RESEARCH ARTICLE (Open Access)

Bioaccumulation Factors of Mercury in Liver, Muscle, and Gills of three Fish Species from the Adriatic Sea, Albania

ALTIN METALLA[1*], ERINDA LIKA[1], JOSE LUIS VALVERDE PIEDRA[2]

[1]Department of Preclinical Modules, Faculty of Veterinary Medicine, Agricultural University of Tirana, Tirana, Albania.

[2]Department of Pharmacology, Toxicology and Environmental Protection, University of Life Sciences in Lublin, Lublin, Poland.

*Corresponding author; E-mail: ametalla@ubt.edu.al

Abstract

This study investigates the bioaccumulation factors (BAF) of total mercury (THg) in the liver, muscle, and gills of three commercially important fish species—Solea solea (Common sole), Dicentrarchus labrax (European seabass), and Mugil cephalus (Flathead mullet)—collected from the Adriatic Sea near the Ishëm River estuary, Albania. Mercury concentrations in fish tissues, as well as in water and sediment, were measured using Cold Vapor Atomic Absorption Spectroscopy (CVAAS; MA-2000 analyzer). BAF values were calculated relative to both water and sediment mercury concentrations. Among the three species, D. labrax exhibited the highest BAF for muscle relative to water (36.67), whereas S. solea had the highest BAF for liver relative to sediment (2.67). M. cephalus generally showed lower BAF values, consistent with its detritivorous feeding habits and lower trophic position. Significant interspecific and tissue-specific variations in BAF were observed, reflecting differences in feeding ecology, habitat use, and physiology. These findings underscore the value of BAF as an integrative metric for assessing bioavailability and trophic transfer of mercury in aquatic ecosystems and highlight the role of species-specific traits in modulating mercury accumulation.

Keywords: Bioaccumulation factor, Mercury, Solea solea, Dicentrarchus labrax, Mugil cephalus.

1. Introduction

Mercury (Hg) is widely recognized as a contaminant of global concern due to its persistence, ability to bioaccumulate, and toxic effects on both wildlife and humans[1] . In aquatic ecosystems, mercury is introduced through natural processes such as volcanic activity and weathering, as well as anthropogenic sources, including industrial emissions, artisanal mining, and urban wastewater[2]. Once in the environment, mercury can undergo biogeochemical transformations, producing methylmercury (MeHg), its most toxic form, which is readily absorbed by organisms and biomagnified along aquatic food webs[3]. The high neurotoxicity of MeHg and its ability to cross the placental barrier pose severe risks to both wildlife and human health, with fish consumption being the primary route of exposure in humans[4]. In Albania, several studies have reported detectable mercury levels in rivers, sediments, and coastal areas. Surface waters of the Ishëm River, for instance, have been reported to contain 0.02–0.1 µg/L of mercury, reflecting the impact of untreated urban and industrial discharges[5]. Sediment concentrations in Albanian rivers and coastal lagoons indicate moderate to heavy pollution, with hotspots recorded near industrial zones such as Vlora Bay[6]. These observations highlight the vulnerability of Albanian aquatic ecosystems to mercury contamination, with potential ecological and public health consequences. Fish are widely used as bioindicators of aquatic pollution due to their ecological relevance, mobility, and ability to bioaccumulate contaminants in tissues[7]. The bioaccumulation factor (BAF) is an important ecological index that quantifies the extent to which contaminants, such as mercury, are accumulated from water and sediments[8]. Differences in BAF values among fish species are influenced by feeding ecology,

*Corresponding author: Altin Metalla; E-mail: ametalla@ubt.edu.al
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trophic level, habitat preference, metabolic rate, and age. Quantifying BAFs across different tissues (liver, muscle, gills) allows for the assessment of mercury bioavailability, tissue-specific accumulation patterns, and potential exposure risks to humans and wildlife[9]. This study focuses on three fish species representing distinct ecological niches in the Adriatic coastal ecosystem: Solea solea (benthic feeder), Dicentrarchus labrax (piscivorous predator), and Mugil cephalus (detritivore). These species were selected because they occupy different trophic levels and feeding strategies, which strongly influence mercury exposure and bioaccumulation pathways[10,11]. Solea solea, a benthic species closely associated with sediments, is highly relevant for assessing sediment–water mercury transfer and is widely used as a sentinel organism for sediment contamination[10]. Dicentrarchus labrax, a high-trophic-level predator, is not only important for evaluating biomagnification but also holds major commercial value in Albania, where it is one of the primary aquaculture and marine-farmed species [Project number: 2017.2192.7-001.00 Fishery Sector Study Report]. Mugil cephalus and Solea solea are also among the species historically recorded in commercial landings along the southern Albanian coast during 2016–2018, confirming their continued importance for coastal fisheries and local consumption[12]. Although fish consumption per capita in Albania remains lower than in EU countries, marine species of commercial relevance—particularly sea bass (D. labrax), mullet (M. cephalus), and flatfish (S. solea)—remain an important source of dietary protein for coastal communities and contribute to the national seafood market [Eurofish International Organisation, (2021), Albania: Fisheries and aquaculture sector overview]. The commercial importance of these species increases the relevance of evaluating mercury levels, as they represent key pathways for human exposure through seafood. By integrating mercury measurements in fish tissues (liver, muscle, gills), seawater, and sediments, this research aims to characterize species- and tissue-specific patterns of mercury bioaccumulation, identify ecological drivers of contamination, and improve understanding of potential risks to coastal ecosystems and human consumers in the Ishëm River estuary region.

2. Material and Methods

2.1. Study area

The study was conducted in the coastal area near Shetaj village, Durrës, Albania, close to the estuary of the Ishëm River (Figure 1). The geographic coordinates shown in Figure 1 (41°36′36.8″N, 19°29′48.8″E) correspond to the sampling zone. Two distinct sampling locations were defined:

The marine water and sediment sampling site (red point), positioned in the coastal zone to characterize mercury levels in seawater and marine sediments.

The fish sampling area (red point), located within a 3 km offshore radius indicated by the red circle, where fishermen operating near Kepi i Rodonit collected specimens.

The Ishëm River drains a 673 km² catchment, flowing through industrial and urban zones before reaching the Adriatic Sea. It is considered one of the most polluted rivers in Albania due to untreated effluents, while its estuarine system and the nearby Patok Lagoon are ecologically important areas supporting fisheries and biodiversity[13–15].

2.2. *Sample collection*

A total of 252 individuals of Solea solea, Dicentrarchus labrax, and Mugil cephalus were collected from fishermen operating in the designated offshore fish sampling area, situated within the 3 km radius highlighted in Figure 1. Fish were sampled between September 2023 and September 2024 and categorized into two size classes: juvenile (<150 g) and adult (>150 g), with 42 individuals per class. Each class was subdivided into six composite samples (seven individuals per pool), following established statistical pooling procedures.

Simultaneously, environmental samples were collected at the red point location shown in Figure 1:

The marine sampling station (red point), representing seawater and marine sediment conditions.

All samples were gathered using pre-cleaned containers to assess background mercury levels in both marine and riverine environments.

2.3. Sample preparation and analysis

Fish tissues (liver, muscle, gills) were dissected, rinsed, homogenized, and stored at −20 °C prior to analysis. For mercury analysis, approximately 50 mg of tissue was weighed and placed in a ceramic vessel, layered with additives (M and B) as interference-reducing reagents, and analyzed using the MA-2000 Mercury Analyzer (Nippon Instruments Corporation) via Cold Vapor Atomic Absorption Spectroscopy (CVAAS)[17]. Water and sediment mercury levels were determined using the same method. Results are expressed in µg/kg wet weight for tissues, µg/L for water and µg/kg dry weight for sediments[18].

Bioaccumulation Factor calculation

The bioaccumulation factor (BAF) was calculated using the formulas **BAF_water = C_tissue / C_water** and **BAF_sediment = C_tissue / C_sediment**, where *C_tissue* represents the mercury concentration in fish tissues (µg/kg wet weight), *C_water* is the mercury concentration in seawater (0.42 µg/L), and *C_sediment* is the concentration in marine sediment (54.0 µg/kg dry weight)[19]. As the analyzed specimens were marine species, BAF values were derived by comparing mercury levels in fish tissues with those measured in seawater and marine sediments. Mercury concentrations in liver, muscle, and gills of *Solea solea*, *Dicentrarchus labrax*, and *Mugil cephalus* were used to calculate these factors, allowing the evaluation of mercury bioavailability and tissue-specific accumulation patterns across species.

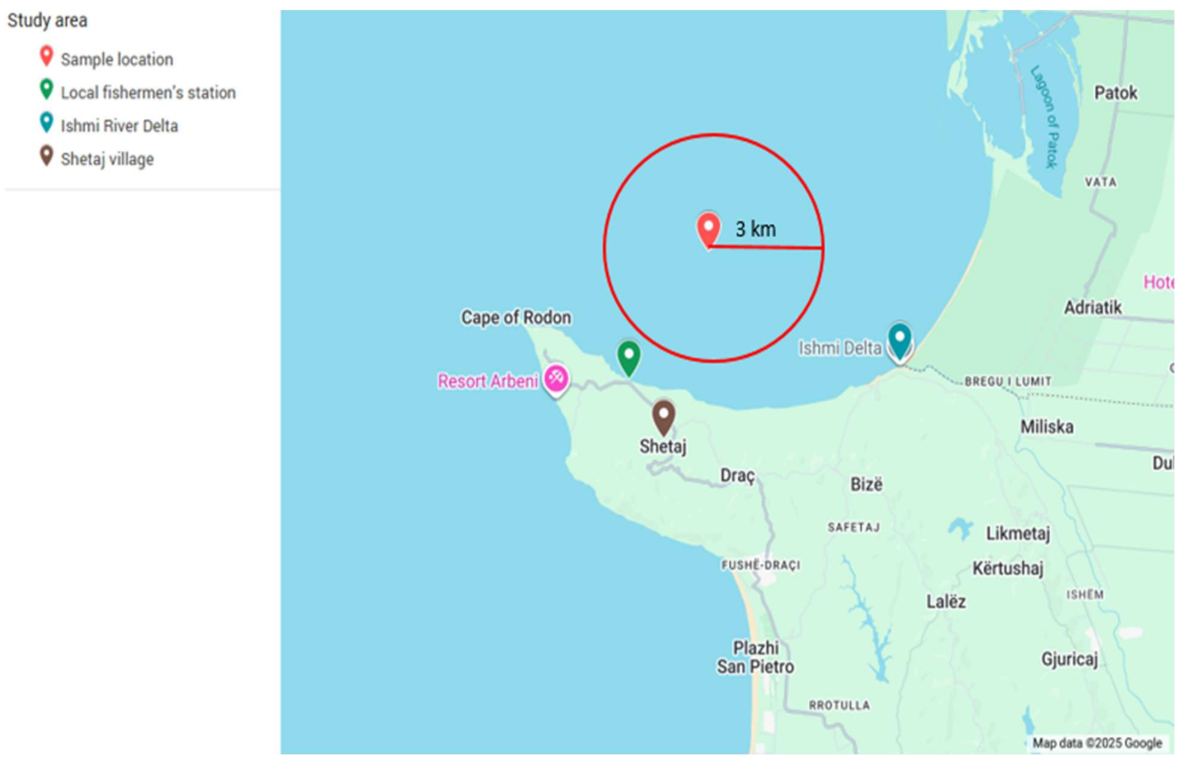

Figure 1. Study area, location of sample collected (fish,water and sediment).

3. Results and Discussion

3.1. *Mercury concentrations in fish tissues*

The mean concentrations of total mercury (Hg) measured in liver, muscle, and gills of the studied fish species are presented in Table 1. Overall, mercury accumulation showed clear interspecific and tissue-specific variations. The highest mean concentrations were observed in the liver, followed by muscle and gills, confirming the liver's role as the main detoxification and storage organ for heavy metals. Among the analyzed species, *Solea solea* (both large and small specimens) and *Dicentrarchus labrax* exhibited higher Hg concentrations in all tissues compared to *Mugil cephalus*. In particular, large *S. solea* individuals showed 14.4 µg/kg in the liver and 12.0 µg/kg in the muscle, while large *D. labrax* presented 12.5 µg/kg and 15.4 µg/kg, respectively. Conversely, *M. cephalus* had the lowest Hg levels, especially in large specimens, with 5.9 µg/kg in the liver and 4.9 µg/kg in the muscle. Interestingly, smaller *M. cephalus* individuals accumulated higher liver mercury (14.2 µg/kg) than larger ones, suggesting sizedependent metabolic or dietary differences. The lowest mercury levels overall were recorded in the gills, ranging from 2.2 to 4.1 µg/kg across all species, reflecting their limited capacity for metal retention compared to internal tissues. For comparison with biotic matrices and for the calculation of the bioaccumulation factor, the concentrations of total Hg in seawater (0.42 µg/L) and marine sediment (54.0 µg/kg) are provided in Table 2.

3.2. *Bioaccumulation factor (BAF) values*

The calculated bioaccumulation factors (BAF) relative to both water and sediment are shown in Table 3 and Figure 2. BAF values relative to water were generally higher than those relative to sediment, highlighting that dissolved mercury in the aquatic environment is more bioavailable and readily taken up by fish. Among species, *Dicentrarchus labrax* (large specimens) exhibited the highest BAF in muscle relative to water (36.7), indicating an efficient mercury transfer through the trophic pathway. Similarly, *Solea solea* (large) showed the highest liver BAF relative to sediment (2.67), reflecting its benthic feeding behavior and close interaction with contaminated sediments. In contrast, *Mugil cephalus* displayed the lowest BAF values across tissues, consistent with its detritivorous diet and reduced exposure to mercury via the food chain. However, small *M. cephalus* had relatively higher liver BAFs (33.8 relative to water and 1.78 relative to sediment) than large ones, suggesting possible ontogenetic differences in feeding strategy or enhanced mercury assimilation in juveniles. Overall, the BAF patterns emphasize both ecological and physiological factors influencing mercury bioaccumulation among species and size groups.

3.3. *Discussion*

The findings of this study demonstrate pronounced species- and tissue-specific differences in mercury bioaccumulation among the investigated fish species[20]. *Dicentrarchus labrax* exhibited the highest muscle BAF relative to water, reflecting its piscivorous feeding habits and higher trophic level, which enhance mercury biomagnification through the food chain[21]. Conversely, *Solea solea*, a benthic species, showed the highest liver BAF relative to sediment, consistent with its close association with the seabed and ingestion of sediment-associated prey, which facilitates mercury uptake from the benthic environment[22]. In contrast, *Mugil cephalus* generally displayed lower BAF values across tissues, in line with its detritivorous diet and lower trophic position; however, smaller individuals exhibited relatively higher liver BAFs than adults, likely due to elevated metabolic rates and the ingestion of fine sediment particles that tend to accumulate higher mercury concentrations[23]. The consistent trend of higher BAFs relative to water than to sediment suggests that aqueous mercury forms—both dissolved and particulate—represent a more bioavailable source for fish uptake, supporting findings from previous studies in marine ecosystems[8]. These interspecific and ontogenetic differences highlight the influence of ecological and physiological traits—such as diet, habitat preference, and metabolic activity—on mercury accumulation dynamics. Moreover, the results emphasize the ecological importance of understanding mercury distribution among different tissues, as the liver functions as a detoxification organ while the muscle represents the main edible tissue relevant to human exposure. The higher mercury levels observed in *D. labrax* and *S. solea*, two commercially valuable and commonly consumed species, underline the potential implications for food safety and public health in the Adriatic region, particularly near the Ishëm River estuary where anthropogenic inputs may enhance mercury availability. Therefore, the study underscores the need for continuous monitoring programs, species-specific risk assessments, and consideration of both environmental and biological factors when evaluating mercury contamination in marine ecosystems.

Table 1. Total mercury concentrations (µg/kg wet weight) in fish tissues.

Species	Hg Liver *(µg/kg)*	Hg Muscle *(µg/kg)*	Hg Gills *(µg/kg)*
Solea Solea large	14.4	12.0	3.7
Solea solea small	14.1	9.60	3.8
Dichentracus labrax large	12.5	15.4	3.7
Dichentracus labrax small	15.5	11.1	4.1
Mugil cephalus large	5.90	4.90	3.7
Mugil cphalus small	14.2	5.60	2.2

Table 2. Total mercury concentrations µg/kg dry weight in sediment, µg/L in water.

Sample	Hg conc.
Water sea	0.42 $\mu g/L$
Sediment sea	54.0 $\mu g/kg$

Table 3. Bioaccumulation factors (BAF) values relative to water and sediment.

Species/Group	BF Liver/ Water	BF Muscle/ Water	BF Gills/ Water	BF Liver/ Sediment	BF Muscle/ Sediment	BF Gills/ Sediment
Solea solea large	34.3	28.6	8.81	2.67	2.22	0.69
Solea solea small	33.6	22.9	9.05	1.76	1.20	0.48
Dichentracus labrax large	29.8	36.7	8.81	2.31	2.85	0.69
Dichentracus labrax small	36.9	26.4	9.76	1.94	1.39	0.51
Mugil cephalus large	14.1	11.7	8.81	1.09	0.91	0.69
Mugil cephalus small	33.8	13.3	5.24	1.78	0.70	0.28

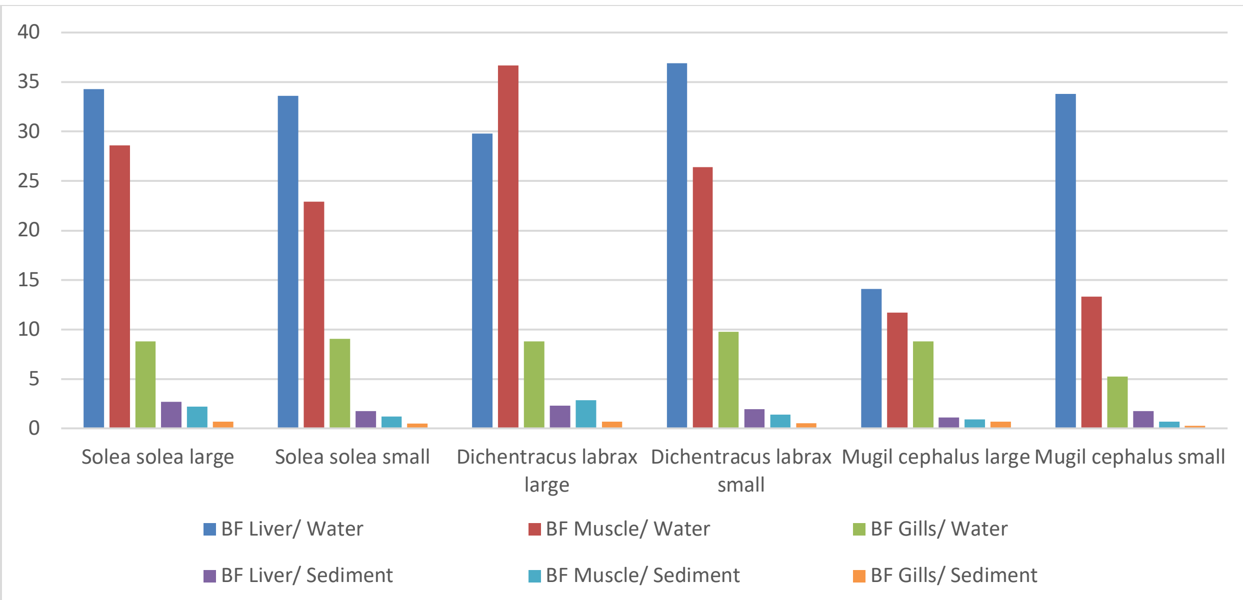

Figure 2. Bioaccumulation factors (BAF) values.

4. Conclusions

This study demonstrates clear species-, tissue-, and size-related differences in mercury bioaccumulation in three ecologically and commercially important fish species from the Adriatic Sea near the Ishëm River estuary. Dicentrarchus labrax showed the highest muscle BAF relative to water, reflecting its piscivorous diet and high trophic level, which facilitate mercury biomagnification. Solea solea, a benthic feeder, exhibited the highest liver BAF relative to sediment, due to its close interaction with contaminated sediments and consumption of benthic prey. In contrast, Mugil cephalus generally had lower BAFs, consistent with its detritivorous diet and lower trophic position, although juveniles showed higher liver BAFs, likely due to ontogenetic differences in feeding and higher assimilation of mercury from fine organic particles. Across species, water-based BAFs were consistently higher than sediment-based BAFs, indicating that aqueous mercury forms are the primary source of bioavailable mercury for fish. Elevated mercury levels in D. labrax and S. solea, both commercially important species, highlight potential risks to human consumers and the importance of ongoing monitoring and management in Albanian coastal ecosystems. Overall, these findings emphasize that mercury bioaccumulation is influenced by ecological traits, physiology, and environmental exposure, underlining the need for species-specific risk assessments and continued environmental monitoring to protect fisheries, ecosystem health, and public safety.

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