Journal of Elementology ISSN 1644-2296

Chmielewski, J., Dietrich, G.J., Walosik, A., Zięba, E., Żeber-Dzikowska, I., Motyl, M., Kosoń, A. and Gworek, B. (2023)
'Fish as bioindicators of mercury contamination in aquatic environments – an underestimated threat to consumer health'
Journal of Elementology, 28(3), 633-648,
available: http://dx.doi.org/10.5601/jelem.2023.28.2.2421

RECEIVED: 30 May 2023
ACCEPTED: 21 June 2023

REVIEW PAPER

Fish as bioindicators of mercury contamination in aquatic environments – an underestimated threat to consumer health*

Jarosław Chmielewski[1], Grzegorz Janusz Dietrich[2], Alicja Walosik[3], Ewa Zięba[4], Ilona Żeber-Dzikowska[5], Michał Motyl[6], Aneta Kosoń[7], Barbara Gworek[8]

[1] The Institute of Environmental Protection
National Research Institute, Warsaw, Poland
[2] The Stanisław Sakowicz Inland Fisheries Institute
National Research Institute in Olsztyn, Poland
[3] Department of Didactics of Biology and Chemistry
Pedagogical University of Krakow, Poland
[4] Institute of Health Sciences, Collegium Medicum
[5] Faculty of Pedagogy and Psychology
The Jan Kochanowski University in Kielce, Poland
[6] Faculty of Medicine
Medical University of Lodz, Poland
[7] The Tadeusz Koźluk Medical University of Warsaw, Poland
[8] Department of Environmental Chemistry and Risk Assessment
National Research Institute, Warsaw, Poland

Abstract

Fish are a recommended component of the diet, supplying complete proteins, vitamins, mineral salts, and omega-3 fatty acids. The presence of mercury in fish tissue, both freshwater and marine, is the effect of its accumulation in the aquatic environment and depends largely on the concentration of mercury in water as well as food. Most of mercury in fish tissues is present in the form of organic complexes, mainly methylmercury, which is much more toxic than metallic mercury. In organisms of predatory fish, such as shark, tuna, swordfish, or eel, mercury will be present in concentrations higher than in other species of fish. It is not just the result of their nutrition, but is also related to their age, mobility and habitat. In fish living near the bottom of a water body, the concentration of mercury will be much higher. It has to be noted that the ongoing climate change and increase in environmental contamination may significantly raise the bioavailability of mercury and its organic complexes in fish. Fish that are at the end of a food chain may contain such large amounts of mercury in their organisms that it may pose a threat to human health. This problem is particularly concerning people whose diets are based on fishmeat. The aim of the following paper is to present the current state of knowledge on sources of mercury released into aquatic environments and the related threats to human health with regard to fish consumption. The article takes note of the increasing number of incoming alerts under the European Rapid Alert System for Food and Feed (RASFF), regarding the contamination of fish and fish products with mercury.

Keywords: mercury contamination, fish, aquatic environment, immunotoxicity, human health

Jarosław Chmielewski, PhD, The Institute of Environmental Protection – National Research Institute, Warsaw, St. Słowicza 32, 02-170 Warsaw, Poland, e-mail: j.chmielewski@ios.gov.pl
* Source of financing: The project is financed from the Research Fund of the Jan Kochanowski University in Kielce, which is intended to support the continuity and development of the university's scientific research.

INTRODUCTION

With the industrial growth and development, which includes technologies using chemical substances in production processes, there was an increase in social awareness with regards to the necessity of monitoring the effect of such chemicals on the environment and human health. Bioindication is used to evaluate the ecological status quality of the natural environment. Bioindication is a method which, by using living organisms at different levels of their organization, determines the direction and degree of changes in natural habitats. Therefore, bioindication entails an assessment of the environmental status or the concentration of the natural environment factors by applying adequately scaled bioindicators. The term bioindication is also used to refer to the process wherein on the basis of quantitative and qualitative changes of a single object (indicator), the state of another object or the entire ecological ecosystem including biotic and abiotic parameters as well as substances and anthropogenic impacts are assessed. Different methods of biomonitoring make use of different indicator organisms with the aim of detecting the temporal and spatial variance of chemical pollution, contributing to the uncovering of their effect on the ecosystem. Different organisms, including both animal and plant species, have been proposed as bioindicators. Bioindicators used in the assessment of water body quality should be easy to identify and show a narrow range of ecological tolerance, which enables a qualitative and quantitative evaluation of environmental conditions. Meanwhile, bioaccumulation is a process wherein the concentration of a chemical substance in an aquatic organism (such as a fish), for example, exceeds its concentration in the environment due to the exposure to this chemical substance present in water. Bioaccumulation and the toxic properties of chemical substances largely depend on both their individual characteristics and the environmental conditions that affect their bioavailability (Yevtushenko, Dudnyk 2014, Jaiswal et al. 2018, Solaun et al. 2021, Dietrich et al. 2022, Lara et al. 2022, Gomez-Delgado et al. 2023).

Mercury (Hg) is a global contaminant of the environment. Hg can be released into the atmosphere from geogenic or anthropogenic sources. It makes its way to the atmosphere in emissions resulting from industrial activity and processes, transport emissions (fuel combustion processes), volcanic ash, etc. With the movement of air, Hg is carried at long distances by the wind and is deposited on the surface of the soil in its molecular form or condensates as rain. Hg is highly toxic, durable, and bioaccumulative in the environment (Wang et al. 2014, Bosch et al. 2016, Chmielewski et al. 2020, Gworek et al. 2020). It is estimated that the total inflow of Hg into the environment is between 5-10 thousand Mg a year, while the anthropogenic input constitutes anywhere between one-third and a half of the total mercury emission (Maily et al. 2003)

Sources of Hg emission can be classified into two types: natural and anthropogenic. The primary natural sources of Hg are volcanic eruptions, rock weathering, forest fires, and soil erosion, while secondary natural mercury emission comes from the soil, sediments, water basins, landfills, etc. Anthropogenic sources include fossil fuel combustion, metal production, concrete production, etc. (Chmielewski et al. 2020). The input of Hg emission from natural sources is estimated to be around 45-66% of the total Hg emission (Gworek et al. 2017). It is estimated that the global anthropogenic emission of Hg to the atmosphere in 2015 amounted to 2220 Mg, which signifies a 20% increase as compared to 2010 (Liang et al. 2021), wherein stationary fossil fuel combustion was responsible for 24% of the estimated emissions from anthropogenic sources (Wang et al. 2020). As indicated by the literature, China was the largest emitter of Hg in the world, contributing to around 25% of the global emission of mercury to the atmosphere (Liang et al. 2021). In the European Union, Hg emissions amounted to approximately 80 Mg a year (<5% of the total global emission), while the majority of the Hg emission was attributed to the coal sector (Xu et al. 2015). The main causes of mercury contamination in the soil are the mining activity and industrial production, as well as leachates from landfills (Liu et al. 2021). Fossil fuel combustion (primarily coal) for electroenergetic and heating purposes is the single highest source of anthropogenic emission of Hg, constituting 45% of the total anthropogenic emission (Pacyna et al. 2010). Available data in the literature indicate that the amount of Hg in the bituminous coal burned in Poland may range between 0.095 and 0.615 mg kg^{-1}, meanwhile in the case of lignite, it ranges between 0.080 and 0.250 mg kg^{-1} (Król, Kukulska-Zając 2016). The mean content of Hg in bituminous coal from China, the USA, and the RSA amounts to 0.20, 0.17, and 0.20 mg kg^{-1}, respectively, which exceeds the global average for coal of 0.1 mg kg^{-1} (Zhao et al. 2019).

Mercury is regarded to be an element largely dispersed in the natural environment, which means that it is only present in trace quantities. It is present in various physical and chemical forms in the environment. Biochemical and geochemical transformations between the different forms of Hg make it so that its distribution takes place both at a local and global scale. Mercury can take various forms in the environment, including volatile compounds (Hg^0, CH_3HgCH_3), water-soluble compounds (Hg^{2+}, HgX_2, HgX_3^- and HgX_4^{2-}, X = OH^-, Cl^-, Br^-) as well as insoluble compounds (CH_3HgS^-, CH_3Hg^+) and as Hg^{2+} bonded with sulfur. In the air, volatile elemental Hg (Hg^0) and dimethylmercury $(CH_3)_2Hg$ dominate. Mercury is present in the atmosphere, surface waters, aquatic sediments, and soil, from which it is absorbed by plants and incorporated into the food chain, the final link of which being humans (Rice et al. 2014, Gworek et al. 2017, Si et al. 2022).

Fish are useful and effective indicators of relative Hg, including methylmercury (MeHg), exposure in the food chain and the toxicological risk it poses to humans (Åkerblom et al. 2014, Scheuhammer et al. 2015 Eagles-Smith et al. 2016).

The amount of Hg introduced to the natural environment in Poland is presented in Table 1. Meanwhile, Table 2 illustrates the amount of Hg emitted to the atmosphere from anthropogenic sources in different industry sectors in various regions of the world.

Table 1

Total emission of mercury by kinds of activity in 2016-2020 in Poland

Specification	Mercury in Mg				
	2016	2017	2018	2019	2020
Total	10.35	9.58	8.74	7.85	7.63
Combustion in energy production and transformation industries	5.18	5.15	5.13	4.49	4.25
Combustion in industry	3.12	0.63	0.47	0.47	0.43
Transport	0.091	0.11	0.12	0.11	0.12
Non-industrial combustion plants	0.94	0.92	n.d.	n.d.	n.d.
Small combustion sources	n.d.	n.d.	0.89	0.74	0.72
Fugitive emissions from fuels	n.d.	n.d.	0.25	0.25	0.22
Industrial processes and product use	n.d	n.d.	1.46	1.48	1.51
Production processes	0.49	2.55	n.d.	n.d.	n.d.
Agriculture	0.0	n.d.	0.0	0.0	0.0
Waste management	0.53	0.21	0.43	0.32	0.37

Source: developed by the authors on the basis of GUS (2017, 2018, 2019, 2020, 2021, 2022), n.d. – no data (is a result of changes in the ways of reporting data)

MERCURY IN THE AQUATIC ENVIRONMENT

To a large extent, mercury is introduced into the natural environment through anthropogenic human activity (manufacturing, automotive industry, industrial and municipal waste combustion, chemical use intensification in agriculture, and water and sewage management). This element undergoes biochemical transformations and is ultimately accumulated in water sediments (Gworek et al. 2016, Chmielewski et al. 2020, Dietrich et al. 2022, Wójtowicz et al. 2022, Żeber-Dzikowska et al. 2022).

As indicated in research, Hg is found in waters all over the globe (Häder et al. 2020, Stock et al. 2021). The fact that mercury contamination is a widespread phenomenon is confirmed by numerous studies, for instance in the Amazon basin (Castro, Lima 2014, Dorea, Marques 2016, Feingold et al. 2019). One of the highest concentrations of MeHg in open waters is found in the Southern Ocean (Cossa et al. 2011). Research carried out in recent years indicates the presence of Hg in the waters of Baikal Lake, which has been listed as a UNESCO World Heritage site (Robert et al. 2019, Morshina et al. 2021). Similar is the case of waters of the Mediterranean Sea

Table 2

Amount of mercury emitted to the atmosphere in 2015 by different industry sectors in different regions of the world (Chmielewski et al. 2020)

World region	Sector groups				Regionally overall (range) (t)	% of the global total
	combustion of fuels (t)	industry sectors (t)	deliberate use (including product waste) (t)	craft sector and small gold mines (t)		
Australia, New Zealand and Oceania	3.57	4.07	1.15	0.0	8.79 (6.93-13.7)	0.4
Central America and the Caribbean	5.69	19.1	6.71	14.3	45.8 (37.2-61.4)	2.1
CIS members and other European countries	26.4	64.7	20.7	12.7	124 (105-170)	5.6
East and Southeast Asia	229	307	109	214	859 (685-1430)	38.6
European Union - 28 countries	46.5	22.0	8.64	0.0	77.2 (67.2-107)	3.5
Middle East	11.4	29.0	12.1	0.225	52.8 (40.7-93.8)	2.4
North Africa	1.36	12.6	6.89	0.0	20.9 (13.5-45.8)	0.9
North America	27.0	7.63	5.77	0.0	40.4 (33.8-59.6)	1.8
South America	8.25	47.3	13.5	340	409 (308-522)	18.4
South Asia	125	59.1	37.2	4.50	225 (190-296)	10.1
Sub-Saharan Africa	48.9	41.9	17.1	252	360 (276-445)	16.2
Total	533	614	239	838	2220 (2000-2820)	100.0

as per the research into the presence of mercury in this body of water spanning 40 years (Cinnirella et al. 2019).

The most ubiquitous form of organic Hg in water is methylmercury (MeHg), which is the main source of organic Hg in ecosystems. MeHg is easily transported with water into aquatic ecosystems. Mercury compounds are sparingly soluble in water, but dissolve easily in lipids (Rice et al. 2014).

The maximum concentration of Hg (II) allowed in drinking water was set by the World Health Organization (WHO) and the United States

Environmental Protection Agency (UESPA) at a level of 2 μg L^{-1} (10 nM) – Ghanei-Motlagh et al. (2016), Sarfo et al. (2017).

According to the data from Statistics Poland (GUS), the source of emission of mercury in Poland in 2020 was primarily fuel combustion in the energy sector (production and transformation of energy). Beyond that, a significant source was also production processes (including metal production). These two sources contributed to approx. 56% and 20% of the overall emission of mercury in Poland, respectively. Heavy metals are carried to the Baltic Sea through lakes and atmospheric deposition. The amount of mercury carried into the Baltic Sea via river outflow is illustrated in Table 3.

Table 3

The outflow of heavy metals by rivers to the Baltic Sea in 2016-2020 in Poland

Year	Total	Mercury contamination of rivers (t/year)											
		by Odra	by Ina	by Rega	by Parsęta	by Grabowa	by Wieprza	by Słupia	by Łupawa	by Łeba	by Reda	by Wisła	by Pasłęka
2016	n.d.	n.d.											
2017	n.d.	n.d.											
2018	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2019	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2020	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: developed by the authors on the basis of GUS (2017, 2018, 2019, 2020, 2021, 2022), n.d. – no data (is a result of changes in the ways of reporting data)

MERCURY IN FISH

Studies show that fish are very sensitive to the impact of toxic substances and for this very reason, they are a very good indicator organism in geochemical studies of water and the contamination of the aquatic environment. Mercury is a strong neurotoxin for fish. The increase in Hg concentration in freshwater may cause its increased absorption by fish (Sarfo et al. 2017, Moiseenko et al. 2018, Ali et al. 2019).

Chemical substances can enter the organism of the fish directly through the gills, the skin layer, and with food via the digestive tract (Huseen, Mohammed 2019). Fish have been researched for Hg contamination (Åkerblom et al. 2014, Scheuhammer et al. 2015, Eagles-Smith et al. 2016, Ferreira da Silva et al. 2020). The level of the chemical substance concentration in aquatic organisms, including fish, is closely related to their age, nutrition, and the water depth they inhabit. As indicated by research, the Hg concentration increases with age in large fish, which is particularly characteristic for perches and pikes (Yevtushenko, Dudnyk 2014, Kimakova et al. 2018, Backstrom et al. 2020). A literature review uncovered the presence of Hg in various species of commercial fish, with anglerfish, common sole, striped mullet, swordfish, mackerel, and cod having been documented (Polak-Juszczak 2017, Zamora-Arellano et al. 2017, Grgec et al. 2020, Barone et al. 2021, Issifu et al. 2022).

It is estimated that 70-100% of total Hg (THg) in fish muscle tissue is MeHg, the most toxic form of mercury (Llull et al. 2017, Polak-Juszczak 2017, Azad et al. 2019, Ferreira da Silva et al. 2020), and its concentration increases with the size and age of long-lived predatory species (Bosch et al. 2016*a* Nicklish et al. 2017, Polak-Juszczak 2017).

In their research, Annibaldi et al. showed that Hg concentration in farmed tuna was below acceptable threshold levels (1 mg kg^{-1}, fresh weight, f.w.) for all of the organisms (0.6 ± 0.2 mg kg^{-1}), meanwhile, wild tuna was found to exceed this limit (1.7 ± 0.6 mg kg^{-1}) – Annibaldi et al. (2019). High Hg concentrations that exceed recommended consumption norms for humans were found in fish inhabiting the Selenga basin (Kaus et al. 2017).

In the final Report of analytic studies regarding priority substances in the biota in rivers and lakes as per Directive 2013/39/UE, tests were presented from 216 measuring-and-control points (mcp) of river USWB and 80 mcp of lake USWB. In 191 mcp of river USWB (88% of the overall mcp total), Hg and its compounds were found to exceed the value of 20 μg kg^{-1} relative to the environmental quality standards (EQS). The concentration values of Hg and its compounds in the examined mcp of river USWB were below the limit of quantification, i.e. <6.0 μg kg^{-1} to 430.0 μg kg^{-1}. In 11 mcp (14% of the overall mcp total) in the lake USWB, the concentration of Hg and its compounds was lower than 20 μg kg^{-1}, meanwhile in 63 mcp (79% of the overall mcp total), exceeding concentrations of Hg and its compounds relative to the EQS (20 μg kg^{-1}) were found. The concentration of mercury and its compounds in the examined lake USWB samples ranged between values below the limit of quantification, i.e. between <6.0 μg kg^{-1} and 190.0 μg kg^{-1}. Basic statistical parameters for the concentration results of Hg and its compounds in the biota of river USWB and lake USWB fish are presented in Table 4. The scale of marine and freshwater fishery in Poland from 2016 to 2021 was illustrated in Table 5. Table 6 shows the concentration of Hg (μg g^{-1}) in 77 fish species (Vieira et al. 2015).

NEGATIVE HEALTH CONSEQUENCES

Fish are an important element of a properly balanced diet at all stages of the human life and development. Due to their commonness in the diet,

Table 4

Basic statistical parameters of the priority substance – mercury – and its compounds in the biota: river USWB fish and lake USWB fish in Poland in 2022

Mercury and its compounds in the river USWB fish biota						
Unit	minimum	maximum	median	mean	SD	CV (%)
(μg kg^{-1})	<6.00	13 000.00	39.00	107.50	882.30	820
Mercury and its compounds in the lake USWB fish biota						
Unit	minimum	maximum	median	mean	SD	CV (%)
(μg kg^{-1})	<6.00	190.00	35.00	42.23	31.43	74

SD – standard deviation, CV – coefficient of variation
Source: developed by the authors on the basis of GIOŚ (2022). For the purpose of the calculations, results below the limit of determination were substituted with values equal to half of the limit of determination.

Table 5

Fishery of marine and freshwater fish in thousands of tonnes in Poland between 2016-2021

Fishery of marine and freshwater fish (thousands of tonnes)						
Year	2016	2017	2018	2019	2020	2021
Marine fish overall, including:	197.1	210	197.2	203.2	191.9	185.9
cods	17.9	27.6	15.8	42.4	49.3	29.1
sprats	60.1	70.0	74.2	74.5	60.6	66.6
herrings	44.1	43.7	52.3	42.0	38.9	28.6
other marine fish	75.0	68.7	54.9	44.3	43.1	61.6
Freshwater fish	52.3	53.3	58.5	59.8	59.4	56.8

Source: developed by the authors on the basis of GUS

Table 6

Concentration of Hg (μg g^{-1}) content in 77 fish species (Vieira et al. 2015)

Hg (μg g^{-1})	Fish (common name)
≤0.1	Anchovy; butterfish; catfish; cod, Atlantic; cod, Pacific; croaker, Atlantic; flatfish; haddock; herring; John Dory; mackerel; perch, ocean and mullet; pike; plaice (European); pollock; rainbow trout (farmed); redfish; saithe; salmon, Atlantic (wild); salmon, Atlantic (farmed); salmon, Pacific (wild); sardines; smelt; sole; sprat; sweetfish; tilapia; wolf fish
>0.1 and ≤0.5	Anglerfish; bass, freshwater; bass, saltwater; bluefish; carp; catshark; croaker, Pacific; dab; eel; goatfish; grenadier; grouper; gurnard; hake; halibut, Atlantic (farmed); halibut, Greenland; hoki; ling; lingcod and scorpionfish; mackerel, horse; mackerel, Pacific; mackerel, Spanish; monkfish; Nile perch; perch, freshwater; pout; sablefish; scorpion fish; seabass; sea bream; skate/ray; snapper, porgy and sheepshead; tilefish, Atlantic; tuna; tuna, albacore; tuna, skipjack; tuna, yellowfin; tusk; whiting
>0.5 and ≤1	Alfonsino; mackerel, king; marlin; orange roughy; shark; tuna, Atlantic bluefin; tuna, bigeye; tuna, Pacific bluefin
>1	Swordfish; tilefish, gulf

their safety is of significant meaning to their consumers. Food safety, including fish, is one of the health policy elements of the European Union (EU) member states. For this purpose, the European Rapid Alert System for Food and Feed (RASFF) was introduced, serving as a means of rapid exchange of information about food that poses a threat to public health (Chmielewski et al. 2021). As indicated by available data, the RASFF system alerts regarding heavy metals constituted 19.8% of all the alerts regarding seafood, 13.9% of which was about Hg in fish, including tuna (10.0%), swordfish (9.6%), and salmon (5.5%) (Pigłowski 2023). In 2017 alone, 135 alerts for fishing products were noted (RASFF 2018). Taking into account the data above with the knowledge that a small percentage of fish and fish products undergo government control, it can be inferred that they are a significant environmental threat. Therefore the consumption of fish by consumers should take into account reliable data regarding their Hg contamination, as well as the possibility of adverse health consequences occurring in case of exceeding recommended consumption norms.

As indicated by available data, the consumption of fish in Poland amounts to approx. 13 kg per person, which is half the consumption average for the European Union overall (Kula, Śmiechowka 2016).

The estimated fish consumption per citizen in select European countries is presented in Table 7 (Vieira et al. 2015).

The consumption of fish and related mercury exposure varies greatly over the globe due to the amount and variance in the fish consumed, as well as different cultural traditions and nutrition practices (Grgec et al. 2020).

A person consuming fish becomes the recipient of the total Hg dose contained in all of the consumed fish (Kimakova et al. 2018). Fish are widely used as a source of nutrition for many human populations (Dong et al. 2015, Fliedner et al. 2016, Lepak et al. 2016). The consumption of predatory fish contaminated with Hg is regarded as a serious exposure pathway (Åkerblom et al. 2014). Populations with traditionally high consumption of food sourced from aquatic habitats are most exposed to Hg in their diet. Studies show that Hg exposure is significantly related to fish consumption (Dong et al. 2015). According to the study run by Liu et al., the main source of Hg exposure for consumers was their diet, with a contribution coefficient of 61.23% - 99.77% (Liu et al. 2021).

Due to the fact that Hg enters the organism with food, numerous countries set limits for Hg in food. Table 8 illustrates the maximum Hg levels set by different organizations and countries (Jinadasa et al. 2021).

The toxic effect of Hg has been well documented in the literature (Beckers, Rinklebe 2017, Okpala et al. 2017).

The presence of Hg and MeHg in some fish species is high enough to be able to cause adverse health effects in vulnerable groups of the population, in particular fetuses and young children (Buchanan et al. 2015, Zamora-Arellano et al. 2017, Grgec et al. 2020, Barone et al. 2021).

Table 7

Estimated fish consumption per inhabitant (kg/year) in selected European countries between 2015-2030 (modified Vieira et al. 2015)

Country	2015	2020	2025	2030
Austria	12	12	12	13
Denmark	26	27	28	29
France	32	32	33	33
Germany	16	16	17	18
Greece	26	27	27	27
Italy	26	27	28	29
Portugal	59	58	58	57
Spain	39	39	39	39
Sweden	27	27	27	27
Poland	13	14	15	16
Latvia	38	38	38	39

Table 8

Maximum permissible levels of Hg and its speciation forms set by different organizations and countries (modified Jinadasa et al. 2021)

Organization	Products	Regulatory limits (w/w basis, if not indicated)
EU	fisheries products (including mollusks, crustaceans, and most fish species) except listed fish in section 3.3.2, EU/EC 1881/2006 – total Hg fish muscle – total Hg food supplement – total Hg	0.5 mg kg^{-1} 1 mg kg^{-1} 0.1 mg kg^{-1}
FDA	action limit for MeHg in fish reference dose (RfD) for MeHg	1 mg kg^{-1} 0.1 µg kg^{-1} body weight/day
FSANZ	gemfish, billfish (including marlin), southern bluefin tuna, barramundi, ling, orange roughy, rays and all species of shark – total Hg other fish, fish products, crustaceans, and mollusks – total Hg	1 mg kg^{-1} 0.5 mg kg^{-1}
CFIA	commercially sold fish (except for shark, swordfish, and fresh/frozen tuna) – total Hg	0.5 mg kg^{-1}
China	MeHg in predator fish (shark, sailfish, tuna, pike) other aquatic products of animal origin – total Hg	1 mg kg^{-1} 0.5 mg kg^{-1}
Japan	fish and shellfish – total Hg MeHg	0.4 mg kg^{-1} 0.3 mg kg^{-1}

EU – European Union, FDA – the United States Food and Drug Administration, FSANZ – Food Standards Australia New Zealand, CFIA – Canadian Food Inspection Agency

Even at very low concentrations (> 2 mg kg^{-1} of body weight daily), exposure to Hg may be responsible for a number of illnesses. The health risks for people consuming Hg-contaminated fish include such adverse health effects as brain damage, heart failure, kidney damage, Minamata disease, pulmonary edema, cyanosis, decrease in the intelligence quotient (IQ), nervous system damage in adults, neurological development disorders in infants and children, loss of sight and hearing, weakened reflexes and memory loss. Hg may affect the development or exacerbation of the symptoms of amyotrophic lateral sclerosis, multiple sclerosis, Parkinson's, Alzheimer's, and autism in children (Rice et al. 2014, Buchanan et al. 2015, Dong et al. 2015, Makam et al. 2018, Chmielewski et al. 2020).

A conceptual model of risk assessment was presented in Figure 1 (Zamora-Arellano et al. 2017).

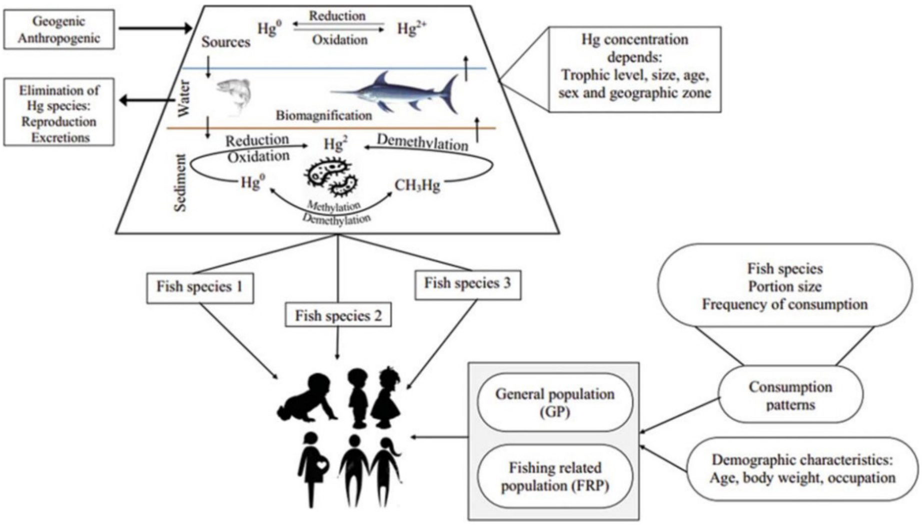

Fig. 1. Conceptual model of mercury exposure through fish consumption (Zamora-Arellano et al. 2017)

CONCLUSIONS

As far as public health is concerned, possible consequences of the long-term consumption of fish and threats to human health related to the bioaccumulation of mercury in the fish organisms have to be recognised. The benefits of fish and fish product consumption ought to be highlighted, while simultaneously informing which species are particularly predisposed to Hg contamination, thus constituting a potential threat.

The analysis of the information and data included in the present study allows one to draw a basic conclusion, which is that fish consumption should not just be recommended for human nutrition, but education measures regarding its consumption norms should be undertaken. In that way, the potential risk of Hg accumulation in the organism of a fish consumer will decrease.

Due to the contamination of fish with Hg, it seems crucial to educate women who are pregnant, breastfeeding, and in their reproductive age about fish consumption, their nutritional value, as well as selecting appropriate species for consumption. Information regarding this topic should be as reliable and objective as possible. The benefits of fish and fish product consumption should be highlighted, while simultaneously informing which species are particularly prone to Hg contamination, posing a potential threat.

Conflict of interest: The authors declare no potential conflict of interest with respect to the authorship and/or publication of this article.

REFERENCS

Åkerblom S., Bignert A., Meili M., Sonesten L., Sundbom M. 2014. *Half a century of changing mercury levels in Swedish freshwater fish*. AMBIO, 43(Suppl 1): 91-103. DOI: 10.1007/s13280-014-0564-1

Ali H., Khan E., Ilahi I. 2019. *Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation*. J Chem., 14. DOI: 10.1155/2019/6730305

Annibaldi A., Truzzi C., Carnevali O., Pignalosa P., Api M., Scarponi G., Illuminati S. 2019. *Determination of Hg in farmed and wild atlantic bluefin tuna (Thunnus thynnus* L.*) muscle*. Molecules, 24(7): 1273. DOI: 10.3390/molecules24071273

Azad A.M., Frantzen S., Bank M.S., Nilsen B.M., Duinker A., Madsen L., Maage A. 2019. *Effects of geography and species variation on selenium and mercury molar ratios in Northeast Atlantic marine fish communities*. Sci Total Environ., 652: 1482e1496. DOI: 10.1016/j.scitotenv.2018.10.405

Backstrom C.H., Buckman K., Molden E. Chen C.Y. 2020 . *Mercury levels in freshwater fish: estimating concentration with fish length to determine exposures through fish consumption*. Arch Environ Contam Toxicol., 78: 604-621. DOI: 10.1007/s00244-020-00717-y

Barone G., Storelli A., Meleleo D., Dambrosio A., Garofalo R., Busco A., Storelli M.M. 2021. *Levels of mercury, methylmercury and selenium in fish: Insights into children food safety*. Toxics, 9(2): 39. DOI: 10.3390/toxics9020039

Bosch A.C., O'Neill B., Sigge G.O., Kerwath, S.E., Hoffman L.C. 2016. *Heavy metals in marine fish meat and consumer health: A review*. J Sci Food Agric., 96: 32-48. DOI: 10.1002/jsfa.7360

Bosch A.C., O'Neill B., Sigge G.O., Kerwath S.E., Hoffman L.C. 2016*a*. *Mercury accumulation in Yellowfin tuna (Thunnus albacares) with regards to muscle type, muscle position and fish size*. Food Chem., 190: 351e356. DOI: 10.1016/J.FOODCHEM.2015.05.109

Buchanan S., Anglen J., Turyk M. 2015. *Methyl mercury exposure in populations at risk: Analysis of NHANES 2011–2012*. Environ Res., 140: 56-64. DOI: 10.1016/j.envres.2015.03.005

Castro N.S.S., Lima M.O. 2014. *Biomarkers of mercury exposure in the Amazon*. Biomed Res Int., 867069. DOI: 10.1155/2014/867069

Cinnirella S., Bruno D.E., Pirrone N., Živković I., Evers D.C., Johnson S., Sunderland E.M. 2019. *Mercury concentrations in biota in the Mediterranean Sea, a compilation of 40 years of surveys*. Sci Data, 6: 205. DOI: 10.1038/s41597-019-0219-y

Cossa D., Heimbürger L.-E., Lannuzel D., Rintoul S.R., Butler E.C.V., Bowie A.R., Averty B., Watson R.J., Remenyi T. 2011. *Mercury in the Southern Ocean*. Geochim Cosmochim Ac., 75(14): 4037-4052. DOI: 10.1016/j.gca.2011.05.001

Chmielewski J., Wojtowicz B., Żeber-Dzikowska I., Łuszczki J.J., Dziechciaż M., Sierpinski R., Marszałek A., Gworek B., Szpringer M. 2020. *Mercury. Sources of release into environment, pollution indicators, threats to human health and the role of education*. Przem Chem., 99(8):1227-1233. (in Polish) DOI: 10.15199/62.2020.8.23

Chmielewski J., Nowińska L., Gworek B., Goś P., Gonczaryk A., Florek-Łuszczki M. 2021. *Primary aromatic amines (PAAs) as a threat to the health of consumers*. J Elem., 26(2): 463-473. DOI: 10.5601/jelem.2021.26.2.2148

Dietrich G.J., Florek-Łuszczki M., Wojciechowska M., Wójcik T., Bąk-Badowska J., Wójtowicz B., Zięba E., Gworek B., Chmielewski J. 2022. *Fish as bio-indicators of environmental pollutants and associated health risks to the consumer*. J Elem., 27(4): 879-896. DOI: 10.5601/jelem.2022.27.3.2322

Dong Z., Jim R.C., Hatley E.L., Backus A.S., Shine J.P., Spengler J.D., Schaider L.A. 2015. *A longitudinal study of mercury exposure associated with consumption of freshwater fish from a reservoir in rural south central USA*. Environ Res., 136: 155-162. DOI: 10.1016/j.envres.2014.09.029

Dorea J.G., Marques R.C. 2016. *Mercury levels and human health in the Amazon Basin*. Ann Hum Biol., 43(4): 349-59. DOI: 10.1080/03014460.2016.1192682

Eagles-Smith C.A., Ackerman J.T., Willacker J.J., Tate M.T., Lutz M.A., Fleck J.A., Stewart A.R., Wiener J.G., Evers D.C., Lepak J.M., Davis J.A., Pritz C.F. 2016. *Spatial and temporal patterns of mercury concentrations in freshwater fish across the Western United States and Canada*. Sci Total Environ., 568: 1171-1184. DOI: 10.1016/j.scitotenv.2016.03.229

Feingold B.J., Berky A., Hsu-Kim H., Rojas E., Pan W.K. 2019. *Population-based dietary exposure to mercury through fish consumption in the Southern Peruvian Amazon*. Environ Res., 108720. DOI: 10.1016/j.envres.2019.108720

Fliedner A., Lohmann N., Rüdel H., Teubner D., Wellmitz J., Koschorreck J. 2016. *Current levels and trends of selected EU Water Framework Directive priority substances in freshwater fish from the German environmental specimen bank*. Environ Pollut., 216: 866-876. DOI: 10.1016/j.envpol.2016.06.060

Ghanei-Motlagh M., Taher M.A., Heydari A., Ghanei-Motlagh R., Gupta V.K. 2016. *A novel voltammetric sensor for sensitive detection of mercury(II) ions using glassy carbon electrode modified with graphene-based ion imprinted polymer*. Mater Sci Eng. C, 63: 367-375. DOI: 10.1016/j.msec.2016.03.005

GIOŚ 2022. *Report on the implementation of monitoring of priority substances in biota*. (in Polish) https://wody.gios.gov.pl/pjwp/publication/287

Gomez-Delgado A.I., Tibon J., Silva M.S., Lundebye A. K., Agüera A., Rasinger J.D., Strohmeier T., Sele V. 2023. *Seasonal variations in mercury, cadmium, lead and arsenic species in Norwegian blue mussels (Mytilus edulis* L.*) – Assessing the influence of biological and environmental factors*. J Trace Elem Med Bio., 76: 127110. DOI: 10.1016/j.jtemb.2022.127110

Grgec A.S., Kljaković-Gašpić Z, Orct T., Tičina, V, Sekovanić A., Jurasović J., Piasek M. 2020. *Mercury and selenium in fish from the eastern part of the Adriatic Sea: A risk-benefit assessment in vulnerable population groups*. Chemosphere, 261:127742. DOI: 10.1016/j.chemosphere.2020.127742

GUS. *Fishing for marine and freshwater fish 2010-2021*. (in Polish) https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/rybolowstwo/polowy-ryb-morskich-i-slodkowodnych,1,1.html

GUS 2017. *Environment 2017*. (in Polish) https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2017,1,18.html

GUS 2018. *Environment 2018.* (in Polish) https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2018,1,19.html

GUS 2019. *Environment 2019.* (in Polish) https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2019,1,20.html

GUS 2020. *Environment 2020.* (in Polish) https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2020,1,21.html

GUS 2021. *Environment 2021.* (in Polish) https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2021,1,22.html

GUS 2022. *Environment 2022.* (in Polish) https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2022,1,23.html

Gworek B., Dmuchowski W., Baczewska A.H., Brągoszewska P., Bemowska-Kałabun O., Wrzosek--Jakubowska, J. 2017. *Air contamination by mercury, emissions and transformations – a review*. Water Air Soil Pollut., 228(4): 123. DOI: 10.1007/s11270-017-3311-y

Gworek B., Dmuchowski W., Baczewska-Dąbrowska A.H. 2020. *Mercury in the terrestrial environment: a review*. Environ Sci Eur., 32: 128. DOI: 10.1186/s12302-020-00401-x

Häder D.-P., Banaszak A.T., Villafañe V.E., Narvarte M.A., González R.A., Helbling E.W. 2020. *Anthropogenic pollution of aquatic ecosystems: Emerging problems with global implications*. Sci Total Environ., 713: 136586. DOI: 10.1016/j.scitotenv.2020.1365

Huseen H.M., Mohammed A. J. 2019. *Heavy metals causing toxicity in fishes*. J Phys Conf., 1294(6): 062028. DOI: 10.1088/1742-6596/1294/6/062028

IOŚ 2020. *Information on the implementation of the tasks of the Environmental Inspectorate in 2020 r*. (in Polish) https://www.gov.pl/web/gios/rok-2021

IOŚ 2021. *Information on the implementation of the tasks of the Environmental Inspectorate in 2021 r*. (in Polish) https://www.gov.pl/web/gios/rok-2022

Issifu I., Alava J.J., Lam V.W., Sumaila U.R. 2022. *Impact of ocean warming, overfishing and mercury on European fisheries: A risk assessment and policy solution framework.* Front Marine Sci, 8: 770805. DOI: 10.3389/fmars.2021.770805

Jaiswal A., Verma A., Jaiswal P. 2018. *Detrimental effects of heavy metals in soil, plants, and aquatic ecosystems and in humans.* J Environ Pathol Tox., 37(3): 183-197. DOI: 10.1615/jenvironpatholtoxicoloncol.2018025348

Kaus A., Schäffer M., Karthe D., Büttner O., von Tümpling W., Borchardt D. 2016. *Regional patterns of heavy metal exposure and contamination in the fish fauna of the Kharaa River basin (Mongolia).* Reg Environ Change, 17(7): 2023-2037. DOI: 10.1007/s10113-016-0969-4

Kimakova T., Kuzmova L., Nevolna Z., Vladimír B. 2018. *Fish and fish products as risk factors of mercury exposure*. Ann Agric Environ Med., 25(3): 488-493. DOI: 10.26444/aaem/84934

Król A., Kukulska-Zając E. 2016. *Monitoring and remediation techniques for mercury-contaminated soil in industrial areas*. Nafta-Gaz, 8: 626-631. DOI: 10.18668/NG.2016.08.06

Kula S., Śmiechowska M. 2016. *The assessment of fish consumption by university students of different academic profiles*. Nauki Inż Technol/Engineering Sciences Technol, 2(21): 28-37. DOI: 10.15611/nit.2016.2.02

Lara A., Galván-Magaña F., Elorriaga-Verplancken F.R., Marmolejo-Rodríguez A.J., González--Armas R., Arreola-Mendoza L., Sujitha S.B., Jonathan M.P., Pantoja-Echevarría L.M. 2022. *Mercury, selenium and cadmium in juvenile blue (Prionace glauca) and smooth hammerhead (Sphyrna zygaena) sharks from the Northwest Mexican Pacific coast.* Mar Pollution Bull., 175: 113311. DOI: 10.1016/j.marpolbul.2021.113311

Lepak J.M., Hooten M.B., Eagles-Smith C.A., Tate M.T., Lutz M.A., Ackerman J.T., Willacker Jr. J., Jackson A K., Evers D.C. Wiener J. G. Pritz C. F., Davis J. 2016. *Assessing potential health risks to fish and humans using mercury concentrations in inland fish from across western Canada and the United States.* Sci Total Environ., 571: 342-354. DOI: 10.1016/j.scitotenv.2016.03.031

Liang S., Chang W., Zhou H., Qi J., Li Y., Feng C., Wang S. 2021. *Global economic structure transition boosts atmospheric mercury emissions in China*. Earth's Future, 9(6): e2021EF002076. DOI: 10.1029/2021EF002076

Liu S., Wang X., Guo G., Yan Z. 2021. *Status and environmental management of soil mercury pollution in China: A review*. J Environ Manage., 277:111442. DOI: 10.1016/j.jenvman.2020.111442

Llull R.M., Garí M., Canals M., Rey-Maquieira T., Grimalt J.O. 2017. *Mercury concentrations in lean fish from the Western Mediterranean Sea: dietary exposure and risk assessment in the population of the Balearic Islands*. Environ Res., 158: 16e23. DOI: 10.1016/j.envres.2017.05.033

Makam P., Shilpa R., Kandjani A.E., Periasamy S.R., Sabri Y.M., Madhu C., Bhargava S.K., Govindaraju, T. 2018. *SERS and fluorescence-based ultrasensitive detection of mercury in water*. Biosens Bioelectron., 100: 556-564. DOI: 10.1016/j.bios.2017.09.051

Moiseenko T.I., Morgunov B.A., Gashkina N.A., Megorskiy V.V., Pesiakova A.A. 2018. *Ecosystem and human health assessment in relation to aquatic environment pollution by heavy metals: case study of the Murmansk region, northwest of the Kola Peninsula*. Rus Environ Res Lett., 13: 065005. DOI: 10.1088/1748-9326/aab5d2

Morshina T.N., Luk'yanova N.N., Mamchenko T.B., Virchenko E.P., Kopylova L.P. 2021. *Mercury and methylmercury in the bottom sediments of Lake Baikal*. Rus J Gen Chem., 91(13): 2924-2930. DOI: 10.1134/S1070363221130211

Nicklisch S.C.T., Bonito L.T., Sandin S., Hamdoun A. 2017. *Mercury levels of yellowfin tuna (Thunnus albacares) are associated with capture location*. Environ Pollut., 229: 87e93. DOI: 10.1016/J.ENVPOL.2017.05.070

Okpala C.O.R., Sardo G., Vitale S., Bono G., Arukwe A. et al. 2017. *Hazardous properties and toxicological update of mercury: From fish food to human health safety perspective*. Crit Rev Food Sci., 58(12): 1986-2001. DOI: 10.1080/10408398.2017.1291491

Pacyna E.G., Pacyna J.M., Sundseth K., Munthe J., Kindbom K., Wilson S., Maxson P. 2010. *Global emission of mercury to the atmosphere from anthropogenic sources in 2005 and projections to 2020*. Atmos Environ., 44(20): 2487-2499. DOI: 10.1016/j.atmosenv.2009.06.009

Polak-Juszczak L. 2017. *Methylmercury in fish from the southern Baltic Sea and coastal lagoons as a function of species, size, and region*. Toxicol Ind Health, 33: 503e511. DOI: 10.1177/0748233716685647.

Rice K.M., Walker E.M. Jr., Wu M., Gillette C., Blough E.R. 2014. *Environmental mercury and its toxic effects*. J Prev Med Public Health, 47(2):74-83. DOI: 10.3961/jpmph.2014.47.2.74

Roberts S., Adams J.K., Mackay A.W., Swann G.E.A., McGowan S., Rose N.L., Panizzo V. Yang H. Vologina E., Sturm M., Shchetnikov A.A. 2019. *Mercury loading within the Selenga River basin and Lake Baikal, Siberia*. Environ Pollut., 259: 113814. DOI: 10.1016/j.envpol.2019.113814

Sarfo D.K., Sivanesan A., Izake E.L., Ayoko G.A. 2017. *Rapid detection of mercury contamination in water by surface enhanced Raman spectroscopy*. RSC Adv, 7(35): 21567-21575. DOI: 10.1039/c7ra02209c

Scheuhammer A., Braune B., Chan H.M., Frouin H., Krey A., Letcher R., Loseto L., Noël M., Ostertag S., Ross P., Wayland M., Wayland M. 2015. *Recent progress on our understanding of the biological effects of mercury in fish and wildlife in the Canadian Arctic*. Sci Total Environ., 509: 91-103. DOI: 10.1016/j.scitotenv.2014.05.142

Si L., Branfireun B.A., Fierro J. 2022. *Chemical oxidation and reduction pathways of mercury relevant to natural waters: A review*. Water, 14(12): 1891. DOI: 10.3390/w14121891

Stock V., Mutschler A., Lindén M., Leopold K. 2021. *Photoactive titanium dioxide films with embedded gold nanoparticles for quantitative determination of mercury traces in humic matter-containing freshwaters*. Nanomaterials, 11(2):512. DOI: 10.3390/nano11020512

Solaun O., Rodríguez J.G., Menchaca I., López-García E., Martínez E., Zonja B., Postigo C., López de Alda M., Barceló D., Borja Á., Manzanos A., Larreta J. 2021. *Contaminants of emerging concern in the Basque coast (N Spain): Occurrence and risk assessment for a better monitoring and management decisions*. Sci Total Environ., 765: 142765. DOI:10.1016/j.scitotenv.2020.1427

Vieira H.C., Morgado F., Soares A.M.V.M., Abreu S.N. 2015. *Fish consumption recommendations to conform to current advice in regard to mercury intake*. Environ Sci Pollut Res., 22: 9595-9602. DOI: 10.1007/s11356-015-4635-z

Wang L., Hou D., Cao Y., Ok Y.S., Tack F.M.G., Rinklebe J., O'Connor D. 2020. *Remediation of mercury contaminated soil, water, and air: A review of emerging materials and innovative technologies*. Environ Int., 134: 105281. DOI: 10.1016/j.envint.2019.105281

Wójtowicz B., Kordyzon M., Bąk-Badowska J., Gregorczyk M., Gworek B., Żeber-Dzikowska I. 2022. *Chemicals in wastewater and sewage sludge – an underestimated health and environmental threat*. J. Elem., 27(4): 847-859. DOI: 10.5601/jelem.2022.27.3.228

Xu J., Bravo A.G, Lagerkvist A., Bertilsson S., Sjöblom R., Kumpiene J. 2015. *Sources and remediation techniques for mercury contaminated soil*. Environ Int., 74: 42-53. DOI: 10.1016/j.envint.2014.09.007

Yevtushenko N.Yu., Dudnyk S.V. 2014. *Mechanisms of income, distribution and excretion of metals in the fish organisms (a review)*. Hydrobiol J, 50(6): 58-68. DOI: 10.1615/HydrobJ.v50.i6.70

Zamora-Arellano N.Y., Ruelas-Inzunza J., García-Hernández J., Ilizaliturri-Hernández C.A., Betancourt-Lozano M. 2017. *Linking fish consumption patterns and health risk assessment of mercury exposure in a coastal community of NW Mexico*. Hum Ecol Risk Assess., 23(6): 1505-1521. DOI: 10.1080/10807039.2017.1329622

Zhao S., Pudasainee D., Duan Y., Gupta R., Liu M., Lu J. 2019. *A review on mercury in coal combustion process: Content and occurrence forms in coal, transformation, sampling methods, emission and control technologies*. Prog Energ Combust., 73: 26-64. DOI: 10.1016/j.pecs.2019.02.001

Żeber-Dzikowska I., Bąk-Badowska J., Gietka M., Gworek B., Wróblewska I., Łuszczki J.J. 2022. *Importance of water, its quality and proper management as a challenge in environmental education*. J Elem., 27(1): 47-57. DOI: 10.5601/jelem.2022.27.1.222