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ORIGINAL PAPER

FISH AS BIO-INDICATORS OF ENVIRONMENTAL POLLUTANTS AND ASSOCIATED HEALTH RISKS TO THE CONSUMER*

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Abstract

Fish is one of the main constituents of human food owing to its content of protein, fats, vitamins and macro- and micronutrients. Some of the chemicals, inter alia, persistent organic pollutants (POPs), including polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), polycyclic aromatic hydrocarbons (PAHs) and specific trace elements, e.g. Ag, Pb, Hg, Cd, Cr, Cu, Ni and Zn, accumulate at the particular links of the food chain when they enter the aquatic ecosystem. In the event of exceeding the doses of the provisional tolerable weekly intake (PTWI), they can lead to lesions that pose a real threat to health and life of consumers. The objective of the study: The aim of this publication is to present possible negative health effects associated with exceedance of the PTWI of fish as well as to systematize knowledge and complement it with the latest research findings. Research methods: Epidemiological studies concerning the possibility of occurrence of adverse health

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effects associated with exceedance of the PTWI of fish have been reviewed. Bibliometrics covering the years 2017-2022, including fish consumption and possible adverse health effects, have been applied. The literature review was conducted by searching the PubMed database. The criterion of selected subject classification entries has been used to analyse the bibliographic data. Results: The current state of knowledge indicates that fish constitute valuable bioindicators for assessment of chemical pollution. Conclusions: The results of this study confirm contamination of fish with xenobiotics. Their consumption should not abandoned with maintaining the proper dietary regime. The benefits of their consumption outweigh the possible potential health risks. In order to minimize negative health effects, consumption of marine and aquaculture fish is recommended. Consumption of long-lived and predatory fish and fish from Asian farms should be avoided.

Kewwords: bioindicators, chemicals, pollution, water, fish, environmental quality, health

INTRODUCTION

Pollution of aquatic ecosystems with chemicals (sewage, pesticides, industrial accidents) is considered one of the most serious problems today. Harmful chemicals,

accumulating in the soil and infiltrating into groundwater, pose a serious threat to humans and the environment. (Dalzochio, Gehlen 2016, Chmielewski et al. 2020, Chmielewski et al. 2020*a*, 2020*b*, Szajner et al. 2021, Walosik et al. 2021, Żeber-Dzikowska et al. 2022).

As confirmed by data from the Central Statistical Office (Polish abbreviation: GUS) in Poland, in the period from 2000 to 2020, the volume of industrial and municipal wastewater requiring treatment decreased from 2,501.5 hm^3 to 2,195.1 hm^3, whereas the volume of untreated wastewater decreased from 301.3 hm^3 to 124.5 hm^3, with a simultaneous decrease in the proportion of mechanically treated wastewater from 732.7 hm^3 to 461.9 hm^3 and an almost doubled amount of wastewater treated in treatment plants with enhanced nutrient removal from 460.4 hm^3 to 1,156.7 hm^3 (GUS 2021). Detail data on wastewater (treated and untreated) discharged through the sewerage network are presented in Table 1.

Release of trace elements into the environment causes imbalances in the natural environment, which is why they have been of great interest for a long time and some of them are included in the environmental monitoring system. Trace elements do not only disturb growth and development of the animal and plant world, however, they also have a negative impact on human health (Dalzochio, Gehlen 2016, Chmielewski et al. 2021, 2022*c*).

Fish have been recognized as bioindicators of environmental contamination, providing integrated insights into the status of their environment over extended periods of time. The notion of a bioindicator is understood as plant and animal organisms with varied sensitivity and characteristic responses to effects of the environmental factors. These are usually species with a narrow range of tolerance to particular substances or changes in their habitat.

Table 1

Treated and untreated wastewater discharged through the sewage network in Poland (GUS 2021)

Specification	2000	2005	2010	2015	2019	2022
	(hm^3)					
Municipal wastewater requiring treatment	1 494	1 274	1 298	1 258	1 343	1 344
Treated	1 243	1 140	1 242	1 254	1 337	1 334
Mechanically	84.8	49.9	1.4	0.4	0.3	0.3
Biologically	705.8	367.2	228.2	189.9	202.0	210.3
With increased biogene removal	451	723	1 013	1 064	1 134	1 123
Untreated wastewater	250.5	133.6	55.4	4.1	6.7	10.4

The source: the authors, based on data of the Polish Central Statistical Office (GUS)

Bioindicators constitute biological traits that can be measured and which tend to change with exposure to negative environmental factors. Fish, inhabiting almost all aquatic habitats, reflect the health condition of their habitat from the molecular to the population level. This is particularly important for identification of most trace elements as they demonstrate very long biological half-lives. Consequently, elevated tissue concentrations may occur even when the exposure is not continuous. Fish are an important food source for humans in many parts of the world and therefore monitoring their trace element levels is important to ensure food safety. This is especially the case for Hg since fish consumption is believed to be the main source of this element for humans. Fish have been used as bioindicators to examine the levels of hazardous metals/metalloids, including: As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, V, Zn, asses the water quality and ecological risk (Courtney et al. 2014, Plessl et al. 2017, Donner et al. 2018, Copat et al. 2020).

Development of industry and, consequently, amounts of industrial, agricultural and household chemicals discharged into the aquatic environment have led to various harmful effects on aquatic organisms. The increase in the demand for water, both by industries and by households, as well as the increase in the use of chemicals constitute the factors that significantly prevent the natural processes of self-purification of water as well as possibilities for recovery of water resources. Contamination of the aquatic environment with various types of chemicals means that due to their presence in fish organisms, they may adversely affect health of consumers (Dalzochio, Gehlen 2016, Chmielewski et al. 2020*d*, Chmielewski et al. 2022, 2022*c*, Żeber-Dzikowska et al. 2022).

OCCURRENCE OF CHEMICAL SUBSTANCES IN FISH

Trace elements

Safe food is of key importance to our health. Fish constitute an extremely significant food group in the human diet. Foods containing chemicals pose a global health risk, contributing to a wide range of diseases, from diarrhoea to neoplasms (Dybkowska et al. 2014, Ochwanowska et al. 2019).

Trace elements, such as Pb, Ni, Cd, Hg, Cu and Zn, present in environmental compartments in quantities exceeding the permissible limits negatively affect the whole environment and human health, to a degree dependent on their toxicity. They have an influence on all groups of organisms and ecosystem processes. They react with essential cellular components to form covalent and ionic bonds. Metals in high concentrations, both essential and non-essential ones, can damage cell membranes, change specificity of enzymes, disrupt cellular functions and damage the DNA structure (Chmielewski et al. 2020c, *f*, *g*).

The presence of trace elements, e.g. Hg, Pb, Cd, Sn, As, in fish tissues is a result of the process of their simultaneous uptake from the environment and food, and depends on their concentration in water and food. The concentration of trace elements in fish also depends on the diet itself and this will be different in herbivorous fish and in predatory fish. Carnivorous fish at the end of the food chain may contain considerably higher concentrations of trace elements in their bodies than other species and – as a result – their consumption in the dose exceeding the provisional tolerable weekly intake may pose a potential health risk to consumers. In aquacultures, in the poor sanitary conditions, in the absence of water of suitable quality and in the conditions of high stocking density (tilapia), there is a risk of the increased content of trace elements (Hg, Cd). For fish living in the natural conditions or requiring high-quality water (trout), concentrations of trace elements will be significantly lower. In the organisms of predatory fish (shark, tuna, swordfish, eel) and fish living at the bottom of water bodies, higher Hg concentrations are observed than in other fish species. However, this is not only due to the diet, as it also depends on age, motility and feeding location. Hg is accumulated in the food chain of aquatic organisms and, consequently, fish are an important source of Hg intake for consumers. Most of the Hg contained in fish is in the form of organic compounds, mainly methylmercury, which is manifold more toxic than metallic Hg (Donner et al. 2018, Abd El Samee et al. 2019, Javed, Usmani 2019, Jinadasa, Fowler 2019, Korkmaz et al. 2019, Laila et al. 2019, Chmielewski et al. 2020*e*, Sonone et al. 2020, Emenike et al. 2021).

Maximum levels for specific contaminants in foodstuffs for fish are set out in Annex 1 of Commission Regulation (EC) No 1881/2006 (Commissin Regulation 2006), as presented in Table 2.

Table 2

Maximum levels for certain contaminants in foodstuffs (amended by Commission Regulation 2006)

Section 3: Metals			
Foodstuffs			Maximum levels (mg kg^{-1} wet weight)
3.1	Lead		
3.1.5	Muscle meat of fish		0.30
3.2	Cadmium		
3.2.6	Muscle meat of the following fish: anchovy (Engraulis species) bonito (Sarda sarda) common two-banded seabream (Diplodus vulgaris) eel (Anguilla anguilla) grey mullet (Mugil labrosus labrosus) horse mackerel or scad (Trachurus species) louvar or luvar (Luvarus imperialis) sardine (Sardina pilchardus) sardinops (Sardinops species) tuna (Thunnus species, Euthynnus species, Katsuwonus pelamis) wedge sole (Dicologoglossa cuneata)		0.10
3.3	Mercury		
3.3.2	Muscle meat of the following fish (24) (25): anglerfish (Lophius species) atlantic catfish (Anarhichas lupus) bonito (Sarda sarda) eel (Anguilla species) emperor, orange roughy, rosy soldierfish (Hoplostethus species) grenadier (Coryphaenoides rupestris) halibut (Hippoglossus hippoglossus) marlin (Makaira species) megrim (Lepidorhombus species) mullet (Mullus species) pike (Esox lucius) plain bonito (Orcynopsis unicolor) poor cod (Tricopterus minutes) Portuguese dogfish (Centroscymnus coelolepis) rays (Raja species) redfish (Sebastes marinus, S. mentella, S. viviparus) sail fish (Istiophorus platypterus) scabbard fish (Lepidopus caudatus, Aphanopus carbo) seabream, pandora (Pagellus species) shark (all species) snake mackerel or butterfish (Lepidocybium flavobrunneum, Ruvettus pretiosus, Gempylus serpens) sturgeon (Acipenser species) swordfish (Xiphias gladius) tuna (Thunnus species, Euthynnus species, Katsuwonus pelamis)		1.0
Section 5: Dioxins and PCBs			
Foodstuffs			Maximum levels
		sum of dioxins (WHOPCDD/F-TEQ)	sum of dioxins and dioxin-like PCBs (WHOPCDD/F-PCB-TEQ)
5.3	Muscle meat of fish and fishery products and products thereof, excluding eel	4.0 pg g^{-1} wet weight	8.0 pg g^{-1} wet weight
5.4	Muscle meat of eel (Anguilla anguilla) and products thereof	4.0 pg g^{-1} wet weight	12.0 pg g^{-1} wet weight

cont. Table 2

Section 6: Polycyclic aromatic hydrocarbons		
Foodstuffs		Maximum levels ($\mu g\ kg^{-1}$ wet weight)
6.1	Benzo(a)pyrene	
6.1.3	Muscle meat of smoked fish and smoked fishery products	5.0
6.1.4	Muscle meat of fish, other than smoked fish	2.0

The source: the authors, based on Commission Regulation 2006

Polycyclic Aromatic Hydrocarbons (PAHs)

In the processes of incomplete combustion or pyrolysis resulting from natural processes in the environment, PAHs are formed, which are then transferred to soil and water with air (Chmielewski et al. 2020*a*).

PAHs remaining in the water become concentrated in the food chain, and specific quantities of these substances may be supplied to fish.

The risk related to the presence of the PAHs in fish may result from the fish processing technology such as smoking. Variations in the content of total PAHs may be due to both specificity of the fish species (size, skin thickness, fat content) and characteristics of smoking (Hamidi et al. 2016, Ochwanowska et al. 2019). Available literature confirms that PAHs become important contaminants in smoked and smoke-dried fish as well as in fish products. Smoking techniques and various parameters contribute to an increase in the content of PAHs in smoked fish. The content of PAHs in smoked fish indicates a strong correlation with fat content (Jinadasa et al. 2020, Racovita et al. 2020). Common consumer practice shows that small fish are consumed with the skin that contains more PAHs than other tissues of the fish. At the early stage of fish development, PAHs are accumulated in the skin and then they migrate to the underlying adipose tissue due to their fat solubility (Fasano et al. 2016, Hokkanen et al. 2018, Racovita et al. 2020).

PAHs have been recognized as priority pollutants due to their carcinogenic and mutagenic properties (Ochwanowska et al. 2019, Jinadasa et al. 2020).

Persistent Organic Pollutants (POPs)

Persistent Organic Pollutants (POPs) include, inter alia, polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and polychlorinated biphenyls (PCBs), organochlorine pesticides (OCPs), organochlorine insecticides (OCI), dichlorodiphenyltrichloroethane (DDT), hexachlorobenzene (BHC). POPs are emitted to the environment as a by-product of industrial activities (chemical, pharmaceutical, paper, metallurgical, agricultural), during combustion of fuels, waste as well as waste landfills. Due to their metabolic resistance and lipophilic nature, POPs accumulate in animal tissues and organs. About 210 possible congeners of PCDDs, PCDFs and PCBs are differentiated among POPs, with different numbers of chlorine atoms and their distribution. They occur as a mixture of various congeners, characterised by a wide distribution in the aquatic and terrestrial ecosystems as well as persistence in the environment (Chmielewski et al. 2020*a*, *b*, *f*, Szajner et al. 2021).

Air transport of PCDDs, PCDFs and PCBs is regarded as the main pathway of their distribution, resulting in their deposits on the soil surface, whereas precipitation brings them into water bodies. In water bodies – due to their hydrophobic nature – they bind to particulate matter suspended in the water and afterwards they undergo sedimentation to bottom sediments, from which they are taken up by benthic organisms, which in turn provide food for fish, which then pose a health risk to the consumer (Sobek et al. 2014, Baran et al. 2020, Ndunda, Wandiga 2020).

In 2016, the European Commission (EU) issued a recommendation to eliminate fish exceeding PCDD/PCDF/PCB limits from the Community market. The recommendation applies to fish and their products from the Baltic Sea region in relation to the fish species and fishing zones listed therein. The recommendation provides guidance stating which fish species and from which fishing zones can be marketed without testing and which need to be checked for the presence of PCDDs/PCDFs/PCBs. Due to the suspicion that the liver of the cod caught in the Baltic Sea region does not meet the PCDD/PCDF/PCB limit standards, each batch should be analysed to confirm the compliance before being placed on the EU market (Commission Recommendation 2016).

Despite the prohibition on the use of OCI (DDT, HCH, HCB and others) in plant protection, environmental contamination with these substances occurs (Umulisa et al. 2020), particularly in surface waters, which simply leads to the contamination of fish intended for consumption. Polychlorinated biphenyls (PCBs) that are also fat-soluble and can be accumulated in particular links of the food chain have the properties similar to OCI. They enter water bodies with industrial and municipal wastewater, precipitation and as a result of waste landfill fires (Chmielewski et al. 2020*a*, *b*).

The main sources of PCB intake are products of animal origin, especially fish, both freshwater and marine in which much higher concentrations have been found. The higher the fat content of the fish, the greater the risk of higher levels of OCPs and PCBs (Xie et al. 2020).

Fish – as a source of polyunsaturated fatty acids – are an important part of the diet and thus also a source of PCDD, PCDF, PCB and pesticide intake for humans (Cui et al. 2018, Nøstbakken et al. 2021).

MATERIAL AND METHODS

The range of scientific content taken from PubMed, an English-language online database of the National Library of Medicine, National Institutes of Health, Bethesda, MD, USA (http://www.ncbi.nlm.nih.gov/PubMed), SCOPUS, Google Scholar, covering articles within the scope of medicine, biological sciences, agricultural sciences, sciences and life sciences, was analysed taking into account the accumulation of trace elements in fish resulting from water contamination with chemicals and the associated health effects on consumers. Literature published in available scientific information databases between 2017 and 2022 was reviewed, adopting the 5-year time span for the analysis on the assumption that it covers the most recent scientific reports on the subject issue. In the process of searching for scientific articles, advanced search options were applied, based on key words or a combination of key words (step 1, Table 3) and a fixed time interval (2017-2022). Reviews, conference materials, letters to the editor, book chapters as well as conference and training notes were not included in the review and were excluded from the analysis.

Table 3

Step one of the analysis of the literature trends on the basis of key words

Key words	fish as bioindicators; accumulation of trace elements in fish; impact of fish contaminated with trace elements on human health

RESULTS AND DISCUSSION

The analysis revealed that there are 2,117 publications in the PubMed scientific database (as of 22 June 2022) concerning the accumulation of trace elements in fish and their impact on human health between 2017 and 2022. Table 4 presents a quantitative list of publications on water pollution and

Table 4

Publications on water contamination with trace elements and their accumulation in fish and the impact of fish consumption on consumer health in the years 2017-2022

Year of publication	Number of publications based on searching by key words			
	fish as bioindicators	accumulation of trace elements in fish	impact of fish contaminated with trace elements on human health	total
2017	235	57	9	301
2018	276	85	14	375
2019	269	79	8	356
2020	318	89	17	424
2021	313	103	7	423
2022	177	56	5	238
Results in total	1 588	469	60	2 117

The source: the authors, on the basis of a review of the PubMed database, (http://www.ncbi.nlm.nih.gov/PubMed) health impacts during the analysed time period. Out of the total of 2,117 papers (100% of publications), publications searched by keyword combination – fish as bioindicators – accounted for 70.01% (n=1.588) of all publications, papers dedicated to the accumulation of trace elements in fish accounted for 22.15% (n=469) of all papers, while those dedicated to the impact of the fish contaminated with trace elements on human health comprised 2.83% (n=60) of all papers. Sixteen papers related directly to possible health effects associated with the consumption of fish contaminated with trace elements were analysed in detail, as illustrated in Table 5.

As confirmed by the result of the analysis, the issue of consumption of fish contaminated with trace elements and its impact on human health is of little interest to researchers. According to the authors, this state of affairs results from complexity and problematic nature of the issue, organisational difficulties of the research process and its cost-intensity.

The use of analytical tools to assess chemicals does not provide a comprehensive study of the complex ecosystem. Consequently, additional complementary methods that can directly address biological effects resulting from exposure to chemicals are necessary. Thus, biological studies aiming at assessment of a selected water body (ocean, sea, lake, river), through numerous bioassays and other ecotoxicological tests, have been added to the process of monitoring of chemicals in the aquatic environment. These include (eco) toxicological tests that expose biological components (cells, individuals, populations, communities) to the effects of (environmental mixtures of) chemicals in order to record the biological effects. Selected chemicals have been identified as substances most threatening to the aquatic ecosystems. The Water Framework Directive enforces examination of the chemical parameters within the scope of toxicology. Standards for specific toxic substances, their potential indicators, ecological risk assessments have been set (Arp et al. 2017, Schuijt et al. 2021).

Contaminants like trace elements pose a particular threat to human health since the effects of their action may appear even after many years. These elements are not subject to biological degradation and may exhibit carcinogenic effects (Chmielewski et al. 2020*c*, *g*).

Fish, like other foods, contain some substances that are undesirable in human nutrition. Their presence results mainly from contamination of the aquatic environment; thus, fish constitute an indicator of the contamination of their habitat. Fish can accumulate trace elements, primarily Hg, Pb, Cd and As. Not only are these elements toxic, but they also have an unfavourable impact on the bioavailability of minerals essential for the human body, such as Mg, Fe, Zn, Cu and Se (Ochwanowska et al. 2019).

The WHO (World Health Organisation) reports that approximately 99% of organic forms of Hg are taken up by humans with food. The subject literature confirms that 75-95% of Hg in fish is in the form of methylmercury (MeHg). Its concentration in fish varies greatly and depends on numerous factors. Of key importance are the geographical aspect, which is related to the location of habitats of particular fish species and the quality of available food, and the biological factor, which refers to species characteristics, such as the body size, amount of muscle tissue and absorption mechanism. Large predatory fish, e.g. swordfish, shark or tuna, accumulate higher amounts of methylmercury due to high consumption resulting from a long life span. Hg accumulated in fish constitutes a source of risk to human health if ingestion of a dose exceeding the PTWI takes place. Mercury in the human body easily crosses the blood-brain barrier, causing changes in the central nervous system. The main site of its accumulation in the body is the cerebral cortex and cerebellum. Symptoms of Hg neurotoxicity include spontaneous tremour of the limbs or head, ataxia, sleep disturbances, depression, anger outbursts, loss of the sight and hearing, impaired reflexes and memory loss. Mercury may influence development or exacerbation of symptoms of amyotrophic lateral sclerosis, multiple sclerosis, Parkinson's disease, Alzheimer's disease and autism in children. Once Hg enters the central nervous system (CNS), dysfunction may occur in the form of tremour of the limbs, insomnia, emotional vacillation, headaches, memory and cognitive impairment, general weakness and damage to hearing and/or sight. Furthermore, deviations in psychomotor abilities, with particular attention to paresthesias, slurred speech and impaired concentration, are observed in some exposed individuals (Kot et al. 2016, Cyran et al. 2019, Ochwanowska et al. 2019, Chmielewski et al. 2020*c*, *e*, *f*). Table 6 presents the Hg contamination of marine fish in different water areas (Chmielewski et al. 2020e).

PCDDs and PCDFs are highly toxic substances; they weaken the immune system, disrupt the endocrine system as well as exhibit mutagenic, carcinogenic and teratogenic effects. The content of PCDD/Fs in food is regulated by Commission Regulation (EC) No 1259/2011 (Commissin Regulation 2011).

PCBs cover approximately 200 compounds; some of them exhibit similar toxic effects to PCDD/Fs. PCBs are well-soluble in fats and they can accumulate in all links of the food chain. The main sources of PCBs in the diet are animal products (fish, meat, milk) that account for up to 90% of the total intake. Particular attention should be paid to marine and freshwater fish which contain much higher concentrations of these compounds than other food groups. Their content in products is closely related to environmental contamination (Fernandes el at. 2018, Ochwanowska et al. 2019, Chmielewski et al. 2020*a*).

Fish are exposed to PAHs in water and bottom sediments (Olayinka et al. 2019). Animal products rich in fat (meat and fish) and vegetable oils have the highest share in supplying PAHs to consumers (Bansal, Kim 2015). PAHs constitute a group of highly carcinogenic and mutagenic compounds; sixteen of them have been recognized as priority pollutants by regulatory authorities. Specific PAHs were present in particularly high concentrations in smoked, baked and grilled fish (Rascón et al. 2019).

Table 5

Evaluation of the incidence of health consequences related to the consumption of fish contaminated with trace elements in people

Fish species:	Trace elements or chemical compounds	Health effect studied	Result	Reference
European carp (*Cyprinus carpio*), African sharptooth catfish (*Clarias gariepinus*), Mozambique tilapia (*Oreochromis mossambicus*) from two impoundments in the Hex River system (Western Cape, South Africa)	As, Cd, Cr, Cu, Ni, Pb, Pt, Zn	As has non-carcinogenic (HQ = 2-7) and carcinogenic risks (33-93 out of 10,000 people), while Cr (3-10 out of 10,000 people) and Ni (2-6 out of 10,000 people) possesses only carcinogenic risks. Regular consumption of all three fish species may cause adverse human health effects.	+	Erasmus et al. (2022)
Two pelagic streaked Spanish mackerel (*Scomberomorus lineolatus*), common hairfin anchovy (*Setipinna tenuifilis*) and five demersal fish species: bull shark (*Carcharhinus leucas*), blackfin barracuda (*Sphyraena qenie*), Indian halibut (*Psettodes erumei*), largehead hairtail (*Trichiurus lepturus*), tiger-toothed croaker (*Otolithes ruber*) from the Miri coast (Sarawak, Borneo, Malaysia)	Cr, Mn, Co, Ni, Cu, Zn, Rb, Cd, Pb	Concentrations of trace elements were below the maximum permissible limits (MPL) of Malaysian and International seafood guideline values and safe for consumers.	-	Anandkumara et al. (2018)
European carp (common carp – *Cyprinus carpio*), and Indian trout (trout barb – *Raiamas bola*) from Atatürk, Keban and Karakaya reservoirs (Turkey)	Na, K, Ca, Mg, P, As, Cd, Pb	Toxic trace elements do not have a significant health risk to consumers.	-	Varol, Sünbül (2020)
Pama croaker (*Otolithoides pama*), Chewa (*Pseudapocryptes elongatus*), giant river prawn (*Macrobrachium rosenbergii*), goldspot mullet *(Chelon parsia)*, emerald shiner (*Notropis atherinoides*), Gobi fish (*Apocryptes bato*), and corsula (*Rhinomugil corsula*) from Halda river (Bangladesh).	As, Pb, Cd, Cu, Ni, Zn	As, Pb, and Ni surpassed provisional tolerable weekly intake (PTWI)-recommended concentrations. The non-carcinogenic health effect might not appear for consumers. Children were more vulnerable to non-carcinogenic (67.3%) and carcinogenic risk effect (47.3%) for Pb.	+	Ahmed et al. (2020)

cont. Table 5

Fish species:	Trace elements or chemical compounds	Health effect studied	Result	Reference
Ilish (hilsa – *Tenualosa ilisha*) and American gizzard shad (mud shad – *Dorosoma cepedianum*) from fish markets (Bangladesh)	Pb, Cd, Cr, As, Hg	Toxic concentrations of Cd, Cr and As may cause a high risk of cancer. These fish species should not be considered safe for human consumption.	+	Atique et al. (2019)
Indian rui (*Labeo rohita*), Indian carp (*Catla catla*), and dwarf goonch (*Bagarius bagarius*) from Dhaleshwari River, (Bangladesh)	Cr, Cd, Pb, Cu, As	Cu, Pb, and Cr concentrated in fish have a carcinogenic risk	+	Lipy et al. (2021)
23 fish species (5 car-nivores and 18 non-carnivores) from the Tapajós River in the (Brazilian Amazon)	Hg, Se	Hg and Se accumulated in carnivores fish species. To decrease Hg exposure local people should choose non-carnivores species and avoid carnivores fish.	+	Lino et al. (2018)
Milkfish (*Chanos chanos*) from coastal areas (Taiwan)	As, Cu, Zn	Lower risk of hematological effects due to As–Zn interactions probably because Zn supplementation reduces As-induced hazards.	-	Lin et al. (2017)
Two demersal fish species: marbled spinefoot (*Siganus rivulatus*) and sand steenbras (*Lithognathus mormyrus*) and one pelagic species red-eye round herring (Etrumeus teres) from the Lebanese coast (Eastern Mediterranean)	Al, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Ag, Cd, Sn, Sb, Ba, Hg, Pb, U	Herbivorous marbled spinefoot showed the highest level of contamination compared to the two other species. Concentrations of Hg, Cd, and Pb were below the levels set by the European Community with no potential risk on human health.	+	Ghosn et al. (2020)
182 samples of edible fish from UK marine regions, but extending northerly to the coast of Norway and south to the Algarve	PCDD/F, PCB, PBDE, PBB, PCN, PFAS	The high frequency of contaminant occurrence combined with the instances of samples that lie above the regulated limits.	+	Fernandes et al. (2018)

cont. Table 5

Fish species:	Trace elements or chemical compounds	Health effect studied	Result	Reference
13 fish species: Pacific cod (*Gadus microcephalus*), bastard halibut (*Paralichthys olivaceus*), ditrema (*Ditrema temminckii*), shishamo (*Spirinchus lanceolatus*), largehead hairtail (*Trichiurus lepturus*) from the Bohai Sea (China)	dl-PCB, PCDD/F	The muscle and skin concentration ratios for the dl-PCBs and PCDD/Fs for the different species varied greatly. The total PCDD/F and dl-PCB TEQs were slightly lower for skin than muscle.	+	Cui et al. (2018)
6 fish species: salmon (*Salmo salar*), sea trout (*Salmo trutta m. trutta*), sprat (*Sprattus sprattus balticus*), herring (*Clupea harengus membrus*), cod (*Gadus morrhua callarias*) and flounder (*Platichthys flesus*) – from Baltic Sea (Poland)	PCDD, PCDF, PCB	Despite the decreased levels of PCDD/F and PCBs in Baltic fish, this decrease is not enough to make the Baltic fish safe for frequent consumers.	+	Mikołajczyk et al. (2021)
7 fish species: European eel (*Anguilla anguilla)*, rainbow trout (*Oncorhynchus mykiss*), bream (*Abramis brama)*, sturgeon (*Acipenser* sp.), common carp (*Cyprinus carpio)*, and zander (*Sander lucioperca)* – from Polish farms and panga *(Pterogymnus laniarius)* – from Vietnamese farms	PCDD, PCDF, PCB	Frequent consumption of some species (i.e., eel and bream) can have a health risk to vulnerable consumers and children and pregnant women.	+	Mikołajczyk et al. (2020)
Two fish species: African sicklefish (*Drepane Africana*) and sompat grunt (*Pomadasys jubelini*), crabs (*Callinectes amnicola*) and shrimps (*Penaeus notialis*) around the Atlas Cove jetty, Lagos, Nigeria.	WWA	Total PAHs were higher in whole fish than in fillet samples (muscle) in both fish species. The concentrations of PAHs in analyzed sediment and organisms were higher than the maximum permissible limit of the United State Environmental Protection Agency (USEPA).	+	Olayinka et al. (2019)
Fish samples (salmon, sea bass, anchovy, prawn, hake, swordfish (*Xiphias gladius*), blue whiting (*Micromesistius poutassou)*, sardine) from European markets	WWA	Some PAHs were present at high concentrations in smoked, roasted and grilled fish compared to raw samples.	+	Rascón et al. (2019)

Table 6

Hg content in various marine fish from different water areas of the world (modified Chmielewski et al. 2020*e*)

Origin of the sample	Concentration	Unit
The Caspian Sea	< 0.05-0.79	(mg kg^{-1} d.w.)
The Pacific, Alaska	0.19-0.40	
The Pacific, California	0.24-0.73	
The Barents Sea, Greenland	0.19-1.10	(mg kg^{-1} w.m.)
The Indian Ocean, Mozambique	0.21-3.97	(mg kg^{-1} d.w.)
The Atlantic Ocean, Ghana	0.004-0.122	(mg kg^{-1} w.w.)
The Atlantic Ocean, Azores	0.19-1.44	
The Black Sea, Turkey	0.025-0.084	
The Baltic Sea, Poland	0.018-0.118	
The Adriatic Sea, Croatia	0.001-0.52	

d.w. – dry weight, w.w. – wet weight

CONCLUSIONS

In order to increase awareness of the scale and complexity of possible threats to aquatic environments in relation to fish consumption and its impact on human health, the issue should be understood in an multidisciplinary manner.

Fish and fish products are rich in n-3 polyunsaturated fatty acids, complete proteins and iodine, selenium and fluoride as well as vitamin D. Despite the existing risks associated with fish consumption due to contamination with trace elements, health benefits resulting from their moderate consumption while adhering to PTWI principles outweigh the health risks.

Health risk assessment associated with fish consumption constitutes a vital, albeit necessary multi-step procedure to identify the health effects in humans as a result of exposure to possible chemical contaminants.

Food, including fish, constitutes the main source of human exposure to trace elements. Consequently, special emphasis should be placed on nutritional education to prevent over-consumption with food.

In order to minimize negative health effects, it is recommended to consume marine and aquaculture fish while following the PTWI principles. Consumption of long-lived and carnivorous fish, fish from Asian farms as well as smoked, baked and grilled fish should be avoided due to the possible presence of high concentrations of PAHs.

Conflict of interest

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

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