RESEARCH PAPER | Science | Volume : 5 | Issue : 8 | August 2015 | ISSN - 2249-555X

Fish as bioindicators of heavy metals pollution in marine environments: a review

KEYWORDS: Marine algae, marine fish, toxicity, heavy metals, pollution, bioindication, environment, Organism.

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ABSTRACT *Fish meat is a perfect foodstuff which is up to the standard of rational nourishment. It is a source of healthy and good digestible material rich in proteins, minerals and vitamins. The metal contamination in marine water is considered to be unsafe not only for fish but, also for human beings because they consume fish. Thus, bioindication using fish represents a good monitoring tool especially with regard to pollution aspects.*

In this review the recent studies on heavy metal accumulation in marine fish will be presented, also metal speciation in and some factors affecting their bioavailability will be reviewed, as well as to gather more information on the use of different species of marine fish organs as universal bioindicators for heavy metal pollution in aquatic environment.

1- The concept of bioindicator and biomonitoring

A bioindicator is an organism (or part of an organism or a community of organisms) that contains information on the quality of the environment (or a part of the environment). A biomonitor, on the other hand, is an organism (or a part of an organism or a community of organisms) that contains information on the quantitative aspects of the quality of the environment. A biomonitor is always a bioindicator as well, but a bioindicator does not necessarily meet the requirements for a biomonitor (Markert *et al.* 2003).

Heavy metals are natural trace components of the aquatic environment, but their levels have increased due to industrial, agricultural and mining activities. As a result, aquatic animals are exposed to elevated levels of heavy metals. The levels of metals in upper members of the food web like fish can reach values many times higher than those found in aquatic environments or in sediments. (Stanchevai *et al.* 2013). Aquatic organisms vary in their metal uptake. They can be grouped into two categories: regulators (excluders) and accumulators (non-excluders).

Accumulation of heavy metals in tissues of marine organisms has been identified as an indirect measure of the abundance and availability of metals in the marine environment. For this reason, monitoring fish tissue contamination serves an important function as an early warning indicator of sediment contamination or related water quality problems and enables us to take appropriate action to protect public health and the environment (Rabajczyk *et al* .2011).

Heavy metal concentrations in aquatic ecosystems are usually monitored by measuring their concentrations in water, sediments and associated biota, which generally exist in low levels in water and attain considerable concentration in sediment and biota (Edward *et al.* 2013).

2- Marine pollution: a global concern

Environmental pollution has increased substantially in the last decades due to a great number of industrial, agricultural, commercial and domestic waste, effluents and emissions as well as hazardous substances. The majority of environmental pollutants are threatening initially human and environmental health but also the integrity and function of ecosystems (Valavanidis and Vlachogianni) Aquatic pollution is the predominant form of pollution since the majority of chemical pollutants are entering seas, rivers, lakes and wetlands. Marine and coastal ecosystems are characterized by their complexity and their sensitivity to various inorganic and organic pollutants. Internationally accepted procedures for environmental / ecological impact and risk assessment have been established to manage human impact on coastal environments. Many chemical contaminants, including organochlorine compounds, herbicides, petroleum products and heavy metals are now recognized to have adverse effects on ocean environments, even when released at low levels. Little attention had been given to this problem until shortly before the 19th century. The adverse effects of environmental pollution have been well documented in recent years (Torres *et al.*2008) Metal pollution may damage marine organisms at the cellular level and possibly affect the ecological balance. Exposure and ingestion of polluted marine organisms as sea foods can cause health problems in people and animals including neurological and reproductive problems (Stanciu *et al.* 2005).

2-1 Heavy metals as pollutants of the marine environment

A number of trace metals are used by living organisms to stabilize protein structures, facilitate electron transfer reactions and catalyze enzymatic reactions. For example, copper (Cu), zinc (Zn), and iron (Fe) are essential as constituents of the catalytic sites of several enzymes. Other metals, however, such as lead (Pb), mercury (Hg), and cadmium

(Cd) may displace or substitute for essential trace metals and interfere with proper functioning of enzymes and associated cofactors. Metals are usually present at low or very low concentrations in the seas. In coastal waters, metals can occur at much higher concentrations. (Torres *et al.* 2008). Metals are associated with community and occupational exposure. Out of these, 23 are described as heavy metals. These elements are generally released in small amounts into the environment. Heavy metals become toxic when they are not excreted by the body and accumulate in the soft tissues (Sobha *et al.* 2007). Heavy metals enter the aquatic environment naturally through weathering of the earth crust. In addition to geological weathering, human activities have also introduced large quantities of metals to localized areas of the sea. Aquatic systems are very sensitive to heavy metal pollutants and the gradual increase in the levels of such metals in aquatic environments has become a problem of primary concern. This is due to their persistence as they are not usually eliminated either by biodegradation or by chemical means. Moreover, the decay of organic materials in aquatic systems together with detritus formed by natural weathering processes provides a rich source of nutrients in both the sea floor sediments and overlying water body (Khaled, 2004).

The heavy metals are of particular concern due to their persistence, undegradable nature, and and potential bioaccumulation in different aquatic species. (Javed and Usmani, 2012) (Khaled, 2004). Heavy metals including both essential and non-essential elements have a particular significance in ecotoxicology since they are highly persistent and all have the potential to be toxic to living organisms (Edward *et al.* 2013)

3- Sources of heavy metals in marine environment

Generally, the higher metal concentration in the environment, the more may be taken up and accumulated by fish. The relationship between metal concentrations in fish and in the water has been observed in both field and laboratory studies.

Metals in natural waters occur in particulate or soluble form. Soluble species include labile and non-labile fractions. The labile metal compounds are the most dangerous to fish. They include various ionic forms of different availability to fish. Many data show that the amounts of metals in the labile fraction, and the share of various metal ions strongly depend on environmental conditions (Jezierska and Witeska, 2006) (Chalapathi, 2012), (Javed and Usmani, 2012).

Chemicals of industrial effluents and products of ships and boats such as heavy metals which find their way into different water systems can produce toxic effects in aquatic organisms Petroleum products are one of the most relevant pollutants to aquatic ecotoxicology. Exposure to crude oil and derivatives can induce a variety of toxic symptoms in experimental animals. Petroleum hydrocarbons can act as a mediator in free radical generation in fish (Stanciu *et al.*2005).

3-1- Sediments as source of heavy metals in water

Heavy metal concentrations in aquatic ecosystems are usually monitored by measuring their concentrations in water, sediments and associated biota, which generally exist in low levels in water and attain considerable concentration in sediment and biota. Sediments are important sinks for various pollutants like pesticides and heavy metals and also play a significant role in the remobilization of contaminants in aquatic systems under favorable conditions and in interactions between water and sediments (Edward *et al.*2013).

One of the significant negative properties of these metals is their ability to accumulate in sediments. Mercury has great ability to accumulate in aquatic organisms. Mercury passes from water into bottom sediments in flowing waters and dams, where it accumulates mostly in the form of sulfide. The content of mercury in bottom sediments is in relation to the pollution burden of the locality, but also to the character of the sediment. Bottom sediments could be as suitable indicators of contamination of surface waters by lead and cadmium. Samples of sediment with a bulk of mud and organic parts have in most cases higher content of mercury in comparison to samples of sandy character. The remarkable accumulating ability of sediments poses a source of eventual contamination of fish meat by dangerous elements (Toth *et al.* 2012).

4-Mechanism of heavy toxicity metals in fish.

The reaction and survival of organisms exposed to heavy metals depend not only on the biological state of the organisms but also on the toxicity and exposure time and type of the toxicant (Vinodhini and Narayanan, 2009). The heavy metals such as As, Cd, Pd and Hg are classified as most toxic to humans, animals, aquatic organisms and environment. They affect ecosystems due to their bioaccumulation in animals which causing toxic effects such as reduce the fitness on biota and even mortality in living beings. Fishes are inhabitants which can be highly affected by heavy metals. The toxicity of heavy metals on fishes depending on fish age, size and other physiological factors. These elements enter in biogeochemical cycle leading to toxicity in different organs (Govind and Madhuri, 2014).

Sublethal concentration of heavy metals such as Cd could cause severe disturbances in fish metabolism such as abnormal behavior, locomotor anomalies and anorexia. However, Lead has considered to change hematological system by inhibiting the activities of different enzymes involved in heme biosynthesis. After absorption of lead, it is distributed chiefly to the immune system, heart, kidney and liver. Moreover, some morphological transformations in numerous cellular systems and chromosomal arrangement may cause when fish exposed to nickel. Many of heavy metals causing oxidative stress by generating reactive oxygen radicals (Damien et al., 2004; Vinodhini and Narayanan, 2009).

Certain heavy metals become toxic due to formation of toxic soluble compounds. However, a number of metals are without any biological role or they are not required by the body and they become toxic just in specific forms. However, Pb may cause harmful effect at any level of its amount. Beryllium and iron can also exhibit toxicity. Thus, most of the heavy metals are toxic to living beings. With abnormal oxidation state metals also can elicit toxic effect such as tetravalent chromium [Cr (VI)] exhibits the carcinogenic effect, however, trivalent chromium [Cr(III)] is recognized as an essential trace-nutrient for human and animals (Govind, 2013; Govind and Madhuri, 2014).

Fish diversity of any ecosystem has great importance in evaluation of that zone reference to environment and pollution. Several studies have investigated that fish is very sensitive to heavy metals. The studies performed in a range of fishes indicated that heavy metals may change the physiological and biochemical functions both in tissues and blood in common carp (Gohil and Mankodi, 2013; Govind and Madhuri, 2014).

Heavy metals can make harmful effects on tissues of aquatic organisms themselves. At high concentrations they may lead to mortality of the organism. This level of toxicity is known as lethal toxicity. At lower concentrations, organisms can show different kinds of adverse effects but no mortality seen. Histological changes can occur in the digestive tubular tracks, gills and neurological system. The reflection of alteration in enzymal or hormonal activities lead to the organism becomes weak and ecologically vulnerable to death. The disturbances in the respiration, growth or reproduction rates, or susceptibility to parasitic pathogens and diseases may occur but not easily detectable. Such effects are referred as sub-lethal toxic effects (Al-Sulamiet al., 2002).

Lethal or sub-lethal toxicity effect may be referred as chronic toxicity effect if it occurred by accumulation of low-level contaminants over an extended period of time. All heavy metals show to be susceptible to bioaccumulation to a greater or lesser extent, and its oxidation state will largely determine the amount and the corresponding toxicity of the metal. Moreover, the metal is present in an ionized form of an oxidized or reduced state, complexed with an organic substance, or adsorbed on an organic or inorganic particulate, is a factor determining its uptake by, and toxicity towards, the organisms (Al-Sulamiet al.,2002). Several studies from laboratory and field experiments indicated that accumulation of heavy metals is dependent on environmental factors such as salinity, pH, hardness and temperature, although, water concentration of metals and exposure period of fish to metals play significant roles in heavy metals accumulation. Ecological needs, sex, size and molt of aquatic organisms were also found to affect metal accumulation. The sizes of aquatic organisms have been shown to play an essential role in heavy metals levels of tissues; however, this evidence was consistent normally for mercury in different groups of aquatic organisms. For example, mussel, decapod crustacean, fish, marine mammals and seabirds in the marine food-chain indicated a positive relationship between mercury contents and animal sizes (Canli and Furness,1993; Canli and Atli 2003). In other report, the concentration of heavy metals (Cd, Cr, Cu, Fe, Pb, Zn) in the liver, gill and muscle of six fish species (Sparusauratus, Atherinahepsetus, Mugilcephalus, Sardinapilchardus and Scomberesoxsaurus) from the northeast Mediterranean Sea was estimated and results showed that metal concentrations were significantly different in each tissue from diverse fish species. These variations might be related to different ecological factors causing different feeding behavior, swimming behavior and the metabolic activities among different fish species (Kalayet al., 2000; Canli and Atli 2003).

Heavy metals pollution considered as a significant threat for human health because of their toxicity, bioaccumulation and biomagnifications in the food chain sequence (Alturiqi, and Albedair. 2012). More researches have been dedicated recently on the concentrations of heavy metals in fish and other foods uncovering their hazardous influence on human health. The uptake of pollutants by fish in the polluted aquatic ecosystem from plant source or animal depending of the mode of fish nutrition can accumulate then transfer these toxic metals through food chains and it can be high enough to bring about harmful concentrations in the tissues of fish. Food chain may start from polluted primary source i. e. seagrass and consumed by small fish feed on transferring the toxicity to other predators in the food chain ending up in human body (Dallinger, e.t al. 1987). Metals were found less toxic at lower temperatures and high salinity than at high temperatures and lower salinity. Toxicity of a metal is also dependent upon residence time of metals concerned. Generally, most metals have a long residence time and hence exert their toxic effect over a long time. Heavy metals introduced in the marine ecosystem are mostly concentrated in coastal areas, near densely populated and industrialized regions. Heavy metals are usually associated to particles. These particles are often very small, and can therefore stay in solution for a very long time. Nevertheless they will end up in the sediments, therefore concentrations in the sediments are often 10 to 100 times higher than those in solution. In the sediments, these particles may form an important secondary source of contamination, even after the primary source has disappeared (Elliot and Hemingway, 2002)

5- Factors affecting uptake of heavy metals by marine fish

Multiple factors including season, physical and chemical properties of water can play a significant role in metal accumulation in different fish tissues. Fish have been the most popular choice as test organisms because they are presumably the best-understood organisms in the aquatic environment and also due to their importance to man as a protein source (Rabajczyk *et al.*2011).

According to Kock *et al*. (1996), cadmium and lead levels in *Salvelinus alpinus* liver and kidneys indicate higher uptake rates of both metals in summer when water temperature was higher. The authors explained this as due to increased metabolic rate. Water temperature may cause the differences in metal deposition in various organs. Higher temperatures promote accumulation of cadmium especially in the most burdened organs: kidneys and liver. Increased accumulation of metals by fish at higher temperatures probably results from higher metabolic rate, including higher rate of metal uptake and binding. Many data indicate that water acidification directly affects metal accumulation rates by the fish. Water hardness (mainly calcium concentration) considerably affects uptake of metals across the gill epithelium. According to Playle et al. (1992), enrichment of water with calcium reduced copper accumulation in the gills. Baldisserotto et al. (2005) reported that elevated dietary Ca^{2+} protected against both dietary and waterborne Cd uptake. The results obtained by Barron and Albeke (2000) indicate that calcium reduces zinc uptake by *Oncorhynchus mykiss*. Similarly as hardness, also salinity reduces uptake and accumulation of metals by the fish. Various species of fish from the same water body may accumulate different amounts of metals. Interspecies differences in metal accumulation may be related to living and feeding habits.

6- Detection of heavy metals in fish samples

The choice of which analytical method has to be applied depends on the material to be analyzed, the availability of the method and the goal of the investigation, (Bradl, 2005). Several analytical techniques such as flame atomic absorption spectrometry (AAS), graphite furnace atomic absorption spectrometry (GFAAS), inductively coupled plasma atomic emission spectrometry and inductively coupled plasma mass spectrometry have been proposed for the determination of trace and toxic metals in different environmental sample. Flame atomic absorption spectrometry (FAAS) is one of the most widespread traditional analytical techniques for the determination of trace elements, but it often suffers from its low sensitivity. The determination of trace quantity of heavy metals in environmental samples requires the use of preconcentration methods coupled to

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spectroscopic methods, such as ICP-AES and FAAS (Chalapathi, 2012).

7- Levels of heavy metals in marine fish

The heavy metal levels in various kinds of marine fish have been investigated by several researchers; these fish are available in every season, easy to sample and identify. Some results for heavy metal levels in marine fish investigated by several researchers and its levels in various organs (flesh, liver, gills and bone) are summarized in Tables 1 to 5. Eight common heavy metals are discussed in this report: manganese, nickel, copper, zinc, arsenic, lead, mercury and cadmium. These metals are all naturally occurring substances which are often present in the environment at low levels. In larger amounts, they can be dangerous.

El Bialy *et al.*, (2005) investigated some heavy metals as shown in Table (1). The samples which were investigated represent different types of fish muscle tissue using atomic absorption spectrometry, by two digestive methods, the dry ash and wet ash methods. The obtained concentrations for Zn, Pb, and Cd by the wet ash method are higher than the obtained by the dry ash method. This is due to the high temperature (450 - 600°C) to complete the ashing process, which causes partial or complete loss by volatilization of many trace elements.

Table (1) Concentration of elements in fish muscle (μg/g)

Method	Dry ash		Wet ash	
Year	1998	2000	1998	2000
Mn	3.22-6.90	2.50-7.02	3.35-7.50	3.12-4.72
Ni	0.87-2.76	0.62-2.00	2.10-3.75	1.25-3.52
Cu	2.17-10.51	1.87-8.41	3.33-15.46	3.97-11.98
Zn	19.53-28.21	9.82-13.47	21.64-50.52	10.31-14.50
Pb	1.24-3.10	1.40-2.33	2.20-8.80	1.98-8.75
Cd	2.00-3.11	1.24-2.79	2.10-3.75	1.65-3.75

Khaled investigated some heavy metals in muscles, gills, livers and bones of five fish species namely, *sargus sargus, Siganus rivulatus, Mugil cephalus, Caranx crysos and Scomberomorus commerson* collected from El-Mex Bay, Alexandria, Egypt, during winter were shown in Table (2).

Table (2) Mean concentration of heavy metals (μg/g wet wt.) in the five fish species

Element	Flesh	Liver	Gills	Bone
Mn	0.79-1.49	2.35-4.86	3.49-9.35	3.73-6.74
Ni	0.51- 1.69	0.43 - 1.65	1.21- 2.18	0.92- 2.37
Cu	1.05 - 2.76	4.92- 54.08	1.82- 3.18	1.26- 1.63
Zn	3.82- 8.26	36.06- 279.71	15.02- 23.57	19.68- 28.82
Pb	0.53- 0.89	1.46- 3.12	3.27 -4.44	5.40- 8.64
Cd	0.13- 0.49	0.66-2.65	0.69-1.11	0.75-1.04

The distribution pattern of Cd in this study was in the decreasing order of liver ≥ gills ≥ bone > muscle. In other words, the liver seemed to be the organ which accumulates the highest value of Cd. Liver had accumulated the highest level of Cu while the muscle had the lowest concentration, The study revealed that Mn concentrations were highest in gills and lowest in muscle for all the five fish species under investigation, Nickel recorded its highest concentration in gills and liver and its lowest concentration in muscle in all tested fish species, Bone was the organ which showed the highest accumulation of lead. This is due to the fact that Pb and Ca are similar in deposition in and mobilization from bone. The results showed that metal concentrations were lowest in muscle and highest in gill and liver tissues due to their physiological roles in fish metabolism where target tissues of heavy metals are the metabolically active ones. Therefore, metal accumulation in these tissues is higher compared to muscles where metabolic activity is relatively lower and so there is no risk yet for human consumption of flesh of these fishes.

Aktan and Tekin (2012) were determined some heavy metals from water and 60 fish samples (60 in total) from Antalya Bay, Turkey, in four seasons, autumn, winter, spring, and summer, Table (3) shows some of the detected metals in one season (spring).

Table (3) Heavy metal concentrations in different tissues of *Scomber scombrus* from Antalya Bay (mg kg $^{-1}$)

Tissues	Muscle	Liver	Gill
Mn	0.38-4.52	ND	5.93-16.11
Ni	0.02-0.73	0.03-0.38	0.17-1.10
Cu	0.31-50.64	0.07-30.31	1.42-111.75
Zn	4.02-183.35	0.17-122.49	64.08-172.25
As	2.16-48.12	0.70-33.75	6.34-15.93
Cd	0.02-0.06	0.01-0.07	0.04-0.31

The increasing of metal levels in Spring can be caused by an increase in the air temperature and evaporation, because Antalya is situated in the north of Turkey and the air is getting warmer early. The decrease in metal concentrations caused by heavy rain in autumn. As, Cd, Cr, Cu, Fe in summer and spring, Ni in spring and Zn in all seasons were found to be above for permissible levels given by the Republic of Turkey, Ministry of Agriculture and Rural Areas. The levels of As in all tissues were higher than these maximum levels, while Zn levels were higher than in muscle in Spring and Summer.

Burger and Gochfeld (2005) measured the levels of contaminants in eleven types of fish and shellfish obtained from supermarkets from New Jersey inducting for arsenic, cadmium, chromium, lead, manganese, mercury, and selenium. Table (4) shows the concentration range for Mn, As, Pb, Hg and Cd, (ppm, wet weight) for all species studied. Contaminants in fish can pose a health risk to the fish themselves, to their predators, and to humans who consume them. Most arsenic in seafood is organic arsenic which is less toxic than inorganic arsenic species. Contaminant information on this broad range of metals in commercial fish is generally not available to the public, so the researchers suggested that there is a need for more information on contaminant levels in fish from specific regions. Such data on contaminant levels in fish from particular regions of the world could allow people to make informed decisions about which fish to eat to reduce their risk from the contaminants.

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Table (4) Concentration range (ppm, wet weight) in commercial fish from New Jersey markets

Elements	Concentration range, ppm
Mn	0.1–1.0
As	0.23 - 3.3
Pb	0.04–0.12
Hg	0.05–0.6
Cd	0.0001 - 0.01

Stanchevai *et al.,* (2013) determined and compared heavy metal contents (Pb, Cd, As and Hg) in edible tissue and gills of grey mullet (*Mugul* cephalus). The fish samples were collected from two different Black Sea areas, Varna Lake and Nesebar. The data obtained for heavy metals content in analyzed fish are presented in Table (5).

Table (5).Heavy metal concentration (mg.kg–1 wet weight) in grey mullet from Black Sea coast of Bulgaria (mean ± SD)

Location	Varna Lake		Nesebar	
Tissues	Muscle	Gill	Muscle	Gill
As	0.90 ± 0.10	0.38 ± 0.02	1.10 ± 0.10	0.90 ± 0.10
Hg	0.08 ± 0.01	0.12 ± 0.02	0.05 ± 0.01	0.06 ± 0.01
Cd	0.024 ± 0.002	0.031 ± 0.003	0.012 ± 0.002	0.013 ± 0.002
Pb	0.07 ± 0.01	0.08 ± 0.02	0.05 ± 0.01	0.07 ± 0.01

According to this research, heavy metals accumulate in different tissues of mullet fish with different magnitudes. Generally, metal accumulation in muscle was lower than gills. Cd, Hg and As mainly accumulated in gills while the edible tissue presented lower heavy metals concentrations. The results provide new information on the distribution of these metals in gills and edible tissues of gray mullet.

Stanciu *et al.* (2005) presented aspects regarding the pollution with pesticides and heavy metals (Cd, Pb, Cu and Zn) from mussels tissue (Mytilus galloprovincialis) collected from different zones of the Romanian Black Sea Coast. The highest concentrations in heavy metals were detected in samples as follows: Cu 9.87 µg/g, Cd 1.71 µg/g and Pb 8.92 µg/g. Determination of heavy metals from the Black Sea mussels tissue presents is of major importance, because sea discharged the most effluents with high concentrations of pollutants and mussels having bioindicator properties. Mussels are biofilter organisms which retain small particles from sea water, so the presence of some pollutants in muscle tissue indicates a contamination of marine environment.

Chalapathi (2012) developed a simple preconcentration method for the determination of heavy metals (Cu, Zn and Pb) in fish tissues (gill, liver, eye, muscle, kidney, heart and intestine). The concentration of analytes was determined by flame atomic absorption spectrometry (FAAS). The concentration of heavy metals was found in the order liver > gill > intestine > muscle > heart > kidney > eye. The metal contents found in the studied fish samples are sufficient to cause toxicological effects on human health when these fish are included in the diet. In relation to this, it is recommendable that monitoring studies are periodically performed to assess the human exposure to these toxic elements through fish and fishery product consumption. These results can be used to test the chemical quality of fish in order to evaluate the possible risk associated with their consumption by humans. The concentration of heavy metals recorded in the fish parts also indicated a certain degree of bio-accumulation.

Abdelmoneim et al., (1996) studied trace metals (Cu, Zn, Pb and Cd) in three fish species (*Sardinclla gibbosa. Saurula* sp and *Epincphclus* sp) and their organs from the northern part of the Suez Gulf, Red Sea, Egypt. The results showed that the metals accumulate in the other organs to a greater extent than in the muscle. The lowest accumulated metal is cadmium while the highest is zinc. On the other hand. cadmium and lead recorded their highest values in *Epinephclus* sp . and *Saurula* sp., while zinc recorded its highest value in pelagic fish *Sardinclla gibbosa*. The essential elements such as zinc and copper are accumulate d in soft tissues such as liver and gonads while the non-essential elements such as lead and cadmium are accumulated in hard tissues (bone and gills).

8- Conclusion, Recommendations and further studies

The study clearly indicated significant accumulation of heavy metals in the organs of fish species; marine fish are able to absorb pollutants from the aquatic environment which can be used as bioindicators of metals in the marine environment. Fish have been suggested and used as potential bioindicators of aquatic pollution and its point to important biomarkers. Frequently, aquatic contamination involves various chemicals that interact with one another. For that reason studies on metal-metal interactions are required. On the other hand, some metals are rapidly bound to organic substances and thus cannot be detected in water; however, they can later become accessible in fish food. It should be borne in mind that fish of different species, sex, size, and age are involved in field studies. Further work would be required to compile a definitive review document. Initial modeling studies using physical and chemical constants can provide good, albeit broad, estimates of biogeochemical behavior. The information compiled from the above recommendations can then direct strategies for initial environmental surveys to investigate contamination of heavy metals in marine biota.

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