric acid), and on the other hand by an inter-calibration sample on a biological reference material coded 140/TM, provided by the International Atomic Energy Agency (IAEA, 1995), thus allowing the determination of coefficients of variation for each metal being investigated and the verification of the accuracy and precision of the analytical protocol.

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Statistical analysis

In our present work, the Shapiro-Wilk test was used to determine whether the distribution of the investigated parameters was normal. The mean and standard error of the mean (SEM) were calculated for each group based on six samples. Statistical significance was determined at a *p*-value of ≤ 0.05. One-way analysis of variance (ANOVA) and Tukey's post hoc test were used to evaluate group differences, and for these statistical calculations, IBM SPSS Statistics 26 (Armonk, NY, USA) was used.

Human health risk assessment

The human population principally eats fish muscles as food. Consequently, a number of indices were evaluated in our study in order to estimate the potential health risks that could arise from eating contaminated fish.

Estimated daily intake of metal (EDI)

The estimated daily intake (EDI) is the amount of a substance that can be ingested daily based on body weight.

The tolerable daily intake (TDI) values suggested by the European Food Safety Authority (EFSA, 2009, 2014) and the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2011) are compared to the EDI values.

The following equation was used to determine an adult's daily metal intake (Ebadi Fathabad et al., 2021; Hashempour-baltork et al., 2023):

$$EDI = \frac{\mathrm{Cm} \times \mathrm{FIR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \quad \text{(Eq.1)}$$

where, Cm is the metal concentration in fish (mg/g dry weight), FIR is the fish ingestion rate, set at 12 g/person/day, by MADRP (2016) for an Algerian population, EF is the frequency of exposure (set at 365 days/year), ED is the duration of exposure (76 years) equivalent to life expectancy at birth, BW is the average body weight for an adult (75 kg) (Abbes, 2017), AT is the average exposure time for non-carcinogens (365 days/year × 76 years). EDI was expressed as mg/kg/day.

Non-carcinogenic risk

Target hazard quotient (THQ)

The non-carcinogenic health risk was determined using the Target Hazard Quotient equation.

The Target Hazard Quotient (THQ) is defined as the ratio of the lifetime average daily dose to the reference dose (RfD) (EPA, 1989). The target hazard quotient (THQ) presents a signal of the risk level caused by pollutant exposure but does not predict the actual adverse health impacts on the exposed population.

A dose equal to or greater than 1 (THQ > RfD) will pose health risks to an exposed population, however, a ratio of less than 1 indicates a non-obvious risk (EFSA, 2014).

The following equation is used to calculate it (Hashempour-Baltork et al., 2023):

$$\mathrm{THQ} = \frac{\mathrm{EDI}}{\mathrm{RfD}} \quad \text{(Eq.2)}$$

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where, EDI is estimated daily intake of metal (mg/kg/BW/day), RfD is the reference oraldose (for Zn = 3×10^{-1}mg/kg/day, Cu = 4×10^{-2} mg/kg/day, Pb = 4×10^{-3} mg/kg/day) (USEPA, 2010).

Total target hazard quotient (TTHQ)

The total target hazard quotient (TTHQ) is used in order to determine the possible danger resulting from ingesting more than one heavy metal because consumers are regularly exposed to various pollutants with related combinations or interactive effects.

TTHQ value more than 1 indicates the presence of deleterious health impacts associated with exposure to contaminated food (Nowakowski et al., 2021).

The following equation is used to express TTHQ, which is the sum of the hazard quotients (Núñez et al., 2018).

$$TTHQ = \sum THQi \qquad \text{(Eq.3)}$$

Carcinogenic risk (CR)

When it concerns carcinogens, risks were calculated as the incremental possibility that a person will get cancer over the course of their lifetime as a result of being exposed to a potential carcinogen (EPA, 2011).

The safe limit for cancer risk is ≤ 10^{-6} ,substantial risk limit is nearly 10^{-6} _ 10^{-4},and serious risk level of cancer is ≥ 10^{-4}.

The following equation was used to calculate the Carcinogenic risk (Hashempour-Baltork et al., 2023):

$$\mathrm{CR} = \mathrm{EDI} \times \mathrm{CSF} \qquad \text{(Eq.4)}$$

where, EDI is estimated daily intake of metal (mg/kg/BW/day), CSF is the cancer slope factor (mg/kg/day) Only Pb (8.5×10^{-3} mg/kg/ day) has a CSF value available (USEPA, 2010).

Results

Heavy metals concentration

Spatial variations

Figure 2 shows the spatial distribution of average concentrations of the targeted trace metals zinc, copper and lead in red mullet *Mullus barbatus* (L., 1758) caught in Oran and Ghazaouet bays.

No significant differences in Zn and Cu concentrations were observed between the two sites. Zn remained the most abundant metal at both locations, followed by Cu, with comparable levels in Oran and Ghazaouet. However, a significant spatial variation was detected for Pb, with concentrations in Oran being significantly higher than those in Ghazaouet ($p \leq 0.05$).

Regarding metal distribution, Zn exhibited the highest accumulation at both sites, significantly exceeding Cu and Pb levels ($p \leq 0.05$). Cu showed intermediate concentrations, while Pb was the least abundant metal, with the lowest values recorded

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in Ghazaouet. Zn concentrations were the highest, reaching 3.97 ± 0.62 $\mu g \cdot g^{-1}$ DW in Oran and 3.27 ± 0.45 $\mu g \cdot g^{-1}$ DW in Ghazaouet, followed by Cu with 1.36 ± 0.21 $\mu g \cdot g^{-1}$ DW in Oran and 1.07 ± 0.07 $\mu g \cdot g^{-1}$ DW in Ghazaouet. Pb exhibited the lowest concentrations, with significantly higher values in Oran (0.40 ± 0.18 $\mu g \cdot g^{-1}$ DW) compared to Ghazaouet (0.32 ± 0.16 $\mu g \cdot g^{-1}$ DW).

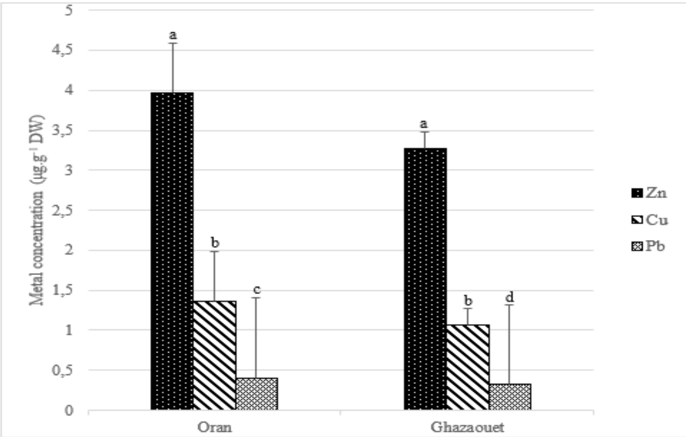

Figure 2. *Spatial variations in the average levels of trace metals (Zn, Cu, and Pb) $\mu g.g^{-1}$ DW in red mullet Mullus barbatus (L., 1758) caught in Oran Bay and Ghazaouet Bay. The lettrers a, b, c, and d indicate significant spatial variations, as determined by Tukey's multiple comparison test for the same matrix*

Seasonal variations

Figures 3 and *4* show seasonal variations in average concentrations of the targeted trace metals zinc, copper, and lead on a dry weight basis, assessed in the three tageted organs (gills, liver, and muscle) of red mullet *Mullus barbatus* (L., 1758) caught in the two study areas.

In Oran Bay, statistical analysis of the mean trace metal content in red mullet (*Fig. 3*) revealed a highly significant seasonal variation ($p \leq 0.001$), while copper (Cu) in the liver, showed a significant variation ($p \leq 0.05$).

The study of seasonal variations in trace metal concentrations revealed that the organs of red mullet, which are collected mainly in the summer, spring, and autumn seasons, had the highest average values. On the other hand, the lowest concentrations were observed in winter.

In the gills, Zn, Cu, and Pb reached peak levels in summer (4.84 ± 0.39 $\mu g.g^{-1}$ DW, 1.75 ± 0.17 $\mu g.g^{-1}$ DW, 0.77 ± 0.03 $\mu g.g^{-1}$ DW, respectively), significantly higher than in winter, where concentrations dropped to 3.44 ± 0.75 $\mu g.g^{-1}$ DW, 1.09 ± 0.13 $\mu g.g^{-1}$ DW, and 0.21 ± 0.16 $\mu g.g^{-1}$ DW.

In the liver, Zn and Pb followed a similar seasonal pattern, with the highest concentrations recorded in summer (4.71 ± 0.43 $\mu g.g^{-1}$ DW, 1.46 ± 0.16 $\mu g.g^{-1}$ DW, 0.63 ± 0.15 $\mu g.g^{-1}$ DW) and significantly lower values in winter, reaching 3.19 ± 0.71 $\mu g.g^{-1}$ DW, 1.10 ± 0.18 $\mu g.g^{-1}$ DW, and 0.19 ± 0.06 $\mu g.g^{-1}$ DW.

In the muscle, Zn, Cu, and Pb also displayed significant seasonal trends, with the highest values in summer (4.61 ± 0.36 $\mu g.g^{-1}$ DW, 1.46 ± 0.15 $\mu g.g^{-1}$ DW, 0.44 ± 0.09 $\mu g.g^{-1}$ DW) and the lowest in winter (3.06 ± 0.75 $\mu g.g^{-1}$ DW, 1.03 ± 0.13 $\mu g.g^{-1}$ DW, 0.14 ± 0.09 $\mu g.g^{-1}$ DW).

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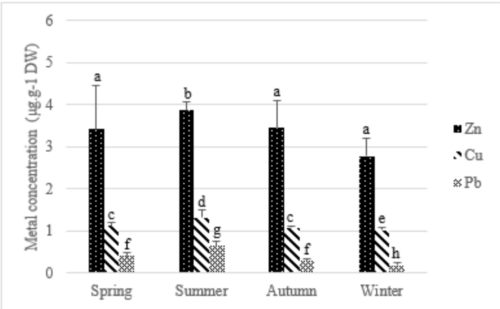

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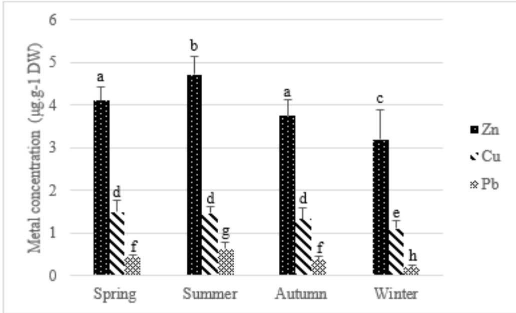

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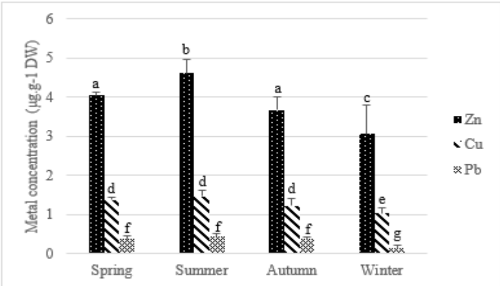
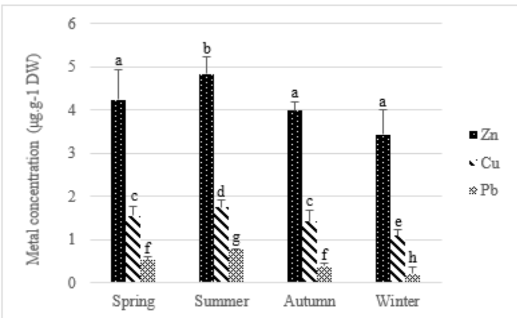


(c)

Figure 3. *Seasonal variations in average heavy metals levels µg.g^{-1} DW in the three target organs (gills (a), liver (b) and muscle (c)) of red mullet Mullus barbatus (L., 1758) caught in Oran Bay. The letters a, b, c, d, e, f, g, and h indicate significant seasonal variations, as determined by Tukey's multiple comparison test for the same matrix*



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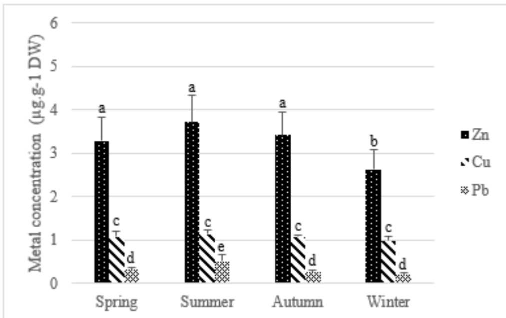

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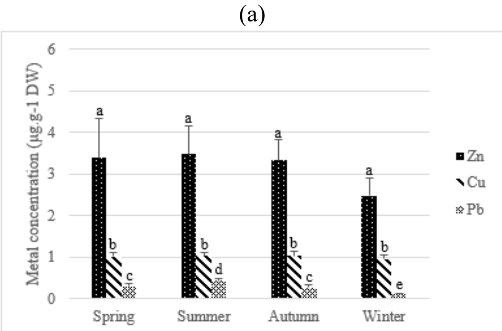

(c)

Figure 4. *Seasonal variations in average heavy metals levels µg.g^{-1} DW in the three target organs (gills (a), liver (b) and muscle (c)) of red mullet Mullus barbatus (L., 1758) caught in Ghazaouet Bay.The lettrers a, b, c, d, e, f, g, and h indicate significant seasonal variations, as determined by Tukey's multiple comparison test for the same matrix*

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In Ghazaouet Bay, statistical analysis of seasonal variations in trace metal concentrations in red mullet (*Fig. 4*) revealed a highly significant variation ($p \leq 0.001$) for most metals. However, Zn in the liver showed only a significant variation ($p \leq 0.05$), while no significant differences were observed for Cu in the liver and for Zn and Cu in muscle tissue.

In the gills, Zn, Cu, and Pb concentrations varied significantly across seasons. The highest levels were recorded in summer, respectively equal to 3.86 ± 0.20 $\mu g.g^{-1}$ DW, 1.31 ± 0.19 $\mu g.g^{-1}$ DW , and 0.64 ± 0.12 $\mu g.g^{-1}$ DW, while the lowest concentrations were observed in winter, reaching 2.78 ± 0.42 $\mu g.g^{-1}$ DW, 1.02 ± 0.07 $\mu g.g^{-1}$ DW, and 0.18 ± 0.06 $\mu g.g^{-1}$ DW.

Similarly, in the liver, Zn and Pb concentrations showed a significant seasonal pattern. The highest values were recorded in summer 3.72 ± 0.61 $\mu g.g^{-1}$ DW, and 0.51 ± 0.14 $\mu g.g^{-1}$ DW, whereas winter concentrations were significantly lower 2.62 ± 0.45 $\mu g.g^{-1}$ DW, and 0.19 ± 0.05 $\mu g.g^{-1}$ DW. However, no significant seasonal variation was observed for Cu in the liver.

In the muscle, seasonal variation was only significant for Pb, with the highest values recorded in summer 0.43 ± 0.06 $\mu g.g^{-1}$ DW Pb and the lowest in winter 0.10 ± 0.04 $\mu g.g^{-1}$ DW. Zn and Cu concentrations in muscle did not show significant seasonal variations.

Human health risk assessment

By comparing our results for heavy metals in the muscle of the red mullet *Mullus barbatus* (L., 1758) against the tolerated threshold (*Table. 1*), we can deduce that the values recorded in Oran Bay and Ghazaouet Bay remain below the permissible limit values for international standards such as FAO, WHO, and FEPA (Demir et al., 2024).

Table 1. *Comparisons of average concentrations of trace metals (Zn, Cu and Pb) in the edible part (muscle) of red mullet caught in Oran and Ghazaouet bays with respect to maximum permissible doses for international standards*

	Zn	**Cu**	**Pb**
Oran	3.85±0.65	1.27±0.19	0.33±0.13
Ghazaouet	3.17±0.46	1.01±0.03	0.28±0.14
FAO	30	30	0.5
WHO	40	30	0.5
FEPA	*	*	2

(Mean ± SD), FAO: Food and Agriculture Organisation, WHO: World Health Organization, FEPA: Federal Environmental Protection Agency

The results obtained in *Table 2* illustrate the correlation between heavy metals (Zn, Cu and Pb) present in the muscle tissue of red mullet *Mullus barbatus* (L., 1758) from two different regions and potential risks to human health.

The EDI values calculated for all metals did not exceed the tolerable daily intake (TDI) threshold established by the European Food Safety Authority (EFSA, 2009, 2014) and the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2011).

THQ values recorded at both sites were much less than 1. Similarly, total target hazard quotient (TTHQ), which describes the combined effect of consuming multiple trace metals from a fish, was also less than 1. However, the risk of cancer from consuming lead did not exceed the 10^{-6} threshold.

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Table 2. *Assessment of the health risks to consumers for each metal found in edible tissues of red mullet Mullus barbatus (L., 1758) from the west coast of Algeria*

Study site	Metal	EDI (mg/kg/day)	THQ	TTHQ	CR
	Zn	6.16×10^{-4}	2.05333×10^{-3}		
Oran	**Cu**	2.032×10^{-4}	5.08×10^{-3}	2.033333×10^{-2}	
	Pb	5.28×10^{-5}	1.32×10^{-2}		$4{,}488 \times 10^{-7}$
	Zn	5.072×10^{-4}	1.69067×10^{-3}		
Ghazaouet	**Cu**	1.616×10^{-4}	4.04×10^{-3}	1.693067×10^{-2}	
	Pb	4.48×10^{-5}	1.12×10^{-2}		$3{,}808 \times 10^{-7}$

EDI: Estimated daily intake, THQ: Target hazard quotient, TTHQ: Total target hazard quotient, CR: Carcinogenic risk

Discussion

The concentration of heavy metals in fish tissues

Coastal areas offer humanity numerous advantages, in terms of food sources and ecological comforts. Heavy metal pollution has become an international concern due to its inherent persistence, non-biodegradability, and accumulative tendencies (Islam et al., 2018). The Algerian west coast is relatively polluted. Pollutant concentrations are high in all indicator marine species, benthic or pelagic, and they differ between individuals and sample sites, which presents a risk for consumers of fish and seafood (Boutiba et al., 2003).

In our study, all the heavy metals we were looking for - zinc, copper and lead - were present in the samples studied (liver, gills and muscle) of red mullet from the Gulf of Oran and Ghazaouet, in high and heterogeneous concentrations. Heavy metal bioaccumulation in this specimen shows a clear seasonal variation.

The highest average concentrations of metal pollutants were recorded in red mullet caught in Oran Bay, followed by Ghazaouet Bay. Whatever the fishing site, average Zn concentrations were the highest, followed by Cu, and Pb. Processing of the results obtained shows that the average metal concentrations measured in red mullet are in the following descending order of accumulation: Zn>Cu>Pb.

The same classification of the TME accumulation gradient has often been observed in this region for different marine species (Guendouzi et al., 2017; Rouabhi et al., 2019; Tabeche et al., 2021; Kaddour et al., 2022). Similar results have also been observed, by Olgunoğlu et al. (2015) in the northeastern part of the Mediterranean Sea of Turkey and Monier et al. (2023) in Damietta, northern Egypt.

The toxicity and persistence capacities of heavy metals, such as copper (Cu), zinc (Zn), and lead (Pb), are so great that they can biomagnify, bioaccumulate, and have combined impacts on the human food chain before reaching a set of limits in the aquatic ecosystem (Ahmed et al., 2015; Kibria et al., 2016). Fish can absorb and accumulate toxic metals from the aquatic environment via ingestion.

The bioaccumulation process of xenobiotic elements in aquatic organisms depends on a number of factors, including the concentration of the metal in the water, the exposure time, the absorption process, environmental conditions (temperature, pH, dissolved oxygen) and intrinsic factors such as age, feeding habits and habitat (Nyarko et al., 2023).

Generally, benthic fish accumulate higher concentrations of heavy metals than pelagic species (Bustamante et al., 2003; Belhoucine et al., 2015; Bouhadiba et al., 2017; Tabeche

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et al., 2021). This trend is similar to what was noted in the South China Sea (Qian et al., 2020), where it has been determined that sediments have a larger role in fish heavy metal accumulation than water does. The red mullet is a benthic species, in close relationship with the sediment, characterized by its low mobility and its food, which is rich in algae, polychaetes, crustaceans, gastropods and fish (Gon and Heemstra, 1990).

Previous research has demonstrated that heavy metals are considered contaminants in coastal and marine environments around the world, originating from anthropogenic, agricultural, and industrial wastes (Belhaouari et al., 2011; Onivogui et al., 2013; Abi-Ayad et al., 2018; Alik et al., 2020; Tabeche et al., 2021).

The Bay of Oran is exposed to various forms of nuisances, such as industrial activity, intensive tourism and massive urbanization, resulting in increasing pollution. The high levels can also be explained by the fact that Oran Bay is under the direct influence of maritime traffic. The paints used to coat boat hulls, considered antifouling, are based on copper compounds and/or synthetic chemicals that persist in the environment over the long term, as well as the engine effects and gasoline vapour emissions that contribute to pollution (Alik et al., 2020). In addition, other sources of pollution include domestic wastewater, mining activities, agricultural spreading and urban activities.

In this context, we can argue that our data are comparable to those recorded by Bouhadiba et al. (2017), Rouane-Hacene et al. (2018), Tabeche et al. (2021), Belhoucine et al. (2022), Kaddour (2021b) and Belhabib et al. (2022).

According to Rouabhi (2020), the Arzew industrial zone, which processes and exports hydrocarbons mostly to Europe, may be the reason for the excessive lead concentrations in Oran Bay. Belhoucine et al. (2014) suggest that the higher concentrations may also be the result of automobile fuel combustion.

The values recorded by Tabeche et al. (2021) and Kalakhi et al. (2022) are almost identical to our results. The latter pointed out that the coastal marine waters of Ghazaouet are continually exposed to industrial, urban and agricultural waste, releasing huge quantities of contaminants and trace metals, particularly Zn and Cd, from a large industrial zinc electrolysis complex near the port of Ghazaouet (Benguedda et al., 2011; Belhadj et al., 2017; Tabeche et al., 2021). This plant produces and commercializes cathode copper, sulfuric acid, zinc and its alloys (Benguedda et al., 2011), and uses seawater to cool its thermal power plant and its facilities for producing sulfuric acid (Bakalem, 1980).

The highest average concentrations of the three metals studied (Zn, Cu, and Pb) were observed during the summer and spring periods in red mullet. Seasonality plays a crucial role in the distribution of data, and is one of the most crucial factors in the accumulation of pollutants.

Comparable seasonal variations in various fish species from the Algerian West coast have been reported, notably *M. cephalus*, *S. solea* and *M. merluccius* (Bouhadiba et al., 2017; Tabeche et al., 2021; Kaddour et al., 2022).

Similar increases in metal levels were observed during the summer in fish species from the Gulf of Iskenderun (Aytekin et al., 2019), and in the work of Miramand et al. (2000) for *Mullus barbatus* from French marine waters, Ennouri et al. (2012) from the Gulf of Tunis, Aissaoui et al. (2021) on the Bay of Algiers, the Gulf of Béjaïa and the Bay of Dellys, Soliman et al. (2021) from the Syrian coast.

The dry season saw a greater buildup of metals than the rainy season; this could be attributed to an increase in human activity during this time of year as well as an increase in fish physiological activity brought on by the increase in temperature.

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Martinez-Gomez et al. (2012) assert that changes in the fish's physiological state during the reproductive season will have an impact on the accumulation of metal elements. Indeed, according to Layachi et al. (2007), the lowest values of *M. barbatus's* vacuity coefficient were observed in winter, with a decline beginning in summer.

Therefore, during the reserve accumulation seasons in this species, the trophic transfer of these metals (autumn/winter) is observed. Merbouh (1997) has noted in *M. barbatus* and *S. pilchardus* an increased hepatic activity occurring before and after spawning, which explains the high accumulation of pollutants due to the trophic regime.

According to Bennett (1978), higher water temperatures lead to increased gill ventilation in response to lower oxygen concentrations in the water. This not only leads to greater metal uptake due to the fish's higher metabolism, but also changes the properties of the metals themselves, amplifying their availability in the environment (El Morhit et al., 2009).

Fish can take in and accumulate toxic metals from their aquatic environments through ingesting, ion exchange through their membrane surfaces and gills, or adsorption by their tissues (Ahmed et al., 2014).

Health-risk assessment for fish consumption

Given the toxicity of heavy metals and their potential influence on human health, various approaches have been developed to assess the potential health risks associated with their consumption. The aim of these approaches is to assess and reduce the hazards associated with heavy metal exposure for individuals consuming these contaminated fish, thereby ensuring the safety and well-being of the population (Dökmeci et al., 2019).

Generally, Algerians don't eat liver and gills, they just eat muscles. As a result, only the muscle has been studied in terms of their impact on consumers' dietary health.

The results in *Table 1* shows that average concentrations of zinc (Zn), copper (Cu), and lead (Pb) in *M. barbatus* muscles (Oran and Ghazaouet) were significantly below the maximum permitted levels set by leading regulatory bodies such as FAO, WHO, and FEPA (Demir et al., 2024). According to the European Commission, lead has been included in the priority list of dangerous substances. Although marine species' muscle tissue frequently contains low concentrations of metals, the harm it provides can occasionally differ depending on how much it is consumed.

In this study, the daily intake of heavy metals was calculated and compared with recommended values to determine whether the levels of metals found in fish samples from the Algerian West coast are acceptable for personal consumption (*Table 2*).

EDI values of Zn, Cu and Pb at both sites (Oran Bay and Ghazaouet Bay) were well below the TDI limits established by the European Food Safety Authority (EFSA, 2009, 2014) and the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2011), meaning that there was no significant health risk to adults consuming the fish samples examined.

In addition, the data shown in *Table 2* show that the target hazard quotient (THQ) values for all metals and at both sites were well below 1, indicating that the concentrations measured in *M. barbatus* muscle do not represent an adverse effect on consumer health. These values are comparable to those reported by Traina et al. (2019) in the red mullet muscle of the Sicilian coast, to those found by Kılıç et al. (2021) in the bays of İskenderun, Mersin and Antalya and to those recorded by Aissaoui et al. (2021) in the three sites Algiers, Bejaia and Dellys.

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However, the total target risk quotient (TTHQ), which describes the combined effect of consuming multiple trace metals from a fish, were less than 1, indicating that consumers would not suffer non-carcinogenic health effects from eating *M. barbatus*.

The probability that an individual will acquire cancer in their lifetime has been determined using the cancer risk (CR) after exposure to carcinogens. The CR values recorded for Pb are less than 10^{-6} (*Table 2*), suggesting that there is no potential risk of carcinogenesis from consumption of fish from this area. Comparable results were reported by Traina et al. (2019) in the muscle of *M. barbatus* from the Mediterranean Sea in Italy.

Based on the EDI, THQ, TTHQ and CR data calculated, it can be concluded that consumption of red mullet from the Algerian West coast poses no risk to human health.

This observation in no way diminishes the potential risk to human health in the medium and long term if urgent measures are not put in place to control the wholesomeness of seafood products, vectors of toxic agents, in particular lead, since this xenobiotic has reached levels that are alarming for public health.

Conclusion

Pollution caused by heavy metals is a global issue with consequences for the proper functioning of ecosystems, food safety and international security. Fish have the ability to transport accumulated metals to humans thanks to their higher metal absorption mechanism in their organs.

This study, whose importance we emphasize, enables us to assess the current situation of Oran Bay and Ghazaouet Bay in terms of coastal and marine environmental pollution, and to evaluate the potential risk to the health of the general population.

According to the results of this study, seasonal differences were observed for trace metal concentration levels in the tissues of *Mullus barbatus* caught on the Algerian West coast, with generally higher levels reported during the summer season Among the dominant metals, zinc stands out clearly from the other two elements, with very high levels. This may be linked to a number of biological factors and under the influence of certain environmental parameters, principally temperature.

As it happens, the variations in average trace metal contents observed in Oran Bay and Ghazaouet Bay indicate a heterogeneous distribution, particularly for Pb.

It has been determined that the estimated amount of metal absorbed by the body through daily consumption of this fish species does not present a lifetime health risk, and that there is no carcinogenic or non-carcinogenic health risk.

Although there is no risk involved in eating these species currently fished on the Algerian West coast, we can't rule out the possibility that this may change in the future. It is therefore advisable to set up a system for continuous monitoring of harmful substance levels in these fish to guarantee their safety for human consumption.

The results obtained show that *M. barbatus* could be considered a good bioindicator of the environmental quality of aquatic ecosystems due to its demersal behavior, feeding habits, and ability to accumulate metals in its tissues.

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