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REVIEW ARTICLE

Characteristics of selected bioaccumulative substances and their impact on fish health

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Abstract

The aim of this article was to evaluate the influence and effects of chosen bioaccumulative substances *i.e.* heavy metals, pesticides, and polychlorinated biphenyls (PCBs) on fish, as well as provide information on time trends and potential threat to human health. Chemical substances which pollute water may affect living organisms in two ways. First of all, large amounts of chemical substances may cause sudden death of a significant part of the population of farmed fish, without symptoms (*i.e.* during breakdown of factories or industrial sewage leaks). However, more frequently, chemical substances accumulate in tissues of living organisms affecting them chronically. Heavy metals, pesticides, and polychlorinated biphenyls are persistent substances with a long-lasting biodegradation process. In a water environment they usually accumulate in sediments, which makes them resistant to biodegradation processes induced by, *e.g.*, the UV light. These substances enter the fish through direct consumption of contaminated water or by contact with skin and gills. Symptoms of intoxication with heavy metals, pesticides, and PCBs may vary and depend on the concentration and bioavailability of these substances, physicochemical parameters of water, and the fish itself.

Keywords: fish, heavy metals, pesticides, polychlorinated biphenyls, toxicology.

Introduction

Food from aquaculture is an important part of the overall food production. In Europe, it reached over 2,900,000 t in 2014 (16). As the main aquaculture animals, fish are particularly vulnerable to changes in the environment associated with the introduction of unwanted substances into water. The problem of fish poisoning is complex and includes several factors. First of all, fish poisoning can occur rapidly, thus it may cause significant economic losses (directly related to loss of farmed fish). Furthermore, chemicals which enter water and are accumulated in fish tissues may be a serious risk to human health, as well as may contaminate the environment. It should be remembered that the presence of pollutants in water sensitises fish to infectious agents. Some chemicals may cause immunosuppression, which contributes to an increased number of fish diseases (3).

Heavy metals, pesticides, and polychlorinated biphenyls are substances that are able to accumulate in fish (Fig. 1), which means they may occur at higher concentration levels compared to the environment in which they live. Although there are several pathways leading to biodegradation of some of these substances (*i.e.* UV activity or biochemical processes developed by microorganisms), they are generally known as highly persistent pollutants and still occur in water and organisms. Moreover, some of these substances may undergo biomagnification, occuring at higher levels in organisms occupying higher trophic level in food chain (Fig. 2). Some studies have shown, however, that process of biomagnification depends on the substance itself as well as on metabolism and biological variables (*i.e.* sex, age, and habitat) of an organism and may be disrupted (8, 15). Some heavy metals do not biomagnify at all (*i.e.* Cu, Pb, Cd, and Zn) (8).

Pollutants may enter the aquatic environment as the result of natural occurrence or as the result of human endeavours, and this may lead to adverse water quality (5). The sources of pollutants causing fish poisoning include: agriculture (spraying, use of fertiliser or pesticides), industry (industrial effluents), and domestic sewage. Toxic substances can get into water with rainfall, meltwater, water leaks from factories, septic tanks leaking, or in case of periodic overload of wastewater treatment plants (3, 5).

Heavy metals. Mercury, copper, cadmium, iron, arsenic, manganese, lead, and strontium are particularly dangerous heavy metals (34). They are present in water sediments where they accumulate. Their level in aquatic sediments can exceed the level observed in water. Another source of these elements may be water systems supplying tanks in fresh water, which are covered with these metals. They usually enter the fish in a direct way, either through water or biota consumption, also leading to bioaccumulation of these elements. Another possible pathway is their penetration through the skin and gill epithelia (9). Their bioavailability depends on the physical and chemical parameters of water (3) and the fish itself, as the latter can eliminate harmful substances from the body and dispose of them by biotransformation (9).

Heavy metals bioaccumulate in fish kidneys, liver, muscles, gills, fat, and brain tissue (3, 15, 33). Their levels may vary significantly depending on the investigated organs, as well as gender, age, weight, reproductive cycle, feeding habits, environment, and fish trophic levels (9, 15, 45). They are present at significant concentrations in fish worldwide (Table 1).

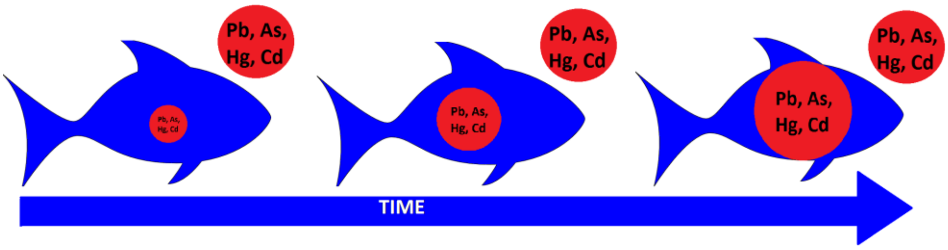

Fig. 1. Bioaccumulation process

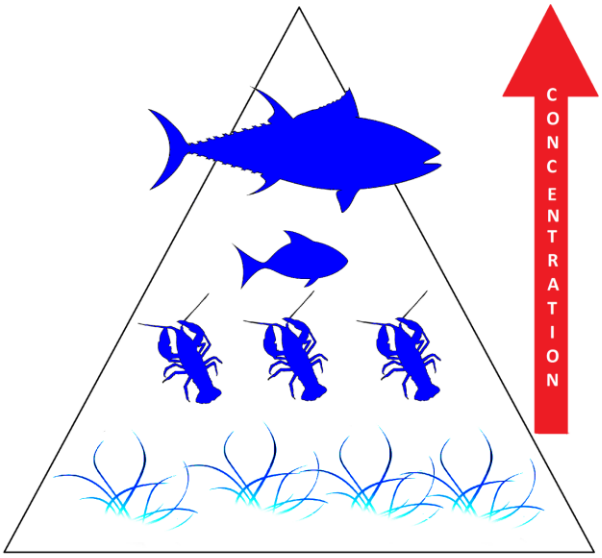

Fig. 2. Biomagnification process

Table 1. Concentration (mg kg $^{-1}$) of heavy metals in fish muscles in different parts of the world

Region	Fish species	Cadmium	Lead	Mercury	Reference
Bangladesh, Sundarban area	*Lates calcarifer* *Acanthopagrus berda*	0.0103[b] 0.0027[b]	0.0584[b] 0.0419[b]	0.235[b] 0.350[b]	8
Bulgaria, Black Sea	bluefish gray mullet	0.008[a] 0.012[a]	0.03[a] 0.05[a]	0.09[a] 0.05[a]	27
Brazil, Paraopeba River	*Pseudoplatystoma corruscans*	0.07[a]	0.94[a]	0.41[a]	4
Ethiopia, Lake Awassa	tilapia catfish	nd nd	0.004[a] 0.003[a]	0.02[a] 0.04[a]	44
China, South China Sea, Meiji (Mischief) Reef	*Acanthurus xanthopterus* *Cephalopholis miniatus*	0.115[a] 0.0017[a]	0.0071[a] 0.0045[a]	nd nd	18
Tunisia, Mediterranean Sea	*Diplodus annularis* *Solea vulgaris* *Liza aurata*	0.76[b] 1.03[b] 0.3[b]	0.11[b] 1.855[b] 0.17[b]	0.38[b] 1.840[b] 0.36[b]	46

[a] – concentration in fresh weight sample; [b] – concentration in dry weight sample; nd – no data

Symptoms of poisoning by heavy metals may appear periodically, for example, during increased needs of energy, when heavy metals are released from fat reserves to blood stream. Their presence in water results in compound deposition (salt mainly) on the surface of spawn and gills, leading to oxygen deficit and paleness of the gills. Oxygen deficiencies force fish to swim towards water surface (gasping), where they try to capture atmospheric oxygen. Furthermore, increased mucous secretion on the skin and gills can be observed. Long-lasting exposure to heavy metals can cause damage of the liver and kidneys which are essential organs for osmosis regulation and proper functioning of the immune system (3, 34). Chronic exposure to arsenic exerts immunotoxic effect by decreasing the number of macrophages in head kidney (12). Furthermore, fish reproductive system is also negatively affected by heavy metals. Bioaccumulation of these compounds in brain tissue results in disturbance of hormonal equilibrium of the hypothalamo-pituitary system, which can unfavourably influence the efficiency of artificial spawning in fish (33). They negatively affect the ability of sperm to fertilise by the reduction or complete loss of spermatozoon movement. In addition, the presence of heavy metals may lead to reduced secretion of oestrogen and androgen (14, 34). When present in water, these compounds may significantly reduce the number of sensitive invertebrates; the lack of the latter results in food shortage, which is especially important for some fish species (*i.e.* carp in the first farming period), leading to decreased survivability of young fish.

Vacuolar degeneration and lipid infiltration of the liver, cellular lesions and vascular haemorrhages in the kidneys, and muscular degeneration (14) can be observed among histopathological lesions.

Pesticides. Pesticides are a wide group of substances belonging to persistent organic pollutants (POPs). They include: algaecides, fungicides, herbicides, insecticides, acaricides, nematocides, molluscicides and rodenticides (34). These substances are highly resistant to biodegradation processes. Furthermore, due to chemical transformation, they may become part of a food web or even increase their own toxicity. Some pesticides are degraded by exposure to light; however, the absence of light in water, especially in bottom sediments, prolongs the threat connected with pesticides for years. Biomagnification of pesticides can be observed in the aquatic environment and the levels of POPs are apparently higher in organisms occupying higher trophic levels (26, 35). Agriculture, industry, and transport associated with these economic sectors (7) are the main sources of pesticides in the environment. Widespread and indiscriminate use of pesticides leads to toxic manifestations in non-target organisms (38). Pesticide toxicity primarily depends on its active substance, and secondly, on excipients included in the preparations and physicochemical parameters of water. Gills constitute the primary route for the entry of pesticides (36). Moreover, some of these substances get into the fish organism *via* the gut or skin and may bioaccumulate in adipose tissue or organs (26). Pesticides, especially organochlorine pesticides (OCPs), are still present in water and living organisms (Table 2).

Movement disorders or increased mucus secretion on the skin and gills (34) can be observed during insecticide poisoning. In the endocrine system, pesticides may cause increased secretion of growth hormone and prolactin, enhanced synthesis of maturation-inducing hormones, and disrupted secretion of ACTH. Pesticides cause reduction of glycogen in the liver. Organochlorine compounds may decrease sperm count, inhibit spermatogenesis, and change the development of the gonads (26). Organophosphorus pesticides are hepatotoxic, causing an increase in alanine aminotransferase (ALT) and aspartate aminotransferase (AST) activity in the liver. Furthermore, they cause oxidative stress. Lipid peroxidation (LPO) is rising simultaneously with an increase in the pesticide concentration in the environment (38).

Histological alterations in the kidneys exposed to pesticide include narrowing of tubular lumen, necrosis of tubular epithelium, disorganisation of renal tubules, and cloudy swellings and degeneration of renal epithelium. Various forms of nuclear destruction, *e.g.* pyknosis, karyorrhexis, karyolysis, were observed in the liver. In the gills, fusion of primary and secondary lamellae, epithelial hyperplasia, and curling lamellae leading to collapse of the organs were frequently observed (38).

Table 2. World-wide levels of DDT in fish

Region	Fish species	∑DDT (ng g^{-1})	Reference
Brazil, Tapajos River	*Plagioscion squamosissimus*	249.5*	29
	Cichla ocellaris	111.9*	
	Calophysus macropterus	7.1*	
Italy, Straits of Messina, Mediterranean Sea	*Thunnus thynnus*	11.8–129.34	35
China, Daya Bay	nd	1.7–462*	19
Ghana, Lake Volta, Lake Bosumtwi and Weija Lake	tilapia	28.68–253.59**	1
	catfish	47.53–2205.50**	

* – wet weight ** – lipid weight, nd – not defined

Table 3. Levels of non-dioxin-like PCBs and dioxin-like PCBs in fish

Region	Fish species	∑NDL-PCB (ng g^{-1})	∑DL-PCB (ng g^{-1})	Reference
Italy, Lake Varese	catfish	0.397–117.910*	0.00003–21.0*	37
Italy, Straits of Messina, Mediterranean Sea	*Thunnus thynnus*	22.55–163.42*	nd	35
Korea	Japanese eel	nd	0.144*	28
	crucian carp	nd	0.476*	
	Pacific herring	nd	1.32*	
Ghana, Lake Volta, Lake Bosumtwi and Weija Lake	tilapia	nd	0.22–3.4**	1
	catfish	nd	0.46–2.7**	

* – wet weight; ** – lipid weight; nd – not defined

Table 4. Effects of exposure of fish to bioaccumulative substances

Substances	Impact on the functioning of internal organs	Reproductive system	Immune system	Other symptoms
heavy metals	hepatotoxicity, nephrotoxicity (14)	reduction or complete loss of sperm movement (14), death of spawn (3), reduced secretion of oestrogen and androgen (14)	immunosuppression (12)	increased mucous secretion on the skin and gills (3)
PCBs	fatty degeneration of the liver (36)	reduced number of fertilised eggs (26), reproductive disorders in adults (26), testicular and ovarian lesions (26)	immunosuppression (21, 26)	gills lesions (36)
pesticides	hepatotoxicity, nephrotoxicity (38)	decreased sperm count (26), inhibition of spermatogenesis (26), gonad development changes (26)	immunosuppression (13)	gills lesions (38)

Polychlorinated biphenyls. Polychlorinated biphenyls (PCBs) are synthetic compounds, biphenyl derivatives, in which a hydrogen atom is replaced with a chlorine atom. They comprise a group of 209 congeners (39). Similarly to pesticides, PCBs belong to persistent organic pollutants (POPs) (26). High persistence of PCBs and their long-term biodegradation contribute to the presence of these substances in the environment all over the world (Table 3).

PCBs were used in various industries as dielectrics for filling capacitor, as coolants and plasticisers in paints, plastics, and sealants (39). The main sources of these substances in the environment are: products (equipment) containing PCBs, emission from reservoirs polluted by them, and thermal processes (23).

Particulate matter adsorbs PCBs which may be transferred to water and bioaccummulated in sediments (39). Because they are hydrophobic substances, bioaccumulation occurs in fish adipose tissue and organs rich in fat (6, 32, 36, 39). There are several processes of degradation of polychlorinated biphenyls (*e.g.* respiration, egestion, metabolism, and growth dilution); however, these processes may be influenced by migratory behaviour, feeding habits of different species, age classes of fish, and the maturation state (39).

Exposure to PCBs may cause adverse effect on the immune, endocrine, and reproductive systems. Moreover, growth rate and behavioural response may be disrupted (26). Organism responds to the presence of these substances by increasing the activation of liver enzymes (6). In fish exposed to Aroclor 1248, adverse effects in the immune system, such as decreased antibody production, long-term immune dysfunction (altered lymphocyte mitogenesis), and reduction in the number of total anterior kidney leukocytes were observed (21, 26). Exposing fish to PCB 126 caused reduction of antibody forming cells (26). After exposure to sublethal levels of PCB 126, fish demonstrated relative drop in total carbohydrates (glucose + glycogen), total protein, and an increase in free amino acid concentration (6). Polychlorinated biphenyls may negatively affect the reproductive system, causing reproductive disorders in adults as well as testicular and ovarian lesions. Furthermore, they may contribute to reduced number of fertilised spawn (26).

Histological analysis of target organs exposed to PCBs together with other substances belonging to the group of POPs showed fatty degeneration of the liver and gill lesions – hyperplasia of primary lamellae epithelium, secondary lamellae fusion, and mast cell infiltration (37).

Pathogenesis. Mechanism of heavy metal, pesticide, and PCB actions in fish is not well-known. Mercury is a toxic heavy metal which accumulates in the fish and undergoes biomagnification process in the environment (8). It exists mainly in three forms: metallic elements, inorganic salts, and organic compounds, each of which possesses different toxicity and bioavailability (22). This metal may also accumulate as organic compound – methyl mercury (MeHg). Brain, muscles, kidneys, and nerves are target organs for mercury. It disrupts membrane potential and interrupts intracellular calcium homeostasis. This metal causes an increase in intracellular calcium content through accelerating the influx of calcium from the extracellular medium and mobilising intracellular stores. Mercury damages the tertiary and quaternary protein structure and alters the cellular function by attaching to selenohydryl and sulfhydryl groups which may indicate alterations in cellular structure (22, 41). An oxidative stress may occur during interactions of mercury with biomolecules. It contributes to an increase in reactive oxygen species (ROS) formation. Successively, ROS may lead to damage of enzymes, nucleic acids, and lipids, and may lead to cell death (43).

Exposure to lead occurs mainly by ingestion. Toxicity of lead in the environment depends on its various forms. Organolead compounds, which are mainly made of covalent bonds, exhibit toxicological effects different from inorganic lead salts (43). Lead causes damage to living systems by releasing free radicals. They may increase directly by generation of ROS such as O_2, H_2O_2, or indirectly through the depletion of antioxidants in cells (43). Lead exerts toxic effects through its ability to inhibit or mimic the actions of calcium and to interact with proteins. Moreover, it binds to sulfhydryl and amide groups of enzymes, altering their configuration and diminishing their activities. For example, lead causes inhibition of δ-aminolevulinic acid dehydratase (ALAD) (41, 43). Interaction of lead and ALAD results in enhancement of ROS formation (41).

Cadmium may get to a body by ingestion or inhalation. It is transported in the blood by albumins to the liver where it binds to cystein-rich proteins, such as metallothionein. The formed complex is released back into the circulation. Proximal tubular cells of the kidneys absorb the Cd-metallothionein complex (22, 43). This form of cadmium causes hepatotoxicity in the liver, and may circulate to kidneys leading to nephrotoxicity (22). Cadmium has the ability to increase free radicals indirectly by replacing iron and copper in various cytoplasmic and membrane proteins. It causes oxidation of proteins, lipids, and DNA, leading to single-strand DNA damage and disruption of the synthesis of nucleic acids and proteins (41, 43).

It is not well-known how PCBs act in the organism. Moreover, a variety of these compounds and their metabolism have a primary impact on their toxicity (17). After entering the organism, they may undergo hydroxylation through oxidation by cytochrome P-450 and become hydroxylated polychlorinated biphenyls (OH-PCB). These compounds exert toxic effects such as: inhibition of mitochondrial respiration, generation of ROS, oxidative damage to DNA, and endocrine disrupting effects (42). The substance itself primarily influences pesticides reaction in the organism. DDT negatively affects endocrine and reproductive systems. There is no clear evidence that this pesticide may cause other types of cancer in humans. However, due to its indirect influence on the liver, through induction of oxidative stress and oxidative DNA damage, DDT is considered as a hepatocarcinogenic factor (20). Through irreversible inhibition of acetylcholinesterase (AChE), organophosphorus pesticides cause a build-up of the neurotransmitter acetylcholine (ACh) at the synapse and subsequent overstimulation of cholinergic neurons. Developmental toxicity and behavioural deficits were observed in fish exposed to this group of pesticides (24).

Time trends. The HELCOM organisation, which is the governing body of the Convention on the Protection of the Marine Environment of the Baltic Sea Area, is monitoring the levels of persistent organic pollutants (POPs) in the Baltic Sea. According to data provided by HELCOM, decreasing trends may be observed among POPs.

Fig. 3 shows that concentrations of PCBs observed in herring muscles are slowly decreasing. Temporal trends of organochlorine pesticide (DDE) concentrations in herring muscles have been declining since the end of the 1970s in all Baltic Sea sub-basins (25). cadmium and mercury concentrations in the Northern Baltic Proper were increasing till mid-1990. From then on, decreasing trends may be noticed (Figs 5 and 6).

Data provided by the HELCOM show declining temporal trends of POP concentrations in different regions of the Baltic Sea; however, the presence of persistent organic pollutants is still noticeable in this region (Table 5).

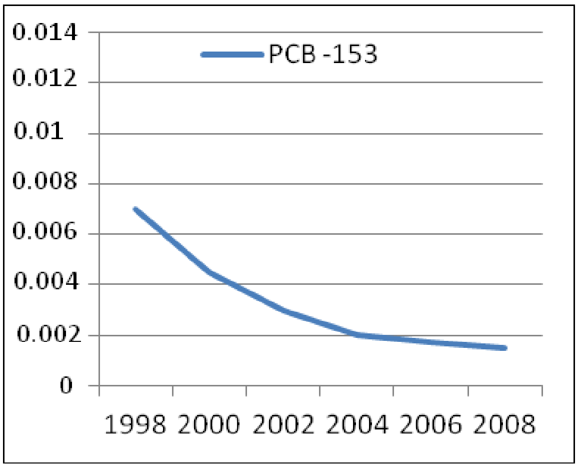

Fig. 3. Trend line of concentrations of PCB-153 in herring muscles (mg kg^{-1} wet weight), Gulf of Gdańsk (25)

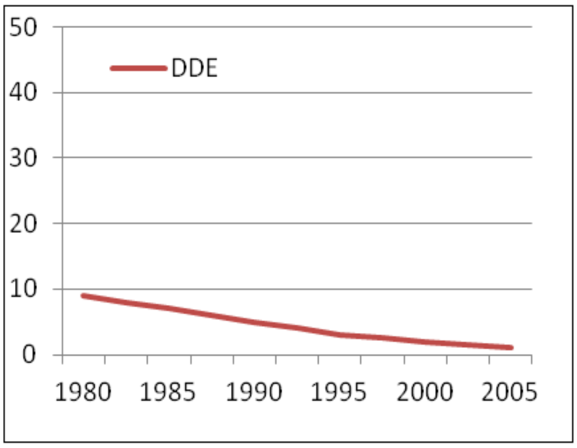

Fig. 4. Trend line of DDE concentrations in herring muscles (µg g^{-1} wet weight), Gulf of Finland (25)

Table 5. Undesirable bioaccumulative substances in fish from the Baltic Sea

Substance	Sample	Unit	Fish species		Reference
			herring	cod	
cadmium	liver	µg g^{-1} dw	0.39–1.8	0.015–0.058	31
mercury	muscles	µg g^{-1} fw	0.019–0.041	nd	31
lead	liver	µg g^{-1} dw	0.029–0.085	0.007–0.016	31
ΣPCB[1]	muscles	µg g^{-1} fw	0.011–0.015	nd	2
ΣDDT	muscles	µg g^{-1}	0.0003	0.0168	40

dw – dry weight; fw – fresh weight; [1] – sum of 28, 52, 101, 138, 153, and 180 congeners , nd – not defined

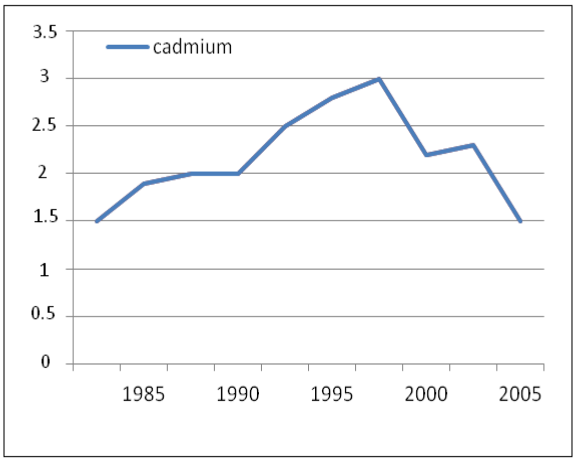

Fig. 5. Trend line of cadmium concentration in fish, (mg kg^{-1} dry weight), Northern Baltic Proper (25)

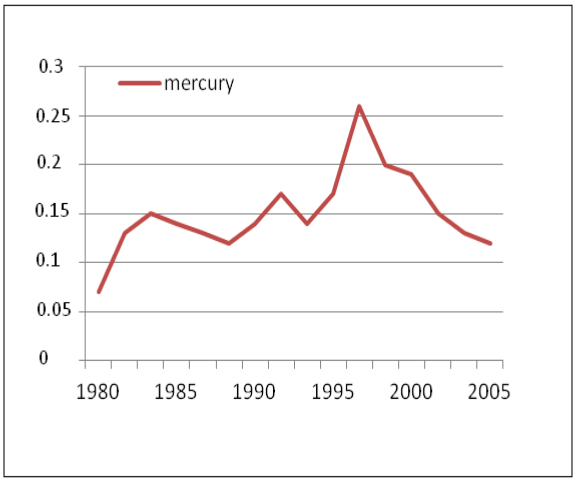

Fig. 6. Trend line of mercury concentration in fish (mg kg^{-1} dry weight), Northern Baltic Proper (25)

Influence on human health. Fish are an important source of protein, essential minerals, and unsaturated fatty acids, and are especially recommended as a source of ω-3 acids in human diet (10, 15). However, their high ability to bioaccumulate heavy metals, PCBs and pesticides may pose a risk to human health.

Mercury, cadmium, lead, and arsenic are especially considered as health hazards for humans due to various adverse effects they may cause. Mercury may enter human organism through consumption of fish and marine mammals. Methyl mercury is the most important form of mercury in terms of toxicity and health effects from environmental exposures. It affects nervous system, manifesting in paresthesia and disruption of coordination. Moreover, it may cause damage of the kidneys and gastrointestinal tract (10). High concentration of cadmium negatively affects function of the kidneys and liver. Chronic cadmium exposure can lead to emphysema and renal and bone lesions (11). Lead may enter human body through the intestines, lungs or by direct swallowing. Chronic lead exposure in humans causes dullness, irritability, poor attention span, constipation, vomiting, convulsions, coma, and death, whereas acute poisoning leads to headache, irritability, abdominal pain, and various symptoms related to the nervous system (10). Arsenic poisoning causes vomiting, diarrhoea, salivation, fever, disturbances of the cardiovascular and central nervous systems, which may lead to death (10).

Food (especially fish and fish by-products) can also be a major source of human dietary exposure to PCBs. They may be divided into two groups: a dioxin-like (DL-PCB) or a non-dioxin-like (NDL-PCB) PCBs. DL-PCB congeners exert their toxicity by binding the aryl hydrocarbon receptor (AhR). Exposure to PCBs may lead to damage of the liver and immune system. Furthermore, PCBs are considered as carcinogenic substances. In addition, they exert adverse effects on the reproductive system (37).

Organochlorine pesticides (OCPs) are also bioaccumulative substances whose presence in fish tissues may cause a potential hazard for consumers. OCPs may exert carcinogenic, teratogenic, and mutagenic effects in humans. Chronic influence of OCPs leads to neurodegenerative diseases, neuro-behavioural dysfunction, reproductive disorders, hypertension, liver diseases, and cancer (30).

Heavy metals, pesticides, and polychlorinated biphenyls are highly persistent substances negatively affecting the environment and living organisms. Although there are several mechanisms of degradation, their presence in the environment is still noticeable. Moreover, these substances accumulate in sediments, making them more resistant to degradation processes. Time trends show that concentrations of heavy metals, PCBs, and pesticides are decreasing; however, these substances are still present in fish and water. Moreover, they undergo bioaccumulation and biomagnification so they can contribute to the occurrence of negative symptoms in fish and may be a source of potential risk to consumers.

Conflict of Interests Statement: The authors declare that there is no conflict of interests regarding the publication of this article.

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