JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(5), 170–180
https://doi.org/10.12911/22998993/200887
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.02.05
Accepted: 2025.02.24
Published: 2025.03.16

Human health risks assessment related to heavy metal bioaccumulation in the muscle tissues of *Cyprinus carpio*, *Sander lucioperca* and *Oreochromis niloticus* from Moroccan continental waters

Sara Ouahb[1], Ferraj Loubna[1], Bousseba Meriem[1], Bensaber Abdelfattah[2], Mly Ouahidi Lahcen[2], El Bouch Mohammed[2], Hasnaoui Mustapha[1]

[1] Environmental, Ecological and Agro-Industrial Engineering Laboratory, Faculty of Sciences and Techniques, Sultan Moulay Slimane University, BP. 523, 23 000 Beni Mellal, Morocco
[2] National Laboratory for Pollution Studies and Monitoring, Rabat, Morocco
* Corresponding author's e-mail: sara.ouahab94@gmail.com

ABSTRACT

The contamination of aquatic ecosystems by heavy metals represents a major environmental issue due to their toxicity, persistence, and ability to bioaccumulate within the food chain. The Common carp (*Cyprinus carpio*), pike-perch (*Sander lucioperca*), and Nile tilapia (*Oreochromis niloticus*) are key indicators of this contamination, as they can accumulate these metals at potentially toxic concentrations. The bioaccumulation of zinc, iron, copper, manganese, chromium, and aluminum in the muscle of the three studied fish species from the Al Massira reservoir was assessed to estimate the health risks related to their consumption. Iron and zinc represent the highest concentrations, respectively (46.77 mg/kg of dry weight for *Cyprinus carpio*, 48.73 mg/kg of dry weight for *Sander lucioperca*, and 38.41 mg/kg for *Oreochromis niloticus*) and (56.22 mg/kg of dry weight for *Cyprinus carpio*, 29.43 mg/kg of dry weight for *Sander lucioperca*, and 34.41 mg/kg for *Oreochromis niloticus*). The analysis of parameters such as the estimated weekly intake (EWI), the percentage of the provisional tolerable weekly intake (%PTWI), the maximum allowable daily intake (CRlim), the estimated daily intake (EDI), the target hazard quotient (THQ), and the hazard index (HI) helps to better understand the risks associated with the consumption of these contaminated fish. The results show that the levels of heavy metals in the three fish species studied remain below the thresholds for non-carcinogenic risks. The hazard index (HI) is very low, indicating that the consumption of these fish does not pose a significant health risk to humans. However, particular attention should be paid to chromium (Cr), as its concentration could become concerning in cases of excessive consumption. This study provides important data for assessing the health risks associated with the consumption of freshwater fish in Morocco. The results obtained can guide aquatic resource management policies and raise awareness among local populations about the potential risks associated with heavy metal bioaccumulation.

Keywords: bioaccumulation, heavy metals, health risk assessment, *Cyprinus carpio*, *Sander lucioperca*), *Oreochromis niloticus*, Al-Massira Dam Lake, Morocco.

INTRODUCTION

Aquatic pollution by heavy metals is one of the most concerning threats to the quality of aquatic ecosystems and human health. Heavy metals such as zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), chromium (Cr), and aluminum (Al) can accumulate in water bodies due to human activities, including industrial, agricultural, and domestic discharges (Chahid et al., 2014). Once present in aquatic environments, these metals can be absorbed by fish, posing a risk to aquatic fauna and human health.

While essential metals must be absorbed by fish for their normal metabolism or bodily functions (Canli et Atli, 2003), heavy metals such as mercury, cadmium, and lead have no biological or beneficial function in living organisms

(Robert, 1991; Ekeanyanwu et al., 2015) and can be highly toxic.

Freshwater fish represent an important source of protein for populations (Benabdelkader et al., 2018). They play a vital role in human nutrition and are a valuable and inexpensive food source. Therefore, it is essential to carefully monitor them to ensure that high levels of toxic heavy metals are not transferred to humans through consumption (Olaifa et al., 2004; Adeniyi et Yusuf, 2003).

The bioaccumulation of these metals in fish can have toxic impacts, including effects on the neurological, renal, and hepatic systems in humans (WHO, 2011). It is therefore crucial to monitor the metal contamination of these species to protect public health and ensure food safety.

This study contributes to assessing the health risks associated with the consumption of freshwater fish in Morocco. It provides valuable data to guide aquatic resource management policies and to raise awareness among local communities about the potential dangers of heavy metal bioaccumulation in fish.

MATERIALS AND METHODS

Study area

The Al-Massira Dam Lake is considered the cornerstone of the watershed management plan for the Oum Er Rbia River basin. Located at 120 km southeast of Casablanca (32°28'32" North, 7°32'15" West), and is the second-largest reservoir in Morocco. It extends over a length of 30 km, with a maximum width of 10 km and a depth that can reach up to 40 m. It covers an area of 139 km², with a storage capacity of 2,760 million m³. The water resources of this watershed mainly come from the surface waters of three major rivers, supplemented by groundwater contributions. Built in 1979, it plays a crucial role in irrigation and houses a hydroelectric power station generating an average of 221 GWh per year.

Sampling

A total of 108 samples were collected from the Al Massira Dam Lake and then transported to the laboratory. For the muscle tissue samples, 0.2 g of each sample was weighed, and 5 ml of 65% nitric acid and 2 ml of hydrogen peroxide were added to each sample. The samples were then placed in a microwave oven at a temperature of 190 °C (Environmental Analysis Expertise Center of Quebec, 2003) for tissue digestion and complete evaporation of the acid. After cooling, the samples were transferred to tubes and adjusted to 50 ml with ultra-pure water. Heavy metals were measured using a microwave plasma atomic emission spectrometer (MP-AES). The metal concentrations in the muscle tissue samples are presented in mg per kg of wet weight.

Human health risk assessment

The estimated daily intake (EDI)

The estimated daily intake refers to the average amount of a contaminant that an individual is likely to ingest each day through the consumption of fish, water, or other environmental sources. It is typically expressed in units of mass per body weight per day (e.g., mg/kg/day). The estimated daily intake of each heavy metal is calculated as follows (USEPA, 2015):

$$EDI\ (mg/kg^{-1}/day^{-1}) = \frac{EF \times ED \times FIR \times C}{WAB \times ATn} \quad (1)$$

where: EF – exposure frequency (in days per year), ED – exposure duration (in years), FIR – fish ingestion rate (13.87 kg per year). This represents the average amount of fish consumed annually by adults and children (Kasmi et al., 2023; Azekour et al., 2020), C – concentration of the heavy metal in the fish muscle tissue (in mg/kg of fish), WAB – average body weight of the adult (in kg). This represents the average weight of an adult individual, often used to calculate exposure relative to body weight. In our case, it represents 73.3 kg for adults (Kasmi et al., 2023; Azekour et al., 2020), ATn – average exposure time or exposure age (in days). This is the period during which the individual has been exposed to the contaminant. It can be calculated by taking the average age of the population and the period during which they have consumed fish.

Target hazard quotient (THQ)

The THQ is an indicator used to assess non-carcinogenic risks associated with exposure to toxic substances. The THQ is calculated (USEPA, 2011) using the following Equation 2:

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

where: RfD – oral reference dose (mg/kg⁻¹/day⁻¹).

According to data from USEPA (2011), the reference dose for zinc (Zn) is 0.3 mg/kg/day, for copper (Cu) it is 0.04 mg/kg/day, for manganese (Mn) it is 0.14 mg/kg/day, and for chromium (Cr) it is 0.5 mg/kg/day. No reference dose has been defined for iron (Fe). For aluminum (Al), the reference dose is extremely low, at 0.0002 mg/kg/day, according to the same source.

The hazard index (HI)

The hazard index (HI) is used to assess the cumulative health risks related to exposure to multiple toxic substances, considering their non-carcinogenic effects. It is calculated as the sum of the target hazard quotients (THQ) for each substance or metal under study (Giri and Singh, 2015).

$$HI = \sum_{i=1}^{n} \text{THQ} \quad (3)$$

Maximum acceptable daily intake (CRlim)

The maximum acceptable daily intake (*CRlim*) is the maximum amount of a food that a person can consume daily without exceeding the safety thresholds related to the toxicity of a non-carcinogenic contaminant, such as a heavy metal (Alipour et al., 2015).

$$CRlim = \frac{\text{RfD} \times \text{WAB}}{\text{C}} \quad (4)$$

Estimated weekly intake (EWI)

The EWI is a measure used to estimate the amount of a contaminant ingested each week by a person through the consumption of contaminated fish.

$$EWI = \frac{Cm \times CR}{WAB} \quad (5)$$

where: *Cm* – concentration of the contaminant in the muscle tissues of the consumed fish, *CR* – (consumption rate, in kg/week): the rate of fish consumption by an individual. In this case, it is 0.25 kg/week, FAO (2016).

Percentage of provisional tolerable weekly intake (%PTWI)

The %PTWI is used to assess whether the weekly consumption of a contaminant exceeds or stays within limits considered safe for human health (Miri et al., 2017).

$$\%PTWI = \frac{EWI}{PTWI} \times 100 \quad (6)$$

where: PTWI – a reference dose established by the FAO/WHO joint expert committee on food additives (JECFA, 2011). It represents the maximum weekly amount of a contaminant that can be consumed without significant health risks (zinc: 7 mg/kg/week, iron: 6.4 mg/kg/week, copper: 3.5 mg/kg/week, manganese: 7 mg/kg/week, chromium: 0.2 mg/kg/week and aluminum: 2 mg/kg/week).

Statistical analysis

Data analyses were performed using the statistical software R (version 4.3.2). An analysis of variance (ANOVA) was used to evaluate differences between species.

RESULTS

Distribution of heavy metals in the muscle tissues of *Cyprinus carpio*, *Sander lucioperca* and *Oreochromis niloticus*

The mean concentrations and standard errors of the six heavy metals studied in muscle of freshwater fish (*Cyprinus carpio*, *Sander lucioperca* and *Oreochromis niloticus*) are presented in Table 1.

To provide more precision on the nature of the heavy metals influencing the average concentrations recorded, the Figure 1 illustrates the average content of different heavy metals (Zn, Fe, Cu, Mn, Cr, and Al) measured in mg/kg of dry weight for the three fish species studied. The error bars indicate the variability of the measurements for each metal.

Table 1. Mean concentrations (± SE) of heavy metals (mg/kg dry weight) in the muscle of the three studied species

Species	Zn	Fe	Cu	Mn	Cr	Al
Cyprinus carpio	56.22 ± 28.23	46.77 ± 13.27	2.61 ± 0.70	1.19 ± 0.56	2.27 ± 0.38	16.05 ± 11.45
Sander lucioperca	29.43 ± 4.45	48.73 ± 94.59	1.46 ± 0.94	0.94 ± 0.44	4.52 ± 12.81	13.66 ± 5.18
Oreochromis niloticus	34.41 ± 9.99	38.41 ± 15.28	1.77 ± 0.81	1.42 ± 0.77	2.41 ± 0.29	12.86 ± 10.35

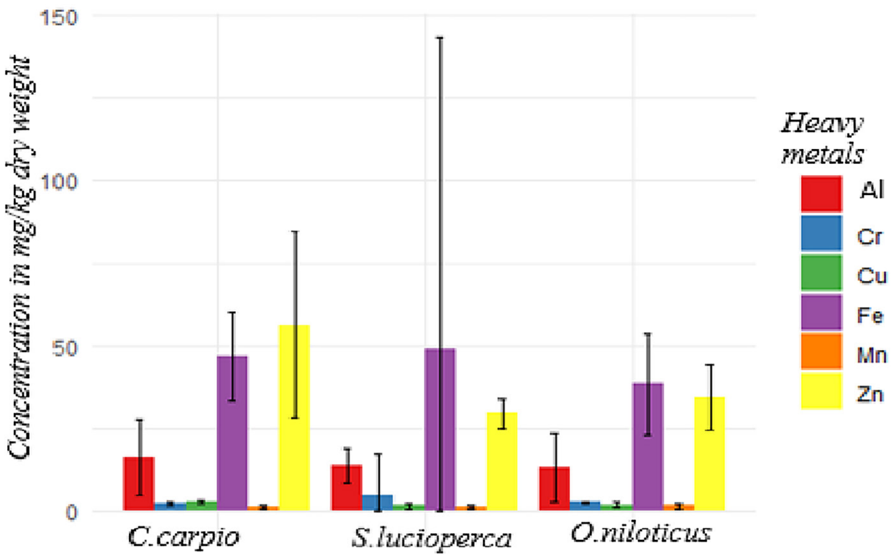

Figure 1. Comparison of heavy metal concentrations in in the muscles of *Cyprinus carpio*, *Oreochromis niloticus*, and *Sander lucioperca* (±SE)

Iron (Fe) is the dominant metal in the muscles of the pikeperch and Nile tilapia. Zinc (Zn) ranks second for all species, with a higher concentration in the common carp muscle.

The other metals (Al, Cr, Cu, Mn) are present in much lower quantities, with no significant differences between species.

Variability is highest for the pikeperch, especially for Fe, which may be due to marked environmental or biological differences. The results emphasize the importance of monitoring Fe and Zn levels in these fish to assess the environmental and dietary risks to human health.

The muscle of the common carp detects variable metal levels, with Zn and Fe being the metals that record the highest values, reaching 56.22 mg/kg of dry weight and 46.77 mg/kg of dry weight, respectively. In contrast, Al, Cu, Cr, and Mn present average to low values, ranging from 16.05 mg/kg of dry weight, 2.61 mg/kg of dry weight, 2.27 mg/kg of dry weight, and 1.19 mg/kg of dry weight. These results do not exceed the recommended regulatory limits (FAO, 2012; NRCC, 1981).

The analysis of the pikeperch muscle showed that Fe has the highest content. The concentrations of Fe and Zn are also notable in the pikeperch, with values reaching 48.73 mg/kg of dry weight and 29.43 mg/kg of dry weight, respectively. Mn is the least present in this species, with a value of 0.94 mg/kg of dry weight. Other heavy metals like Al, Cr, and Cu are also accumulated but at concentrations lower than Fe.

For the Nile tilapia muscle, the concentrations of Fe and Zn are significantly higher than those of the other metals. The average contents of Fe and Zn are 38.41 mg/kg of dry weight and 34.41 mg/kg of dry weight, respectively. The concentration of Al is also notable, with a value of 12.86 mg/kg of dry weight. Cr, Cu, and Mn follow similar trends, with values reaching 2.41 mg/kg of dry weight, 1.77 mg/kg of dry weight, and 1.42 mg/kg of dry weight, respectively.

Health risk estimation

The common carp, due to its wide distribution and role in aquaculture, is an important indicator of water quality. Heavy metals such as zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), chromium (Cr), and aluminum (Al) are often measured to assess the level of contamination in fish.

The objective is to evaluate exposure to these metals in common carp and examine the toxicological risks associated with their consumption. The indices used for this assessment include the estimated weekly intake (EWI), the percentage of the provisional tolerable weekly intake (%PTWI), the estimated daily intake (EDI), the target hazard quotient (THQ), the hazard index (HI), and the critical concentration limits (CRlim). The results are presented in the Table 2.

These results indicate that the concentration of zinc (Zn) and iron (Fe) in common carp is relatively high, with an EWI of 0.059 mg/kg/week and 0.050 mg/kg/week, respectively, corresponding

Table 2. Analysis of metal exposure in common carp muscle and estimations of EWI, %PTWI, CRlim, EDI, THQ, and HI in wet weight.

Metal	EWI (mg/kg/week)	%PTWI	CRlim (mg/kg)	EDI (mg/kg/day)	THQ (10^{-6})	HI
Zn	0.059	0.842	1.266	2.25	7500	0.014
Fe	0.050	0.781	3.524	1.93	2752.67	0.014
Cu	0.002	0.057	27.047	0.11	2695/67	0.014
Mn	0.001	0.014	50.565	0.05	351.23	0.014
Cr	0.002	1	0.002	0.09	62.63	0.014
Al	0.017	0.850	–	0.65	654.76	0.014

to %PTWI values of 0.842 and 0.781. These values suggest that the consumption of these fish contributes significantly to the weekly tolerable intake for these metals, although these intakes remain below the maximum limits recommended by the World Health Organization (WHO, 2007).

Copper (Cu) and manganese (Mn) show lower concentrations in the muscle tissues of the carp, which aligns with findings from other studies (Lemire et al., 2018) reporting that these metals are generally present at low levels in freshwater fish. However, although the EDI for copper is low (0.11 mg/kg/day), this metal remains a risk factor in the case of long-term bioaccumulation in food chains.

Aluminum (Al), despite having a low EWI, presents a high %PTWI of 0.85%, indicating a substantial contribution to aluminum intake through fish consumption, particularly in areas with higher pollution levels. Aluminum is known for its neurotoxic potential, and although the concentrations observed are low, the presence of aluminum in fish tissues could pose a long-term risk to public health (Mie et al., 2017).

Predatory fish, such as pike-perch, occupy high trophic levels in aquatic ecosystems and are therefore prone to accumulating heavy metals from environmental pollution. The following indices have been calculated to assess the health risks associated with pike-perch consumption (Table 3).

Zinc is present at a relatively low concentration in the muscles of Pike-perch, well below the recommended limit (CR_{lim} of 2.267 mg/kg). The percentage of the PTWI is also low (0.47%), indicating that exposure through zander consumption is negligible. However, the high THQ could suggest a potential risk of toxicity under certain intensive consumption conditions, although the HI index remains low, showing that the overall impact is limited.

Iron, although at a higher concentration than zinc, remains well below the recommended limit levels. The percentage of the PTWI (0.93%) is low, and the EDI is far below hazardous values. The THQ is relatively moderate, and the HI index does not present a significant toxicity risk to human health.

Copper is present in very small amounts in the muscles of Pike-perch, with a concentration well below the recommended levels. The percentage of the PTWI is extremely low (0.02%), and the THQ remains low, indicating that there is no risk of toxicity from ingesting this species. The low HI index confirms that there are no health concerns.

Chromium, although at a higher concentration than the other metals (0.005 mg/kg/week), remains far below the recommended limit concentrations (CR_{lim} of 0.003 mg/kg). The percentage of the PTWI (2.5%) is relatively low, and the estimated exposure is well below hazardous values. The THQ is low, and the HI index indicates that there is no significant risk of toxicity.

Table 3. Analysis of metal exposure in pike-perch muscle and estimations of EWI, %PTWI, CRlim, EDI, THQ, and HI in wet weight

Metal	EWI (mg/kg/week)	%PTWI	CRlim (mg/kg)	EDI (mg/kg/day)	THQ ($\times10^{-6}$)	HI
Zn	0.033	0.47	2.267	1.26	4193.86	0.010
Fe	0.060	0.93	5.749	2.29	3274.75	0.010
Cu	0.001	0.02	32.577	0.07	1653.92	0.010
Mn	0.001	0.01	2.233	0.04	292.27	0.010
Cr	0.005	2.5	0.003	0.21	141.85	0.010
Al	0.015	0.75	–	0.6	600.72	0.010

The results of the heavy metal analyze in the tilapia muscles show that the concentrations of the different metals measured are well below the recommended critical limits (CR_{lim}) and that the toxicity and health impact indices indicate a low risk to human health (Table 4).

The zinc concentration in tilapia is 0.038 mg/kg, which is 0.542% of the PTWI. The EDI (estimated daily intake) is 1.45 mg/kg/day, well below hazardous values. The THQ is extremely low at 4821.15×10^{-6}, and the HI index is 0.01017, suggesting a negligible risk of toxicity.

Iron is present at a concentration of 0.043 mg/kg, which is 0.671% of the PTWI. The EDI is 1.65 mg/kg/day, which remains well below concerning thresholds. The THQ is also low ($2360.56.10^{-6}$), and the HI index shows no significant risk to human health.

The copper concentration in tilapia is 0.002 mg/kg, which is 0.057% of the PTWI. The EDI is 0.08 mg/kg/day, well below hazardous threshold values. The THQ is low at $1941.99.10^{-6}$, and the HI index shows no health concerns.

The manganese concentration is 0.001 mg/kg, representing 0.014% of the PTWI. The EDI is low at 0.06 mg/kg/day, and the THQ is $422.76.10^{-6}$, which does not indicate a risk to human health. The HI index remains low, confirming the absence of health concerns.

The chromium concentration is 0.002 mg/kg, representing 1% of the PTWI. The EDI is 0.1 mg/kg/day, well below hazardous levels. The THQ is low at $68.93.10^{-6}$, and the HI index indicates a negligible risk to human health.

The aluminum concentration is 0.014 mg/kg, representing 0.7% of the PTWI. The EDI is 0.56 mg/kg/day, and the THQ is $557.36.10^{-6}$, indicating a low risk. The HI index remains at 0.01017, suggesting no health concerns regarding aluminum.

The Figure 2 shows that the common carp has the highest overall hazard index, predominantly by Zn and Fe, and followed by Cu. The pike-perch has a lower hazard index compared to the Common Carp, but its composition is also dominated by Zn and Fe. Nile Tilapia shows a similar profile to the pike-perch, but with slightly different proportions for each metal. The metals Mn, Cr and Al have relatively low contributions to the hazard index for all species.

DISCUSSION

Accumulation of heavy metals in muscle

The fish muscle is typically analyzed as it is the main part of the fish consumed by humans and is involved in health risks (El Morhit et al., 2013). Traces of the metals sought in the muscle of the studied species are present with varying concentrations from one species to another. It should be noted that Cr, Mn, and Cu are the least concentrated compared to other metals. According to the established order, Zn, Fe, and Al are the major pollutants in the muscle of the studied fish, indicating that the muscle is contaminated by these heavy metals.

The dominant heavy metals are Fe, Zn, and to a lesser extent, Al. The highest concentration recorded in the muscle is that of Fe, followed by Zn. These two metals remain the main metallic contaminants in the muscle and show a wide distribution. They tend to concentrate easily in the muscle. It should be noted that Zn is an essential nutrient for aquatic organisms; at millimolar concentrations, it is a trace element involved in numerous enzymatic reactions (dehydrogenases, proteases, peptidases) and plays an important role in the metabolism of proteins, carbohydrates, and lipids (Kabata and Pendias, 2001). However, if present in excess, it can become harmful (Noppe, 1995). Fe is essential for cellular respiration in animals; it is a powerful catalyst for certain biochemical reactions. However, it is toxic at high doses (Noppe, 1995).

Table 4. Analysis of metal exposure in *Nile tilapia* muscle and estimations of EWI, %PTWI, CRlim, EDI, THQ, and HI in wet weight.

Metal	EWI (mg/kg/week)	%PTWI	CRlim (mg/kg)	EDI (mg/kg/day)	THQ (10^{-6})	HI
Zn	0.038	0.542	1.97	1.45	4821.15	0.01017
Fe	0.043	0.671	4.894	1.65	2360.56	0.01017
Cu	0.002	0.057	22.504	0.08	1941.99	0.01017
Mn	0.001	0.014	45.984	0.06	422.76	0.01017
Cr	0.002	1	0.003	0.1	68.93	0.01017
Al	0.014	0.7	–	0.56	557.36	0.01017

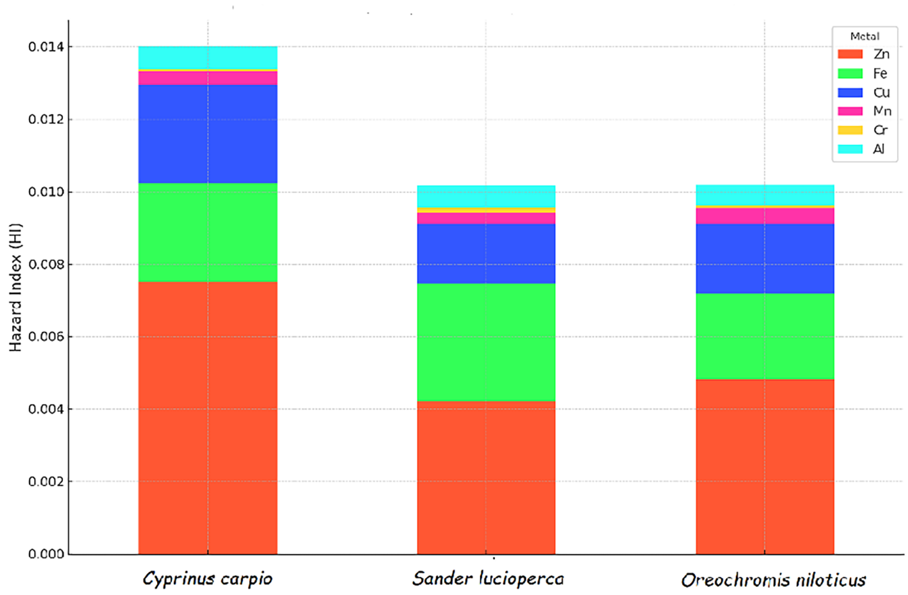

Figure 2. Composition of the hazard index (HI) for the different heavy metals in the three species of fish studied

The accumulation of heavy metals in fish is influenced by synergistic and antagonistic interactions between elements. In this study, high iron (Fe) levels in *Cyprinus carpio* (46.77 mg/kg), *Sander lucioperca* (48.73 mg/kg), and *Oreochromis niloticus* (38.41 mg/kg) suggest it may impact the bioavailability of zinc (Zn), copper (Cu), manganese (Mn), chromium (Cr), and aluminum (Al). These interactions have been widely studied in aquatic ecosystems, as they influence metal uptake, toxicity, and accumulation in fish tissues (Bury et al., 2003; Kowalska et al., 2021).

Competition for absorption

Iron competes with Zn^{2+}, Mn^{2+}, and Cu^{2+} for intestinal transporters such as Divalent Metal Transporter 1 (DMT1), which is responsible for the absorption of essential metals in vertebrates. High Fe levels can reduce the absorption of these metals by saturating transport sites, leading to lower Mn and Cu bioavailability in the studied fish (Bury et al., 2003). This competition is well-documented in freshwater fish, where Fe inhibits Cu and Mn uptake, affecting their physiological functions (Andrews, 2000; Glover et al., 2003). The relatively low Mn and Cu levels in the fish analyzed in this study could be explained by this competitive inhibition at the absorption stage.

Complex formation & metal precipitation

Iron, especially in its oxidized form (Fe^{3+}), has a strong tendency to form insoluble hydroxides, which can trap other metals like Cr and Al, reducing their availability to aquatic organisms (Stumm & Morgan, 1996; Tessier & Campbell, 1987). This phenomenon has been observed in sediment-rich environments, where Fe binds with trace metals, preventing their uptake by fish (Li et al., 2020).

In low-oxygen environments, Fe(III) is reduced to Fe(II), a more soluble form, which can release co-adsorbed metals, increasing their bioavailability (Stumm & Morgan, 1996). This process may explain why certain metals, such as Mn, remain available in lower concentrations while Fe accumulates in higher amounts in the studied species.

Synergistic effects with zinc

Iron and zinc are the most abundant metals in the muscle tissues of the studied fish. These elements share common absorption pathways, meaning Fe can enhance Zn uptake under certain conditions. Research has shown that Fe stimulates Zn transporter expression, leading to increased Zn absorption (Andrews, 2000). However, excess Fe may inhibit Zn absorption through direct competition, as observed in several studies on freshwater fish (Reid & McDonald, 1991; Kowalska et al., 2021).

In this study, Zn levels are relatively high, particularly in *Cyprinus carpio* (56.22 mg/kg), suggesting that the interaction between Fe and Zn may not be entirely inhibitory but could involve a balance between enhancement and competition, depending on environmental factors and metal concentrations (Kasmi et al., 2023).

Impact on metal toxicity

High Fe levels have been shown to reduce the toxicity of heavy metals such as Pb and Cd by limiting their intestinal absorption and transport in fish (Glover et al., 2003). This protective effect occurs because Fe competes with these toxic metals for binding sites on biological membranes, reducing their accumulation and harmful effects (Othman et al., 2020).

Similarly, Fe can influence the toxicity of Cr, depending on its chemical form. Cr(III) is relatively non-toxic, whereas Cr(VI) is highly toxic. Fe plays a role in reducing Cr(VI) to Cr(III), thereby mitigating its harmful effects (Tessier & Campbell, 1987; Li et al., 2020). In this study, low Cr levels in fish muscle may be linked to Fe interactions, reducing its availability and potential toxicity.

Comparison with other studies in North Africa

Several studies on Moroccan freshwater bodies have reported similar levels of Fe and Zn accumulation, with higher concentrations in benthic and omnivorous fish like *Cyprinus carpio*.

El Morhit et al. (2013) studied heavy metal contamination in fish from the Atlantic coast and Moroccan rivers and found Zn and Fe as dominant metals, similar to this study.

Kasmi et al. (2023) reported high Zn and Fe levels in *Sardina pilchardus* from the Moroccan Mediterranean coast, indicating that these metals are commonly bioaccumulated in fish across Moroccan aquatic ecosystems.

Othman et al. (2020) investigated heavy metal levels in *Oreochromis niloticus* from Egyptian freshwater bodies and reported higher levels of Cr (4.5–6.2 mg/kg) and Cu (3.1–4.5 mg/kg) compared to the present study (Cr: 2.41 mg/kg, Cu: 1.77 mg/kg). This suggests that industrial and agricultural pollution in Egypt may contribute to higher Cr and Cu accumulation.

Comparison with global studies

Kowalska et al. (2021) studied heavy metal contamination in predatory fish from Eastern European rivers and found higher Zn (60–80 mg/kg) and Fe (50–70 mg/kg) levels in species like pike and perch.

Li et al. (2020) reported similar Fe and Zn concentrations in freshwater fish from China, indicating that these metals are commonly accumulated across different geographical regions.

Variation in metal concentrations according to fish species

The concentrations of metallic elements in the studied fish are found to be highly heterogeneous, varying from one species to another. Among the main causes of these fluctuations are the physiological and biological parameters of these species (organs, size, sex, age, diet, etc.). This finding closely aligns with the statements of Langston and Spence (1995) and Wang and Fisher (1997), who showed that biological parameters such as age, size, growth, breeding season, permeability of external membranes, feeding habits, and the nature of internal ligands significantly contribute to the variability in the bioaccumulation of heavy metals.

This study identified that *Cyprinus carpio* (common carp) is the fish that accumulates the most heavy metals, with a total concentration of 125.13 mg/kg of dry weight. Indeed, the carp is an omnivorous, opportunistic, and benthophagous species. It digs up to 20 cm into the muddy bottom (Dosdat et al., 1996). It feeds at the bottom of the reservoir and is always in contact with the sediment, which is considered a major reservoir of pollutants, making the carp more likely to accumulate heavy metals compared to the other studied fish. The work of Caccia et al. (2003) showed that metals tend to accumulate more in benthic species due to their low mobility and their diet, which is primarily based on benthic organisms that rely on the sediment.

The contamination of *Cyprinus carpio*, *Sander lucioperca*, and *Oreochromis niloticus* is moderate, and continuous consumption by the local population could expose consumers to health risks due to the accumulation of these metals in the body. The risk is not limited to humans but also extends to piscivorous animals.

Health risks related to trace elements

Regarding the THQ, the values calculated for all metals, particularly zinc, indicate that the levels of these metals in the fish are well below established safety thresholds. However, the HI remains low (0.014), suggesting a low overall toxicity risk for consumers of common carp in the studied areas.

Overall, the heavy metal concentrations in the muscles of the pike-perch measured are low and well below the recommended critical limits for each metal. The toxicity indices (THQ) and the health impact index (HI) both show a low risk to human health. There are no major concerns regarding pike-perch consumption in relation to these heavy metals, although further studies may be needed to confirm long-term safety in populations with high fish consumption.

The THQ values were below 1 for each heavy metal in the three fish species studied, indicating that there is no non-carcinogenic health risk associated with the ingestion of a single metal from the consumption of these fish. The highest THQ value was estimated for Zn, followed by Fe. Zn, Fe, and Cu were the main contributors to the HI in all three fish species. Although the THQ values for individual metal ingestion are within acceptable limits, continuous and excessive consumption of these fish, particularly the common carp, could lead to chronic non-carcinogenic effects. these results are comparable to those of other research conducted on freshwater fish. For instance, a study by Kowalska et al. (2021) observed similar levels of zinc and iron in predator fish from rivers in Eastern Europe, with negligible risk levels. Another study by Li et al. (2020) reported similar concentrations of copper and manganese in freshwater fish in China and concluded that these levels posed no risk to public health.

The concentrations of heavy metals in the tilapia muscles measured in this study are low and well below the recommended critical limits. The toxicity indices (THQ) and the health impact index (HI) show that exposure to these metals through tilapia consumption poses no significant risk to human health. Therefore, there are no major concerns regarding tilapia consumption in relation to these heavy metals. The results obtained in this study are similar to those observed in other research on Nile tilapia in various regions. In Egypt the study conducted by Othman et al. (2020) reports similar concentrations of heavy metals in tilapia, with zinc, iron, and copper levels not exceeding safety limits. Another study in South Africa carried out by Chaves et al. (2019) reported comparable levels of aluminum and chromium, well below concerning levels.

CONCLUSIONS

The study of metal contamination in the muscle of the three studied species from the Al Massira reservoir demonstrates the presence of micropollutants at moderate levels. The levels of heavy metals detected in the muscle suggest that these fish are capable of concentrating and bioaccumulating metals in their bodies from the aquatic environment. Following these various analyses, Fe is considered the element with the highest concentrations among the metals analyzed in the fish, followed by Zn, Al, Cr, Cu, and Mn. The concentrations of heavy metals in the muscle tissues of the studied fish are generally low and well below the recommended critical limits. The (THQ) and the (HI) indicate a low risk to human health, suggesting that the consumption of these fish does not pose a significant danger related to the presence of heavy metals. However, although the current results indicate low exposure and low risk, further studies may be necessary to confirm long-term safety, especially in populations with high fish consumption, and to monitor the evolution of metal contamination levels in aquatic ecosystems.

REFERENCES

1. Adeniyi, A.A., & Yusuf, K.A. (2003). Determination of heavy metals in fish tissues, water and bottom sediments from Epe and Badagry Lagoons in Lagos, Nigeria. *Environ. Monit. Assess*. *37*, 451–458.
2. Alipour, H., Pourkhabbaz, A., & Hassanpour, M. (2015). Estimation of potential health risks for some metallic elements by consumption of fish. *Water Quality, Exposure and Health*, *7*(2), 179–185
3. Andrews, N. C. (2000). Iron metabolism: Disorders of iron transport and storage. *New England Journal of Medicine, 342*(17), 1293–1304.
4. Azekour K., Idir I., Lahrach, N., & El Bouhali B. 2020. Prévalence de l'obésité et du surpoids en milieu scolaire, oasis de Tafilalet, sud-est du Maroc. *Pan African Medical Journal*, *35*(1).
5. Benabdelkader, A., Taleb, A., Probst, J. L., Belaidi, N., & Probst, A. (2018). Anthropogenic contribution and influencing factors on metal features in fluvial sediments from a semi-arid Mediterranean river basin (Tafna River, Algeria): A multi-indices approach. *Science of the Total Environment*, *626*, 899–914.
6. Boudou, A., & Ribeyre, F. (2020). Aquatic ecotoxicology of heavy metals: bioaccumulation and trophic transfer. *Environmental Science & Pollution Research*.
7. Bury, N. R., Walker, P. A., & Glover, C. N. (2003). Nutritive metal uptake in teleost fish. *Journal of Experimental Biology, 206*(1), 11–23.
8. Caccia V.G., Millero F.J., et Palanques A., 2003. The distribution of trace metals in Florida Bay sediments. *Marine Pollution Bulletin*, *46*, 1420–1433.
9. Canli, M., & Atli, G. (2003). The relationship

between heavy metal (Cd, Cr, Cu, Fe, Pb, Zn) levels and the size of six Mediterranean fish species. *Environ. Pollut*., *121*, 129–136.

10. Chahid, A., Hilali, M., Benlhachimi, A., & Bouzid, T. (2014). Contents of cadmium, mercury and lead in fish from the Atlantic Sea (Morocco) determined by atomic absorption spectrometry. *Food chemistry*, *147*, 357–360.
11. Chaves, C. L., et al. (2019). Heavy metal contamination in farmed tilapia: Implications for human health. *Aquatic Toxicology*, *219*, 105–113.
12. Dosdat A., Servais F., Matailler R., Huelvan C., et Desbrayeres E., 1996. Comparaison of nitrogenoas losses rates from Atlantie Salmon. *Aquaculture*, *141*, 107–127.
13. Ekeanyanwu, R.C., Nwokedi, C.L., & Noah, U.T. (2015). Monitoring of metals in Tilapia nilotica tissues, bottom sediments and water from Nworie River and Oguta Lake in Imo state, Nigeria. *Afr. J. Environ. Sci. Technol*, *9*(8), 682–689.
14. El Morhit M., Belghity D., El Morhit A., 2013. Contamination métallique de pagellus acarne, sardina pilchardus et diplodus vulgaris de la côte atlantique sud (Maroc), *Larhyss Journal*, 131–148.
15. Environnement Canada., 2003. Liste des substances d'intérêt prioritaire –Rapport d'évaluation –Rejets de radionucléides des installations nucléaires (effets sur les espèces autres que l'être humain), Gouvernement du Canada.
16. FAO. (2012). From heavy metal regulations Faolex. Retrieved 2012.
17. FAO. Fishery information data and statistics unit. FISHSTAT + Databases and Statistics. Food and Agriculture Organization of the United Nation, Rome, Italy (2016)
18. FAO/WHO (2007). Evaluation of certain food additives and contaminants. *WHO Technical Report Series*, *940*, 1–57.
19. Giri, S., & Singh, A. K. (2015). Human health risk and ecological risk assessment of metals in fishes, shrimps and sediment from a tropical river. *International Journal of Environmental Science and Technology*, *12*, 2349–2362.
20. Glover, C. N., Hogstrand, C., & Wood, C. M. (2003). Mechanisms of toxic action and adaptation to metals in fish. *Fish Physiology, 22*, 37–85.
21. Joint FAO/WHO Expert Committee on Food Additives (JECFA). (2011). *Summary and conclusions of the sixty-sixth meeting of the Joint FAO/WHO Expert Committee on Food Additives (JECFA)*. Food and Agriculture Organization of the United Nations/ World Health Organization.
22. Kabata-Pendias, A. (2001). Trace metals in soils-a current issue in Poland. *Acta Universitatis Wratislaviensis. Prace Botaniczne*, *79*, 13–20.
23. Kasmi, K., Belhaj, K., Nasri, H., Slimani, D., Allai, L., Mansouri, F., & Chafi, A. (2023). Heavy metals concentration in *Sardina pilchardus* from the Moroccan Mediterranean coast and potential human health risk assessment. *Journal of Food Quality, 2023*(1), 1–14.
24. Kowalska, A., Kowalski, R., Rzymski, P., & Dobrzyńska, D. (2021). Heavy metal contamination in predatory fish: A study of the impact on human health in Eastern Europe. *Environmental Science and Pollution Research, 28*(5), 5124–5133.
25. Langston W. J., et Spence S. K., 1995. Biological factors involved in metal concentration observed in aquatic organisms. Metal speciation and bioavailability in aquatic systems. *John Wiley & Sons. Chichester,* 407–478.
26. Li, X., Feng, H., Shen, C., Wang, T., Guo, W., & Yu, L. (2020). Analysis of heavy metals in freshwater fish from China: Risk assessment for human consumption. *Environmental Monitoring and Assessment, 192*, 56.
27. Mie, A., Andersen, H. R., Gunnarsson, S., Kahl, J., Kesse-Guyot, E., Rembiałkowska, E., ... & Grandjean, P. (2017). Human health implications of organic food and organic agriculture: a comprehensive review. *Environmental Health*, *16*, 1–22.
28. Noppe K. 1995. Contamination métallique des sédiments des cours d'eau du bassin Artois-Picardie et son impact sur la contamination des chairs et des foies de poissons. D.EA Hydrologie, Hydrogéologie, Géostatistiques et Géochimie 1995–1996, Laboratoire de Géologie Appliquée. Université Pierre et Marie Curie – Paris.
29. NRCC. 1981. Teneurs des métaux admissibles pour les poissons selon le conseil de recherche national (NRC) canadien, 1981. Effects of heavy metals in the Canadian environment. NRCC, Comité associé pour les critères scientifiques de qualité de l'environnement.
30. Olaifa, F. E., Olaifa, A. K., Adelaja, A. A., & Owolabi, A.G. (2004): Heavy metal contamination of Clarias gariepinus from a lake and fish farm in Ibadan, Nigeria. Afr. J. Biomed. Res., *7*, 145–148.
31. Othman, M. S., El-Khatib, A. M., Abdel-Kader, T. G., & El-Salam, S. M. A. (2020). Heavy metal contamination in *Oreochromis niloticus* from Egyptian freshwater systems: Health risk assessment. *Environmental Pollution, 260*, 114013.
32. Robert, G. (1991). Toxic effects of metals. In: Casarett and Doull's toxicology. Pergamon Press. 662–672.
33. Stumm, W., & Morgan, J. J. (1996). *Aquatic chemistry: Chemical equilibria and rates in natural waters* (3rd ed.). John Wiley & Sons.

34. Tessier, A., & Campbell, P. G. C. (1987). Partitioning of trace metals in sediments: Relationships with bioavailability. *Hydrobiologia, 149*(1), 43–52.
35. U.S. Environmental Protection Agency. (2011). *Reference doses (RfDs) for heavy metals*. U.S. Environmental Protection Agency.
36. United States Environmental Protection Agency (USEPA) (2011). Regional Screening Level (RSL) Summary Table: November 2011.
37. USEPA (United States Environmental Protection Agency) (2015). Regional Screening Level (RSL) Summary Table, November 2015.
38. Wang W. X., et Fisher N. S., 1997. Modeling the influence of body size on trace element accumulation in the mussel Mytilus edulis. Mar. Ecol. Prog. Ser., 161, 103–115.
39. World Health Organization. (2011). *Evaluation of certain food additives and contaminants: Sixty-third report of the Joint FAO/WHO Expert Committee on Food Additives*. World Health Organization.