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From water to plate: Reviewing the bioaccumulation of heavy metals in fish and unraveling human health risks in the food chain

Suryapratap Ray, Rahul Vashishth *

Department of Biosciences, School of Biosciences and Technology, Vellore Institute of Technology, Vellore, 632014, India

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A B S T R A C T

As we tread upon the ever-evolving canvas of our planet, one of the emerging concerns is the silent threat of heavy metal toxicity, a modern challenge that calls for both awareness and action. A single gram of mercury which is a potent and widespread aquatic contaminant, can contaminate a 20-acre lake to the extent that fish from the lake may become unsafe for human consumption. On the other hand, the wide application of HM-based chemical substances such as insecticides (market value of 19.5 billion USD in the year 2022 worldwide which is expected to increase by 28 billion USD by 2027) is growing significantly. This alarming fact highlights the far-reaching consequences of heavy metal pollution in our precious aquatic environments. The current review discusses one of the global issues which is bioaccumulation of heavy metals (HMs) in fish, concerns related to HM bioaccumulation, gathered data on HM concentrations in various fish organs, and research gaps primarily within India. The critical approach is made by emphasizing the intricate connection between the food chain and HM bioaccumulation, highlighting the consequent transfer of contaminants to humans. The scope of this article also covers the severity of toxicity induced by HMs in both humans and fish. Overall, this review serves to provide a comprehensive overview of the emerging issues concerning HM bioaccumulation in fish and its impact on human health highlighting the need for extensive studies in relevant areas.
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1. Introduction

The presence of heavy metal contamination in aquatic water bodies is a matter of great concern due to its adverse impact on the organisms associated with these bodies, particularly aquatic organisms [1]. Although heavy metals are naturally present in the environment, their excessive utilization and release of untreated sludge by various industries have significantly disrupted the ecosystem. Generally, anthropogenic activities, such as crop cultivation, erosion from agricultural fields, and the release of industrial and household waste, are recognized as the primary sources of heavy metals in aquatic systems. Once heavy metals infiltrate these systems, they dissolve in the water and readily accumulate in various organs of aquatic organisms, including fish, subsequently entering the bodies of consumers who consume these contaminated fish (Fig. 1). The accumulation of heavy metals in fish leads to various complications in fish health and their physiological functions [1]. The severity of metal toxicity, such as its carcinogenic, teratogenic, and mutagenic effects, varies significantly depending on various factors. Those factors can be fish species, concentration of toxicants, and the duration of exposure. Aquatic organisms can be contaminated with heavy metals originating from both the water and sediments of the aquatic ecosystems. The toxicity mediated by heavy metals detrimentally affects the nervous system of fish, thereby disrupting the interaction among species and their surroundings. The unregulated usage and accumulation of these metals have emerged as a significant health concern, as most of them lack the capability to degrade into non-toxic forms and consequently have destructive impacts on aquatic organisms as well as human health by entering into the food chain. The contamination of heavy metals negatively influences the growth and reproductive activity of fish by reducing their gonadosomatic index (GSI), fecundity, fertilization, and hatching rate. Furthermore, the toxicity of heavy metals hampers the normal development and progression of fish embryos and larvae. Although certain metals are

* Corresponding author.
E-mail addresses: suryapratap1504@gmail.com (S. Ray), rahul.vashishth@vit.ac.in (R. Vashishth).
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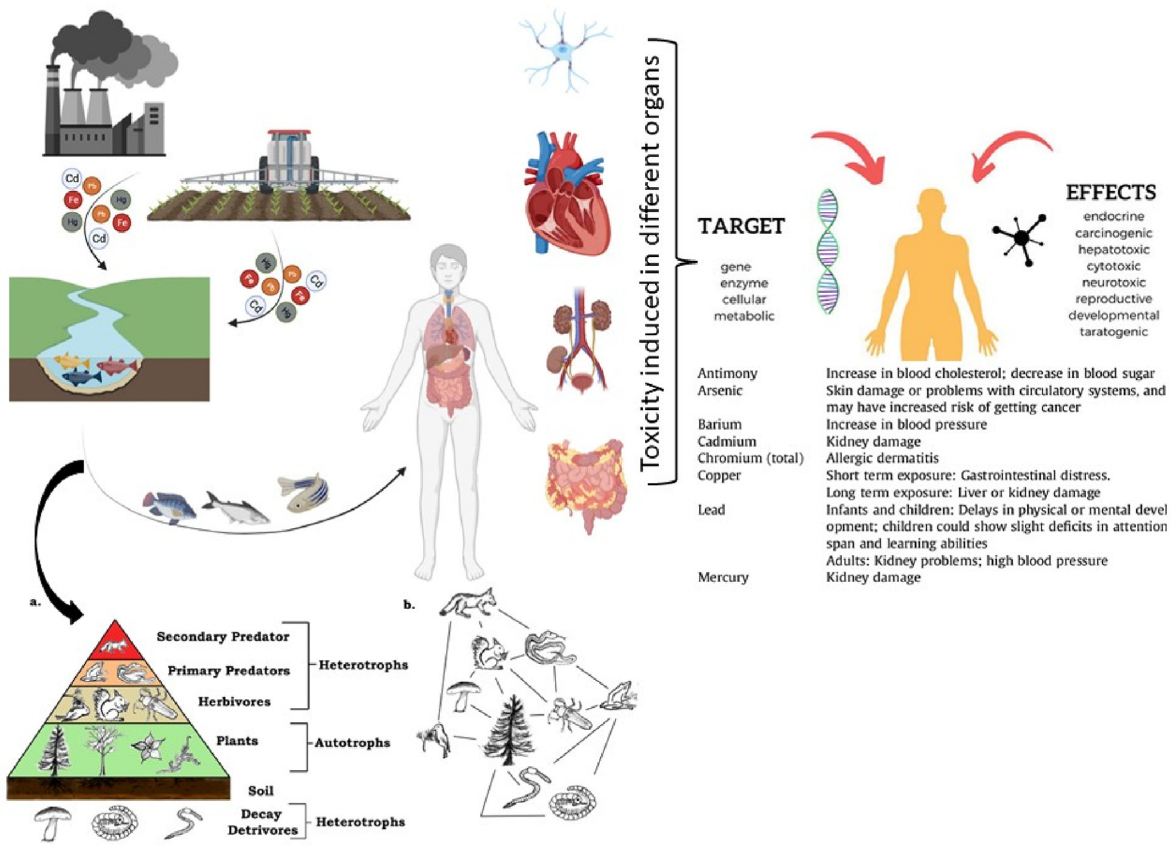

Fig. 1. A visual representation conveying the process of contamination drift from source to the food chain and the toxicities associated with the same in human.

essential for the survival of living organisms, most of them pose a great danger, even in minute quantities. Additionally, some metals, such as arsenic (As), cadmium (Cd), copper (Cu), Chromium (Cr), lead (Pb), mercury (Hg), nickel (Ni), selenium (Se), zinc (Zn), etc., are highly toxic [2].

The concentration of heavy metals in fish has been extensively investigated in current review considering the literature available over the course of last decade or so. Research findings have demonstrated that the degree to which heavy metals accumulate in fish is contingent upon the type of metals, the specific species of fish, and the respective tissues, all of which directly impact the accumulation of heavy metals in fish. Additionally, it is known that sediment plays a significant role in the accumulation of heavy metals in fish, as it is widely recognized primary source of contaminants for bottom-dwelling and bottom-feeding aquatic organisms. Consequently, sediment serves as the concentrated reservoir of heavy metals in the dietary intake of fish [3]. The Central Pollution Control Board (CPCB), which serves as India's environmental regulatory authority, claimed the involvement of 43 industrial conglomerates in the country in activities that contribute to the contamination of water bodies (CPCB 2009). Certain regions in the eastern part of India, specifically Orissa, Jharkhand, West Bengal, and the industrial city of Durgapur, have been identified as highly polluted areas (CPCB 2009) [4].

The bioaccumulation and toxic characteristics of metals are heavily influenced by both their inherent properties and the surrounding environmental conditions, which play a crucial role in determining the bioavailability of these metals. To gain insights into the impact of local contamination on the accumulation of metals in fish, experimental studies conducted in natural settings prove to be instrumental. Consequently, the focal point of interest lies in examining how even a slight elevation of metal concentration levels in water, resulting from global element fluxes, diffuse contamination of major waterways, or leaching caused by acidification in atmospheric precipitation, can affect the bioaccumulation of these metals by fish. It should be noted that when metals are present in low concentrations in water, their toxic properties are contingent on ecological factors such as pH, as well as the concentrations of calcium and organic ligands [5].

The discussion further made emphasizes various toxicities developed in fishes and humans due to the exposure of HMs including As, Cd, Hg, Cr, and Pd. While keeping the importance of monitoring such persistent contaminants under consideration, we have given the current status of HM contamination in various water bodies, and fish species collected from various places in India at different time periods. The data gathered and represented here are collected from various authoritative sources.

2. Overview of various HMs and toxicities

Inorganic and some of the organic heavy metal forms are resistant to decomposition, and exhibit a tendency to build up in sediments. Bioaccumulation and biomagnification in living tissues is a complex process while illustrating the inability to detoxify through processes such as oxidation, precipitation or bioremediation, etc., making these elements a matter of special concern [6]. Aquatic ecosystems, particularly rivers, and oceans, are the primary recipients of such toxic metals. Slight changes in the surrounding quality (such as physicochemical properties) can induce adverse effects on the normal functioning of aquatic organisms, especially

Fig. 2. Google satellite image: The Heavy metal analysis was done between 2013 and 2023 as per the data collected from authoritative sources in the pinned locations (rivers).

fish as these are highly sensitive to such alterations. Fish, being at the top of the aquatic food chain, are considered excellent subjects for toxicological and toxicogenomic studies. They are extremely sensitive to any type of environmental changes, which makes them suitable bioindicators for monitoring aquatic ecosystems, as they efficiently metabolize, detoxify, and accumulate toxic metals within their bodies. Toxic metals can enter a fish's body through food intake, absorption of water for respiration, or ion exchange through a partially permeable membrane, leading to their accumulation in various tissues throughout the body [2].

While some of the HM in the water are necessary for the health of aquatic organisms at certain concentrations, their excessive concentrations can be detrimental, while others that are not necessary can have a negative impact even at lower concentrations. The United States Environmental Protection Agency (USEPA) employs the Chronic Daily Intake (CDI) term which refers to the evaluation of possible hazards that heavy metals can cause in various concentrations. This approach assesses the bioavailability of HMs in the subject's body to determine the levels of toxicity [7].

Heavy metals can enter the body through inhalation of contaminated air, ingestion of contaminated food and water, and dermal contact with contaminated surfaces [8]. Once absorbed, heavy metals can accumulate in various organs and tissues, leading to a range of adverse health effects [8]. Neurological damage, cardiovascular diseases, renal dysfunction, hepatotoxicity, respiratory problems, and reproductive disorders are among the health problems associated with heavy metal toxicity [9–11]. Lead, for example, is commonly inhaled through contaminated air in industrial settings or ingested via lead-contaminated food, water, soil, and dust. Its toxicity can cause neurological damage, cardiovascular diseases, renal dysfunction, and reproductive disorders [11,12]. Exposure to high levels of lead in children has severe and potentially irreversible health consequences. It can lead to seizures, headaches, coma, and even death [12]. Children are particularly vulnerable to lead exposure as their developing nervous systems are more susceptible to damage from heavy metals. Even low levels of lead exposure can have detrimental effects, especially in children, leading to cognitive deficits, developmental delays, and neurobehavioral disorders [13]. Mercury, primarily inhaled as vapor in industrial areas or ingested through contaminated seafood, can lead to neurological damage, cardiovascular issues, renal dysfunction, hepatotoxicity, and reproductive toxicity. The health effects of mercury exposure depend on the chemical form (elemental, inorganic, or organic) and route of exposure. Elemental and inorganic mercury primarily affect the central nervous system, causing tremors, memory loss, and cognitive deficits. Organic mercury, such as methylmercury found in seafood, can cross the blood-brain barrier and affect the central nervous system, leading to neurological damage, cognitive deficits, and developmental delays [14]. Cadmium, found in contaminated air, food, and water

Table 1
Contamination level in various fish species collected from different geographical areas in (μg/g) [55–57].

	Ennore Creek, Southeast Coast of India						Bay of Bengal (Station 1 sample) Fish sample	
Heavy metal	Sea water	*Penaeus monodon*	*Perna viridis*	*Crossosstrea madrasensis*	*Mugil cephalus*	*Terapon jarbua*	*M. cephalus*	*O. mossambicus*
Hg	1.78 ± 0.20	0.90 ± 0.11	0.85 ± 0.16	0.43 ± 0.07	0.41 ± 0.07	0.68 ± 0.10	–	–
Cu	47.27 ± 1.71	9.30 ± 2.96	22.35 ± 2.42	30.84 ± 0.89	2.75 ± 0.53	14.56 ± 0.66	–	–
Cr	14.13 ± 1.44	0.51 ± 0.27	22.35 ± 2.42	3.30 ± 0.23	1.77 ± 0.67	2.32 ± 0.38	0.13 ± 0.05	0.11 ± 0.003
Zn	10.26 ± 1.15	15.86 ± 0.67	8.32 ± 0.74	7.57 ± 0.55	9.78 ± 1.02	5.00 ± 0.53	2.25 ± 0.10	2.26 ± 0.34
Ni	10.26 ± 1.15	3.62 ± 1.37	9.14 ± 1.45	7.42 ± 0.46	4.34 ± 0.66	4.53 ± 0.46	0.31 ± 0.03	0.33 ± 0.01
Pb	4.93 ± 0.77	4.37 ± 0.33	3.42 ± 0.29	4.00 ± 0.29	2.59 ± 0.31	3.42 ± 0.29	0.10 ± 0.08	0.13 ± 0.001
Cd	14.55 ± 4.42	19.25 ± 0.53	11.26 ± 1.14	6.20 ± 0.40	6.58 ± 0.61	5.81 ± 0.46	0.13 ± 0.049	2.13 ± 0.368
AS	2.57 ± 0.29	1.82 ± 0.58	2.05 ± 0.23	1.37 ± 0.20	1.54 ± 0.40	1.75 ± 0.39	–	–
Fe	–	–	–	–	–	–	19.97 ± 0.54	19.97 ± 0.54
Mn	–	–	–	–	–	–	0.9 ± 0.14	1.2 ± 0.34
Co	–	–	–	–	–	–	0.008 ± 0.002	0.04 ± 0.004

sources, can cause renal damage, osteoporosis, and respiratory problems. Acute exposure to high levels of cadmium can cause symptoms such as nausea, vomiting, diarrhea, and abdominal pain [15]. Chronic exposure to lower levels of cadmium can lead to renal damage, osteoporosis and respiratory problems. Furthermore, cadmium is classified as a human carcinogen, with long-term exposure linked to lung, prostate, and kidney cancer [15]. Arsenic exposure, commonly through contaminated air, food, and water, can lead to dermatological issues, respiratory problems, cardiovascular diseases, and renal dysfunction. Inorganic arsenic is classified as a human carcinogen, with long-term exposure linked to skin, lung, bladder, and liver cancer [16]. Chromium exposure, primarily through inhalation or ingestion of contaminated air, food, and water, can cause respiratory issues, dermatological effects, gastrointestinal problems, renal dysfunction, and carcinogenic effects. Hexavalent chromium is classified as a human carcinogen, with long-term exposure linked to lung, nasal, and gastrointestinal cancer. Trivalent chromium is considered less toxic but can still cause respiratory effects such as asthma and chronic bronchitis [12].

2.1. Arsenic (As)

One of the deadly metals that has a significant harmful effect at lower dosages is Arsenic (As). Acute exposures can cause instantaneous demise (LD_{50} of $NaAsO_2$ is approximately 28 ppm) [17]. Fishes exposed to arsenic (As) have developed breathing issues as coagulated mucous film clogs their gills and arsenic (As) ions directly damage blood vessels. This results in a vascular collapse in the gills causing anoxia. Arsenic (As) has a bacteriostatic effect and is employed by fish to guard this area against microorganisms due to the strong concentration of the chemical in the eye, throat, and gills, which is in the most obvious mucus membrane region [17,18]. The reproduction process was found to be significantly affected by arsenic (As) because it inhibits spermatogenesis and oogenesis. This results in a high number of impotent eggs and sperm while adversely impacting the hatching and fertilization rate [19].

2.2. Cadmium (Cd)

Previous research reported the impact of Cd on fish reproduction resulting in multiple dysfunctions [18,20]. Numerous studies have shown that fish have trouble reproducing due to aberrant oocyte shape, unfilled follicles, loss of follicular line, retraction and cytoplasm condensation, and lower total GSI (Gonadosomatic Index). Additionally, other ill effects such as contraction in spermatic lobules in the testis, decreased sperm motility and viability, etc., can develop in different fishes [19,21]. Wherein, the fertilization rate is also reduced by Cd intoxication. Various studies reported that fish with Cd toxicity developed tumors, hypertension, permanently lost ability to reproduce, and kidney/liver malfunction [19].

2.3. Chromium (Cr)

Ingestion of HM contaminated water or food can lead to the accumulation of HM in the body. As per various studies, chromium (Cr) levels in water have increased significantly in recent years due to increasing anthropogenic activities which range from 1 to 10 μg/L of average contaminated water [7,9,20]. The growth and feed conversion of several fish species can be affected by Cr, as it gets involved in the metabolism process of nutrients such as carbohydrates, proteins, and fats. Because of its summative destructive effects on living organisms, it is considered one of the most toxic heavy metals. Over an extended period of time, exposure to Cr resulted in blood related diseases, including anemia, lymphocytosis, and eosinophilia with renal and/or bronchial lesions. Chromium (Cr) poisoning is most prevalent in fish that swim near effluent disposal [7,9,19,22,23].

2.4. Mercury (Hg)

The environment's one of the most toxic and commonly found HMs is mercury. Due to the high rate of industrialization in recent years, mercury contamination in the environment significantly rose in the 20th century. Mercury can enter a fish's body through the gills, skin, and alimentary canal when it is consumed [24]. At sublethal concentrations, mercury is extremely poisonous to fish and changes the structure, physiology, and biochemistry of the fish's nervous system. Methyl mercury is regarded as the most damaging substance since it can accumulate in the fish's nervous system while penetrating the blood-brain barrier due to its lipophilic nature [25].

2.5. Lead (Pb)

In addition to the impact on locomotion, lead bioaccumulation in fish primarily affects the liver, spleen, kidney, and gills. According to various studies, the deadly lead concentration for fish is 10–100 mg/L [25]. Fish experience behavioral changes, impotency, and development retardation at sublethal lead exposure concentrations [26–28]. Histological alteration was also reported considering after exposure effects of lead which illustrated that the fish exposed to lead showed signs of necrosis of parenchyma cells, fibrosis of hepatic cords and connective tissue, loss in growth and

Bay of Bengal (Station 1 sample) Fish sample				Bay of Bengal (Station 2 sample) Fish sample (μg/g)					
A. caelatus	*C. chanos*	*L. fulviflamma*	*T. jarbua*	*M. cephalus*	*O. mossambicus*	*A. caelatus*	*C. chanos*	*L. fulviflamma*	*T. jarbua*
–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–
0.13 ± 0.04	0.11 ± 0.004	0.1 ± 0.07	0.12 ± 0.07	0.06 ± 0.005	0.09 ± 0.006	0.16 ± 0.04	0.8 ± 0.014	0.31 ± 0.1	0.22 ± 0.05
2.01 ± 0.45	1.24 ± 0.12	7.1 ± 0.9	1.6 ± 0.8	1.33 ± 0.04	1.33 ± 0.04	2.4 ± 0.121	2.04 ± 0.10	2.7 ± 0.31	1.7 ± 0.6
0.04 ± 0.04	0.05 ± 0.002	0.1 ± 0.03	0.1 ± 0.07	0.02 ± 0.002	0.04 ± 0.004	0.03 ± 0.003	0.03 ± 0.002	0.06 ± 0.09	0.05 ± 0.03
0.05 ± 0.03	0.08 ± 0.02	0.25 ± 0.2	0.4 ± 0.05	0.05 ± 0.003	0.08 ± 0.005	0.09 ± 0.003	0.06 ± 0.003	0.4 ± 0.09	0.07 ± 0.01
0.02 ± 0.01	0.23 ± 0.09	0.06 ± 0.02	0.1 ± 0.27	16.5 ± 0.4	26.25 ± 0.06	6.95 ± 0.21	14.4 ± 0.197	3.31 ± 0.5	0.9 ± 0.4
–	–	–	–	–	–	–	–	–	–
10.3 ± 0.24	3.8 ± 0.16	13.2 ± 1.7	5.2 ± 0.9	1.5 ± 0.053	3.9 ± 0.034	3.2 ± 0.05	3.5 ± 0.01	5.7 ± 0.9	6.2 ± 2.1
0.3 ± 0.04	0.3 ± 0.07	0.1 ± 0.05	0.03 ± 0.01	0.18 ± 0.003	0.67 ± 0.11	0.8 ± 0.03	0.6 ± 0.01	0.4 ± 0.3	0.2 ± 0.1
0.12 ± 0.05	0.02 ± 0.001	0.17 ± 0.02	0.05 ± 0.003	0.07 ± 0.002	0.05 ± 0.004	0.01 ± 0.001	0.02 ± 0.003	0.04 ± 0.02	0.03 ± 0.02

body weight, and collapse of blood vessels [25].

2.6. Impact on fish health due to HMs exposure

2.6.1. Reproduction in fish

The adverse effects of heavy metals on fish reproductive health can result in the production of inferior quality gametes, which can negatively impact the fertilization success rate as well as the hatching and life cycle of offspring. Heavy metals accumulated in the environment disrupt the formation and function of various organs and tissues including reproductive systems. Various investigations considering the same areas of study found that Arsenic (As) had a significant impact on the reproductive activities of fish while hindering their spermatogenesis/oogenesis processes [19,29]. This results in a low number of degraded sperm/egg quality, and slow hatching/fertilization rates. Furthermore, Cd is considered as incredibly toxic, leading to various reproductive dysfunctionalities in fish. Research has revealed several issues with fish reproductive health, such as abnormal oocyte structure, empty follicles, impaired or distended cilia, condensation of cytosol and reduced GSI. Reduced spermatic lobules, testicular fibrosis, reduced fertility and fertilization rate, and decreased cytotoxicities are all side effects of Cd toxicities [19].

2.6.2. Olfaction

Heavy metals are also found to have an impact on fish olfaction. Metal ions in the water column have an immediate effect on the chemoreceptors in the nasal canal which often binds to receptor proteins [30]. The olfactory sense perception is of great importance to fish, as it assists in essential functions such as food access, detecting potential predators and toxic substances, regulating social interactions, and reproduction [30,31]. High levels of specific heavy metals can cause permanent damage to innate receptor cells. Previous research has revealed that copper (Cu) exposure caused the necrosis of receptor cells, hemorrhaging, and necrosis in other tissues and organs. Moreover, the death of cells caused by heavy metals is supported by research on guppies, *Poecilia viridis*, which were exposed to waterborne zinc [32].

2.6.3. Neurology and musculature

Copper ions in the water were found to be associated with higher plasma ammonia levels in previous studies. Plasma ammonia levels were raised in the control group of trout. However, they were significantly lower than those found in subjects subjected to copper treatment. The study suggests that trout do not exhibit ammonia buildup during rest and exercise, as per the findings. The physiology of these fishes can be disturbed by sublethal copper ion concentrations in the water, as well as other factors such as pH and temperature change, which can have adverse effects on their swimming performance as well [21,32]. Further studies on the generation of ammonium ions through HM exposure have demonstrated that HMs can affect several ion and energy-metabolizing enzymes. The central and peripheral nervous systems of fish may have been directly affected by the increase in ammonium ions, leading to neuropathy, according to a study reported [32].

3. Human health risks

There are several manners by which heavy metals get transmitted up the food chain, although they mostly come from man-made and natural sources [33]. Plants are essential to this transfer process because they use certain transport mechanisms to accumulate heavy metals from the soil. Plants that accumulate heavy metals may experience changes in physiological and biochemical processes that hurt their ability to grow and develop [34]. Moreover, plants growing in soil polluted with heavy metals may become nutrient-deficient due to the impact of heavy metals on plant nutrition. Because heavy metals may bioaccumulate in food materials, this contamination poses major health risks [35]. On the other hand, HM can get drifted by means of air, water, or various organisms to various adjacent locations including rivers, ponds, lakes, and oceans. The fish and various other aquatic organisms that bioaccumulate the contaminants further cause exposure to other animals including humans as food sources.

In a study conducted in 2023 at Gulf of Guinea, the outcomes suggested the concentration of HMs (Cu:12.08 ± 1.46 μg/g, Zn: 19.20 ± 2.27 μg/g, As: 8.46 ± 2.42 μg/g, and Cd: 0.03 ± 0.01 μg/g) in *Penaeus notialis* and *D. angolensis* (Hg: 0.14 ± 0.03 μg/g) [36]. Mercury was present in relatively high amounts in *D. angolensis* [36]. Risks of cancer due to the consumption of *P. notialis* exceeded the 10^{-6} level for all age groups in Ghana as per reports [36]. To prevent potential health risks, it is advised to ingest certain fish species with caution, especially shrimp *P. notialis* [20,36,37].

Tenualosa ilisha, Gudusia chapra, Otolithoides pama, Setipinna phasa, Harpadon nehereus, Polynemus paradiseus, Sillaginopsis panijus, and Pampus chinensis were among the commercial fish varieties studied from the Karnaphuli River in Bangladesh. As and Pb had carcinogenic risk values of 10^{-6} and 10^{-4} respectively, indicating that consistent intake of fish may increase the risk of cancer. Although fish is an excellent source of nutrients, the environment influences how nutritious fish is. Due to their potential for bioaccumulation and non-biodegradability, small amounts of metal offer a bigger concern. Heavy metal toxicity, which can harm key organs such as the brain, central nervous system (CNS), and blood, can result from eating fish from contaminated aquatic ecosystems [20].

Exposure for a long time can also cause neurological, muscular,

Table 2
Level of heavy metals concentration in river water, riverine sediment and fish organs from Kali River at Muzaffarnagar [51].

Heavy metals concentration		Cd	Cr	Pb	Zn
Surface water	**Minimum Concentration**	0.001	0.002	0.001	0.004
	Maximum Concentration	0.024	0.087	0.34	0.367
Sediment sample	**Minimum Concentration**	0.11	0.35	14.22	8.07
	Maximum Concentration	3.38	20.11	81.53	258.45
Puntius ticto	**Minimum Concentration**	19.25	24.6	7.84	30.38
	Maximum Concentration	22.4	30.25	9.2	42.5
Heteropneustis fossilis	**Minimum Concentration**	39.6	69.5	21.58	59.12
	Maximum Concentration	45.4	98.24	26.25	70.24

Note: fresh water (mg/l): WHO (1993); sediment (mg/g): Canadian EPA (1976); freshwater fish (mg/g): WHO (1993).

Table 3
Concentrations metals in fish tissues (μg/g dry wt) in Mumbai Harbor [58].

Fish Species	Fe	Zn	Mn	Cr	Cu	Cd	Pb	Hg (wet)
Location:Vashi								
Johnius elongatus	240.5	41.5	4.47	0.62	2.15	0.57	0.22	0.23
Polynemus tetraductylus	32.11	31.2	1.17	0.07	1.84	0.47	0.01	0.01
Carangodiae sp.	91.5	52.9	1.7	0.1	5.8	0.42	0.12	0.03
Arius maculetus	107.3	55.3	2.24	0.08	1.75	0.49	0.26	0.17
Dentrophysa russelli	78.05	38.69	2.12	0.16	1.65	0.08	0.13	0.02
Tetraden sp.	101.2	30.34	1.96	0.09	2.4	0.11	ND	0.01
Coilia dussumieri	207.2	54.83	3.87	0.63	5.59	0.14	0.17	0.04
Therapon jarbua	70.63	57.72	2.9	0.89	2.54	0.04	0.14	0.03
Lutjanus johni	62.31	25.55	2.08	0.47	1.88	0.07	ND	0.01
Thryssa mystax	53.87	60.75	5.65	1.06	1.55	0.03	0.16	0.01
Location: Colaba								
Fish Species	Fe	Zn	Mn	Cr	Cu	Cd	Pb	Hg
Therapon jarbua	46.7	36.15	4.42	0.74	2.05	0.31	0.24	0.09
Plotosus limbatcus	51.58	14.38	1.48	ND	1.27	0.08	0.09	0.05
Arius arius	112.3	43.53	3.65	0.18	6.51	0.02	0.14	0.08
Thryssa hamiltonii	69.26	53.11	7.27	1	1.98	0.08	0.02	0.1
Scatophagus argus	84.99	34.53	4.99	0.1	2.41	0.11	0.13	0.09
Trypauchen sp.	40.74	12.77	1.4	ND	1.16	0.1	0.24	0.11
Trichiurus lepturus	141	42.34	6.34	1.55	2.11	0.12	0.04	0.07
Coilia dussumieri	105.8	38.81	7.75	1.04	2.24	0.50	ND	0.08
Johnius macropterus	74.93	20.3	2.39	0.55	0.87	0.04	0.11	0.06
Liza macrojepis	68.93	26.21	1.6	0.1	1.62	0.02	0.04	0.07

Table 4
Average concentration of heavy metals in surface water and sediment of Subarnarekha river (each value is average of five samples) [50] ("-" refers to: Data nonavailability).

Locations	As	Cu	Fe	Pb	Ni	Zn	Cr	Co	Sr
Surface water (μg/L)									
Tatanagar	0.65	0.55	59.02	-	0.82	13.2	1.25	0.08	86.48
Mosabani	0.63	16.5	64.74	-	3.68	12.4	1.16	0.23	96.17
Mahapal	1.07	0.48	81.0	-	1.43	5.22	0.03	0.07	170.3
Kirtania	20.3	17.8	140.2	-	4.57	5.64	1.00	0.21	1779
Sediment (μg/L)									
Tantanagar	0.763	44.4	24,766	65.0	27.7	182.1	70.59	13.50	16.8
Mosabani	0.328	168.5	17,683	48.1	36.9	53.60	53.62	11.39	25.7
Mahapal	1.353	43.2	21,867	37.6	39.2	59.50	94.02	11.97	29.3
Kirtania	1.450	25.7	20,899	26.1	25.3	52.20	75.01	8.62	32.8

and physical conditions like Parkinson's, Alzheimer's, and multiple sclerosis in humans. Numerous people suffer from allergies and prolonged exposure to some metals that can potentially result in cancer [36,38,39]. Chemically significant heavy metal toxicity can cause disease, a decline in quality of life, and finally death. Studies show Fish consumption per person worldwide has dramatically increased since 1960, hitting 20.4 kg in the year 2019 [36]. A million metric tonnes of fish are consumed annually in Ghana, one of the top fish-eating nations. Since fish is the most affordable protein source, it makes up a sizable portion of the animal protein diets in Africa. Since heavy metals are persistent, non-biodegradable, and have the ability to accumulate in organs and tissues over a period of time, they are a persistent and non-biodegradable problem.

Environmental contaminants that are frequently found in both aquatic and terrestrial ecosystems are heavy metals and metalloids [36,40]. Their toxicity, bioaccumulation capacity, and persistence, all influence how dangerous they are. These heavy metals and metalloids (Cr, Ni, Cu, Zn, Cd, Pb, Hg, and As) pose the greatest risks [40–42]. These components' trophic transmission in food chains have a significant impact on wildlife and public health. The levels of harmful heavy metals and metalloids in various environmental components and the local biota must be evaluated and monitored. It is essential to treat hazardous heavy metals and metalloids with the potential to inflict severe harm on humans before they are utilized, in order to mitigate their adverse impacts on both human health and the environment [20].

Table 5
Heavy metal concentration of fish and shrimp in mg/kg collected from Subarnarekha river in India (each value is average of three samples) [50].

Locations	Species	As	Cd	Cu	Fe	Pb	Zn	Cr
Barabinda	***P. indicus***	0.354	0.051	21.22	64.85	0.159	30.83	1.436
	M. gulio	0.184	0.005	0.747	94.75	0.327	67.30	0.695
	P.conchonius	0.112	0.004	1.412	58.56	0.234	63.72	0.592
	L. calbasu	0.175	0.006	2.510	61.65	0266	81.93	0.496
	L. rohita	0.371	0.004	5.620	56.15	0.145	52.12	0.325
	L. bata	0.364	0.004	1.604	57.05	0.280	40.30	0.726
Tatanagar	***P. indicus***	0.603	0.621	29.51	226.1	0.325	109.5	11.36
	M. gulio	0.027	0.026	1.173	75.52	0256	77.51	0.961
	P.conchonius	0.080	0.029	5.157	121.3	0.146	89.40	1.279
	L. calbasu	0248	0.005	1.479	56.52	0.085	99.10	0.680
	L. rohita	0.418	0.005	7.681	177.9	0.325	79.30	1.051
	L. bata	0.421	0.230	2.960	81.60	0.359	65.20	1.520
Mosabani	***P. indicus***	0.671	0.852	145.2	147.6	0.412	96.35	4.230
	M. gulio	0.094	0.101	14.01	103.9	0.341	47.41	0.503
	P.conchonius	0.167	0.063	10.63	175.4	0.237	81.33	1.397
	L. calbasu	0.127	0.008	13.52	98.26	0.096	75.32	0.512
	L. rohita	0.458	0.098	20.83	125.9	0.136	49.28	0.826
	L. bata	0.482	0.510	46.35	128.2	0.214	54.36	0.745
Gopiballavpur	***P. indicus***	0.513	0.045	14.25	116.3	0.063	12.36	1.050
	M. gulio	0.052	0.039	1.255	79.75	0.091	52.10	0.577
	P.conchonius	0.176	0.021	1.250	163.1	0.045	63.25	0.985
	L. calbasu	0.177	0.006	1.256	57.25	0.054	52.36	0.412
	L. rohita	0292	0.054	5.320	107.2	0.112	35.62	0.254
	L. bata	0.284	0.140	19.60	122.3	0.025	52.06	1.040
Mahapal	***P. indicus***	0.263	0.052	10.25	161.8	0.052	14.28	0.690
	M. gulio	0.031	0.027	1.105	106.2	0.081	42.63	0.215
	P.conchonius	0249	0.017	3.330	130.8	0.031	42.06	1.123
	L. calbasu	0.226	0.007	0.965	60.70	0.058	48.61	0.547
	L. rohita	0.313	0.061	4.250	68.10	0.096	42.69	0.314
	L. bata	0.226	0.210	16.32	132.6	0.031	45.21	0.890
Kirtania	***P. indicus***	1.256	0.049	21.73	160.4	0.078	25.22	0.358
	M. gulio	1.518	0.007	1.911	204.4	0.087	42.55	0.964
	L. rohita	0.914	0.020	1.208	203.4	0.062	71.30	0.582
Geometric mean		0.248	0.031	5.16	104.9	0.121	52.2	0.784

Table 6
Determination of some heavy metals in fish, water and sediments from Bay of Bengal [49].

Concentrations (Minimum and maximum values) of Heavy Metal in fish caught from different locations (mg/kg)										
Location	As		Cd		Cr		Pb		Hg	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Pulicat	0.002	0.382	0.083	0.417	0.036	0.518	0.004	0.368	0.002	0.064
Ennore	0.001	0.247	0.001	0.441	0.004	0.463	0.006	0.375	0.004	0.006
Marina	0.002	0.024	0.032	0.432	0.008	0.711	0.012	0.203	0.002	0.008
Mahabalipuram	0.000	0.334	0.002	0.417	0.021	0.465	0.014	0.286	0.003	0.062

Table 7
Heavy metals concentration (mg/L) in River Ganga water at selected sites [52].

Heavy metals	Kanpur	Allahabad	Mirzapur	Varanasi
Cu	1.35 ± 0.25	2.54 ± 0.65	2.54 ± 0.68	4.58 ± 1.54
Pb	0.54 ± 0.05	0.62 ± 0.05	0.85 ± 0.08	0.24 ± 0.04
Cd	0.54 ± 0.07	0.68 ± 0.47	0.78 ± 0.12	0.85 ± 0.24
Cr	0.32 ± 0.06	0.85 ± 0.08	0.36 ± 0.07	0.45 ± 0.06

4. Importance of frequent HM monitoring

The constant monitoring of pollutants (any pollutant as in HMs, pesticides, other industrial waste, anthropogenic, domestic pollutants, etc.) is necessary keeping in mind the various major concerns associated with them. A simple observation can be taken under discussion here i.e. when we see two or more studies that analyzed HMs in a particular geographical area over a period of time, the data showed varying concentration with changing seasons (may or may not be significantly different). This same quantitative data can be significantly different when analyzed in intervals. The reviews pertaining to the decade of published research and reports suggested that HM contamination not only has significant magnitude but also became a sensitive issue having human involvement. The significant variation in HM contents with changing seasons and passing times calls for a regular scientific review of the status of the HM contamination in marine species to keep a regular check on aquatic health and food security. Further, the availability of updated information can be helpful in providing solutions in an efficient manner while encouraging research and development to improve the deteriorating environmental conditions. Apart from this, the updated data can induce accuracy in near future studies to be conducted while assisting various organizations (Governmental/non-governmental) in providing the guidelines or safety measures keeping in consideration the public health aspects [23]. Toxicity persistence can be a factor to be focused on. Various pollutants are found to be non-biodegradable or may get

Table 8
Contamination level in different organs of fishes collected from various geographical areas in (μg/Kg) ("-" indicates information not available) [6,67–69].

Bhadra River during June 2011–July 2012													
	Etroplus maculates					*Cirrhinus reba*					*Ompok bimaculatus*		
HMs	Muscle	Liver	Intestine	Gills	Kidney	muscle	liver	Intestine	Gills	Kidney	Muscle	Liver	Intestine
Cu	01.36 ± 0.02	03.85 ± 0.03	01.64 ± 0.03	01.84 ± 0.03	01.35 ± 0.04	06.37 ± 0.09	01.04 ± 0.01	01.08 ± 0.03	01.06 ± 0.03	01.19 ± 0.05	01.29 ± 0.01	01.30 ± 0.03	01.48 ± 1.27
Zn	03.47 ± 0.05	03.25 ± 0.03	03.79 ±0 .0.04	07.91 ± 0.03	02.30 ± 0.06	04.11 ± 0.04	03.29 ± 0.03	04.07 ± 0.04	04.51 ± 1.27	02.53 ± 0.03	-	-	-
Cd	00.66 ± 0.04	00.59 ± 0.02	00.51 ± 0.02	00.57 ± 0.04	00.47 ± 0.02	00.58 ± 0.01	00.65 ± 0.02	00.56 ± 0.01	00.54 ± 0.01	00.50 ± 0.02	00.60 ± 0.02	00.52 ± 0.03	00.55 ± 0.02
Ni	01.13 ± 0.01	01.45 ± 0.04	00.60 ± 0.03	00.77 ± 0.01	00.73 ± 0.02	00.92 ± 0.03	00.83 ± 0.02	01.33 ± 0.04	01.20 ± 0.02	01.37 ± 0.07	00.29 ± 0.01	01.18 ± 0.04	00.28 ± 0.01
Fe	12.19 ± 0.10	08.88 ± 0.02	24.07 ± 0.13	23.65 ± 0.25	07.02 ± 0.08	15.46 ± 0.24	17.49 ± 0.02	12.14 ± 0.08	08.38 ± 1.27	08.32 ± 0.09	-	-	-
Pb	00.79 ± 0.03	00.70 ± 0.01	01.48 ± 0.04	01.18 ± 0.04	01.29 ± 0.04	01.15 ± 0.02	00.89 ± 0.03	01.22 ± 0.03	01.50 ± 0.03	01.07 ± 0.06	00.54 ± 0.01	01.66 ± 0.05	00.44 ± 0.02
As	-	-	-	-	-	-	-	-	-	-	-	-	-
Hg	-	-	-	-	-	-	-	-	-	-	-	-	-

degraded at a very slow rate developing a considerable quantity of pollutants in a particular geographical location. This kind of situation may lead to an uncontrolled toxicity introduction to the ecosystem potent of entering into the food chain which impacts various organisms including human health [22,43]. A recent study conducted in Swat and Panjkora river reported a significantly high amount of Cr, Cd, Pb, Ni, and Fe exceeding the permissible limits provided by the WHO [44].

5. Tolerable concentrations as recommended by various organizations

Department of Health & Human Services, U.S. Department of Agriculture, Department of Commerce, Department of Justice, Environmental Protection Agency, and Federal Trade Commission are the six departments that constitute the United States Food Safety Control System. and are abbreviated as DHHS, USDA, DOC, DOJ, EPA, FTC respectively [45]. Food Standard Agency (FSA, 2000) is the sole compiled organization that regulates and monitors the standards in the said terms in the United Kingdom. MHLW (Ministry of Health, Labor, and Welfare), Japan; Food Safet and Standards Authority of *India* (FSSAI), India; CPCB (Central Pollution Control Board); Joint FAO/WHO Expert Committee on Food Additives (JECFA) for international level monitoring and regulation, etc. are some more important organizations putting significant effort to various aspects of contaminant regulation and public health [45].

The World Health Organization (WHO) has established Provisional Tolerable Weekly Intakes (PTWIs) for various heavy metals to guide safe human consumption. For chromium (Cr), the PTWI encompasses both trivalent (Cr (III)) and hexavalent (Cr (VI)) forms, expressed as micrograms per kilogram of body weight per week [46,47]. It's noteworthy that this guideline is not specific to individual food items but considers total intake from various sources, including food, water, and air. Similarly, WHO's Joint Expert Committee on Food Additives (JECFA) has set a PTWI for cadmium (Cd), indicating the amount that can be ingested weekly over a lifetime without appreciable health risk, with the latest PTWI set at 7 μg per kilogram of body weight [46,47]. For mercury, WHO provides tolerable weekly intake (TWI) guidelines, specifically addressing methylmercury, a form commonly found in fish. The TWI for methylmercury is established at 1.6 μg per kilogram of body weight. Lead is subject to a PTWI set by WHO at 25 μg per kilogram of body weight, and for inorganic arsenic (As), the PTWI is set at 15 μg per kilogram of body weight [46,47]. These guidelines serve as crucial benchmarks to ensure safe levels of exposure to these heavy metals, safeguarding public health from potential adverse effects [46,47]. Apart from the WHO, the FDA has recommended a limit of 1.0 mg/kg of Mercury (Hg) in fish, Japan has a recommended limit of 0.3 mg/kg [45].

6. Contamination level in aquatic organisms and water bodies

The tabular data gathered from various authoritative sources over a period of time (2012–2022) reveals extensive information on heavy metal concentrations in various aquatic environments and organisms across different locations in India (Fig. 2). In Ennore Creek, on the southeast coast, it is evident that heavy metal concentrations in marine organisms, especially fish, exceeded the FAO/WHO guidelines, with cadmium (Cd) levels being a particular concern [48]. Furthermore, data from the Bay of Bengal indicates that Station 2 displays significantly higher total metal concentrations in sediments and fishes compared to Station 1, warranting further investigation and environmental assessment [49] (Table 6). In the Subarnarekha River Estuary, sediment samples consistently showed higher overall metal concentrations than water samples, implying that sediment toxicity is of greater concern [50] (Table 4 and 5). A study conducted in 2014, Kali River at Muzaffarnagar

Table 9
Data from various studies suggesting the HM concentration in various organs of common fish species) [63,70,71].

	Mastacembelus armatus				*H. fossilis* from the Buriganga River (μg/g dry weight)					*Labio rohita* (in ppm)	
HMs	Muscle	Gills	Kidney	Liver	Muscle	Gills	Stomach	Intestine	Liver	Gills	Muscle
Cu	41.36 ± 0.54	199.88 ± 0.20	175.89 ± 0.19	271.67 ± 1.15	8.05 ± 0.00	6.31 ± 1.46	41.58 ± 3.15	19.05 ± 1.42	45.61 ± 1.29	–	–
Ni	58.98 ± 0.09	200.00 ± 1.73	149.33 ± 0.50	449.96 ± 0.06	–	–	–	–	–	–	–
Fe	213.29 ± 0.31	799.66 ± 0.41	149.33 ± 0.50	2601.49 ± 0.50	–	–	–	–	–	–	–
Co	9.03 ± 0.06	ND	ND	25.66 ± 0.57	–	–	–	–	–	–	–
Mn	9.03 ± 0.06	25.36 ± 0.62	ND	49.96 ± 0.05	–	–	–	–	–	0.358	0.379
Zn	186.19 ± 0.18	549.33 ± 0.57	351.28 ± 0.48	1741.95 ± 0.06	26.67 ± 0.14	17.81 ± 2.93	21.21 ± 1.13	24.81 ± 0.85	60.81 ± 0.37	–	–
As	–	–	–	–	0.3 ± 0.00	0.86 ± 0.00	3.59 ± 0.08	2.53 ± 0.44	2.61 ± 0.31	–	–
Pb	–	–	–	–	1.99 ± 0.03	5.83 ± 0.41	12.11 ± 0.85	8.06 ± 0.22	18.53 ± 0.52	0.021	0.01
Cd	–	–	–	–	0.36 ± 0.01	3.62 ± 0.26	1.39 ± 0.27	2.88 ± 0.21	3.92 ± 0.40	0.006	0.004
Cr	–	–	–	–	1.56 ± 0.11	3.62 ± 0.74	3.96 ± 1.35	2.45 ± 0.92	2.45 ± 0.92	0.412	0.463

Bhadra River during June 2011–July 2012		Visakhapatnam and Bheemili region, northeast coast of Andhra Pradesh, India										
Ompok bimaculatus		*Cybium guttatam*			*Rastrelliger kanagurta*			*Pampus argenteus*			*Liza macrolepis*	
Gills	Kidney	Muscle	Liver	Gill	Muscle	Liver	Gill	Muscle	Liver	Gill	Muscle	liver
01.48 ± 1.27	01.09 ± 0.03	04.97 ± 0.16	07.08 ± 0.63	06.51 ± 0.73	03.46 ± 0.03	05.10 ± 0.41	04.82 ± 0.17	06.64 ± 0.05	08.62 ± 0.17	06.29 ± 0.36	33.20 ± 1.70	34.20 ± 1.80
-	-	08.37 ± 0.09	12.49 ± 0.26	09.13 ± 0.14	15.64 ± 0.14	19.82 ± 0.18	17.05 ± 0.16	21.78 ± 0.34	26.19 ± 0.41	23.41 ± 0.26	34.60 ± 1.40	38.20 ± 1.50
00.54 ± 1.27	00.63 ± 0.01	00.04 ± 0.02	01.93 ± 0.16	01.67 ± 0.32	00.09 ± 0.05	03.27 ± 0.13	02.61 ± 0.21	00.12 ± 0.03	02.41 ± 0.12	01.57 ± 0.35	00.8 ± 0.19	00.9 ± 0.19
01.19 ± 1.27	01.16 ± 0.02	-	-	-	-	-	-	-	-	-	10.40 ± 1.40	11.80 ± 1.30
-	-	-	-	-	-	-	-	-	-	-	-	-
01.18 ± 1.27	00.88 ± 0.02	00.18 ± 0.02	02.41 ± 0.19	02.05 ± 0.21	00.15 ± 0.09	05.91 ± 0.27	03.85 ± 0.08	00.09 ± 0.04	04.14 ± 0.37	03.16 ± 0.16	14.20 ± 1.30	15.50 ± 1.30
-	-	00.37 ± 0.28	03.13 ± 0.16	02.90 ± 0.32	01.07 ± 0.03	03.02 ± 0.18	02.76 ± 0.07	00.16 ± 0.24	00.91 ± 0.04	01.63 ± 0.09	-	-
-	-	-	-	-	-	-	-	-	-	-	02.10 ± 0.56	02.90 ± 0.40

demonstrates substantial metal accumulation in sediment and fish organs, underscoring the need for monitoring and potential remediation efforts [51]. Along the Bay of Bengal coast, the data displays variations in heavy metal concentrations in fish from different locations, emphasizing the importance of environmental and human health considerations. Moving to the Ganga River, water samples indicate varying metal toxicity levels, with Varanasi having the highest overall concentration [52] (Table 7). The data also highlights the significance of specific fish organs as a site for metal accumulation [53]. Additionally, the data points to the liver, gills, and muscles as the organs with the highest metal toxicity in several fish species. The site of the collection and the specific fish species also influence the results, underscoring the need for tailored monitoring and management strategies. Furthermore, the data from the river Gomti reveals that metal concentrations vary by season, with summer consistently demonstrating the highest overall metal toxicity [53]. Finally, data from the Gingee River in Puducherry suggests that post-monsoon seasons exhibit higher metal toxicity in freshwater fish [54]. From the above information we can have a clear knowledge that continued monitoring, management, and assessment of heavy metal contamination in aquatic environments is necessary in order to protect both ecosystems and human health.

Ennore Creek, Southeast Coast of India" has the highest overall total concentration of heavy metals in fish compared to seawater [59,60]. The sum of heavy metal concentrations in fish at Ennore Creek is 246.11 μg/g, while the sum of heavy metal concentrations in seawater is 99.47 μg/g. This indicates a significant difference in the combined concentration of heavy metals in fish compared to seawater in this region, and it's the highest among all the locations (Table 1). Because of the involvement of multiple factors such as no uniformity in collected species (sample) in all the studies, variable environmental factors depending on fish habitat, etc., it is a challenging task to ascertain which fish species accumulated with more HM from the available data Table 2.

7. Contamination in different organs of fish

In a study conducted, the accumulation of heavy metals in the organs of *Mastacembelus armatus* was determined and a significant level of HM contaminant were found [61] (see Table 3). Heavy metal accumulation varies across different organs [21,62,63]. It was observed that the liver contains the highest concentration, followed by the gills, kidney, integument, and muscle, with muscle having the lowest heavy metal accumulation (Table 9) [61]. The reason for muscles bioaccumulating less HMs can be attributed to the various conditions. In general, HMs affinity towards muscles is less as it is a site to store energy and perform various actions related to different functionalities rather than a site to perform metabolic reactions. A rapid detoxification of HMs in muscle tissue and an active ADME process also contributes to the same.

In a study conducted at Buriganga River the HM concentrations in different tissues of *H. fossilis* (μg/g dry weight) were reported in 2013. In H. fossilis, heavy metal concentrations vary across different tissues. The liver contains the highest concentration, followed by the intestine, stomach, gills, and muscle, with the muscle and gills having relatively moderate concentrations (Table 9) [64].

The heavy metal concentration in different tissues of *Panaeus monodon*, a type of shrimp, varies significantly, with the highest levels found in the *hepatopancreas* (50.184 μg/g), indicating its role in detoxification and storage. In addition to this, as per the reported outcomes, muscle tissue contained 24.6129 μg/g of HMs cumulatively. Muscle is commonly consumed by humans and found to carry significant levels of HMs which is more or less close to the acceptable per week intake level reported by CPCB and UNEPA. While raising concerns about food safety this alarming situation calls for necessary research and development to mitigate the emerging issues. Further, gills (24.4391 μg/g), responsible for oxygen exchange, also accumulated heavy metals, suggesting potential waterborne exposure. In contrast, the carapace (8.7176 μg/g), the hard outer shell, contains lower concentrations and is not typically consumed by humans (Table 9) [65].

In a study done in 2014 by Basaiah & Sunnadahalli Murthappa, they collected and analyzed three fish species from the Bhadra River before industrial effluent exposure (to minimize conditional elevation in metals concentration) for heavy metals toxicity. The gills exhibited the highest concentration at 35.92 mg/kg, suggesting their active role in accumulating substances from the aquatic environment. The intestine followed closely with 32.09 mg/kg, indicating its potential for absorbing and processing materials from the fish's diet. Muscle, a commonly consumed edible portion of fish, contained a moderate concentration of 19.60 mg/kg, which is of particular interest for food safety and human health considerations. The liver had a similar concentration to muscle at 18.72 mg/kg, as it plays a crucial role in various metabolic processes. The brain consisted a moderate 15.21 mg/kg concentration, suggesting the ability of substances to cross the blood-brain barrier. Finally, the kidney exhibited a relatively lower concentration of substances at 13.16 mg/kg, highlighting its role in filtering waste products from the blood (Table 8) [66].

A study conducted in 2016 in Andhra Pradesh indicated the average HMs concentration in micro per kilogram (mg/kg) of dry weight in the liver and muscle tissues of *Liza macrolepis* collected from the Machilipatnam coast, Andhra Pradesh, India. The calculated overall metal toxicity is higher in the liver as compared to the muscle. These findings suggest that the liver tissue of *Liza macrolepis* contains a higher concentration of heavy metals, making it potentially more toxic than the muscle tissue. The accumulation of heavy metals in the liver can have adverse impact on the health of fish and its suitability for human consumption. Monitoring and

Table 10
Concentration of HMs in various fish species collected in different seasons [57,76].

Heavy Metals	Heavy metals (μg/g) in muscles of fish from Kali River at Muzaffarnagar district						Concentration of heavy metals accumulation in Muscle, Gill and Liver of *Oreochromis niloticus* from the Gomti river at Sultanpur, India								
	Puntius ticto			*Heteropneustis fossillis*			*Oreochromis niloticus* (Muscle)			*Oreochromis niloticus* (Gills)			*Oreochromis niloticus* (Liver)		
	Summer	**Monosoon**	**Winter**	**Summer**	**Monsoon**	**Winter**	**Summer**	**Monsoon**	**Winter**	**Summer**	**Monsoon**	**Winter**	**Summer**	**Monsoon**	**Winter**
Cd	22.4	19.25	20.84	45.4	39.6	42.1	–	–	–	–	–	–	–	–	–
Cr	30.25	24.6	26.54	98.24	69.5	78.6	1.46	0.6	0.82	1.3	0.65	0.87	13.14	6.8	9.11
Pb	9.2	7.84	8.84	26.25	21.58	24.5	0.81	0.41	0.58	3.63	1.61	2.21	14.21	8.14	9.21
Zn	42.5	30.28	37.68	70.24	59.12	64.32	3.21	1.81	2.13	1.47	0.65	0.82	4.57	1.61	8.92
Mn	30.42	24.15	29	60.5	48.4	52.9	–	–	–	–	–	–	–	–	–
Cu	–	–	–	–	–	–	0.62	0.2	0.41	0.81	0.44	0.54	8.21	5.1	9.11

managing heavy metal contamination in aquatic organisms are crucial for both ecological and public health with special considerations in coastal regions like Machilipatnam, where such fish are part of the local diet (Table 8) [72].

The metal concentrations in the liver of *Chanos chanos* were the highest among the different sample types, with a concentration of 5.048 μg/g (micrograms per gram of dry weight) as per a study conducted in 2014 at Kaattuppalli Island, Chennai, southeast coast of India. The metal concentrations in the muscle and gills were lower, with concentrations of 1.741 μg/g and 0.880 μg/g, respectively. Comparing these concentrations to those in sediment and lake water: The sediment had a concentration of 5.210 μg/g, which is relatively high. The lake water had a concentration of 4.808 μg/L, which is the lowest among the provided data. In this specific dataset, the liver of *Chanos chanos* had the highest metal concentration, followed by the sediment, muscle, gills, and lake water. However, to assess metal toxicity and potential risks to aquatic life and human health, further analysis and comparison with established guidelines or regulations for safe metal levels would be necessary. Additionally, the specific metals being measured and their potential toxicity would need to be considered (Table 8) [73].

In 2020, an investigative study done in **Visakhapatnam and Bheemili region, northeast coast of Andhra Pradesh, India** revealed that the liver had the highest metal toxicity among the organs of various fish species it considered. The liver of *Pampus argenteus* had the highest metal toxicity cumulatively (Table 8) [74].

The data from various locations and diverse aquatic organisms consistently highlights the liver as the organ with the highest metal toxicity. This trend is observed across different locations and species, emphasizing the pivotal role of the liver in heavy metal accumulation. Across the diverse locations and organisms examined in the dataset, a common trend emerges - the organ most frequently exhibiting elevated concentrations of heavy metals is the liver. The liver consistently demonstrates the highest metal toxicity across the different species and geographical settings, making it a focal point of concern in understanding the bioaccumulation of heavy metals in aquatic ecosystems.

While specific locations and species naturally show variations in the extent of metal accumulation, the liver's prevalence in accumulating these contaminants is a recurring pattern, underscoring its importance in the overall assessment of heavy metal pollution in aquatic environments. This consistency across diverse settings highlights the universal role of the liver in accumulating and storing heavy metals and emphasizes the need for comprehensive monitoring and management strategies to address this pervasive concern.

The accumulation pattern can vary based on factors such as the type of heavy metal, the water quality, the fish species, and the age and size of the fish. Larger and longer-lived fish species, especially those higher in the food chain, tend to accumulate higher levels of certain heavy metals due to biomagnification [24].

8. Contamination level in different seasons

In a past study overall metal toxicity in case of *Heteropneustis fossillis* during summer had the highest levels, followed by winter and monsoon. Similarly, *Puntius ticto* in summer had higher toxic element accumulation followed by winter, and monsoon. Overall, fishes have higher metal toxicity in the summer season, followed by the Winter season, and then the monsoon season (Table 10) [51,75].

Another study conducted in 2016, in Assam (India), took the challenge to analyze the HMs contamination variation during the period of pre-monsoon (April–June), monsoon (June to September), and post-monsoon (October to December). Based on the sum of heavy metal concentrations and pH values, the overall

Table 11
Analysis of heavy metals from water, sediment, and tissues of Labeo angra (Hamilton, 1822), from an Ox-box lake-a wetland site from Assam, India [pH and concentrations of heavy metals (mean ± SD) in the wetland water in three sampling seasons, n = 10] [77].

Heavy metal conc. (mg/L	Premonsoon (January–April)	Monsoon (May–August)	Postmonsoon (September–December)
Fe	10.4 ± 0.32	4.29 ± 0.09	6.99 ± 0.57
Cu	2.14 ± 0.08	0.36 ± 0.05	0.56 ± 0.01
Zn	11.7 ± 0.11	4.39 ± 0.09	6.35 ± 0.06
Cd	0.546 ± 0.03	0.2 ± 0.03	0.333 ± 0.02
Cr	3.22 ± 0.09	1.52 ± 0.16	2.87 ± 0.07
Pb	0.46 ± 0.02	0.1 ± 0.07	0.273 ± 0.02

Table 12
Assessing heavy metal bioaccumulation in freshwater fish at the Gingee river in Puducherry, India [54].

Mean seasonal concentrations of selected heavy metals in some freshwater fishes from the study area. (Hg concentration is in ppb; Cu, Zn and Mn concentrations are in ppm)					
Species	Seasons	Hg	Cu	Zn	Mn
Tilapia mossambica	Post-monsoon	1.631	1.786	3.612	3.908
	Pre-summer	1.713	1.58	3.198	3.812
Mystus aor	Post-monsoon	1.868	1.608	6.193	4.597
	Pre-summer	1.703	1.593	6.226	4.601
Ophiocephalus striatus	Post-monsoon	1.261	0.812	7.671	5.972
	Pre-summer	1.086	1.108	7.608	5.896
Etruplus muculatus	Post-monsoon	0.67	1.286	3.901	5.301
	Pre-summer	0.492	1.261	3.896	5.567
Ophiocephalus gachuva	Post-monsoon	0.982	1.087	3.886	5.982
	Pre-summer	0.786	0.87	3.802	5.614
Tilapia mossambica	Post-monsoon	1.482	2.121	3.405	4.126
	Pre-summer	1.361	2.262	3.046	4.085
Mystus aor	Post-monsoon	1.701	1.602	6.529	4.637
	Pre-summer	1.672	1.583	6.138	4.108
Ophiocephalus striatus	Post-monsoon	0.852	2.258	4.516	6.164
	Pre-summer	0.716	1.873	4.487	6.076
Barbus puntius	Post-monsoon	0.483	2.116	5.684	4.108
	Pre-summer	0.328	2.108	5.601	3.816
Ophiocephalus gachuva	Post-monsoon	1.087	1.27	4.364	6.801
	Pre-summer	1.016	1.118	3.986	6.678

toxicity was observed to be highest during the post-monsoon season, followed by the Pre-monsoon season, and the monsoon season has the lowest overall toxicity (Table-11) [42] (see Table 12).

Based on the available data (Table 12), the season with the highest overall heavy metal toxicity appears to be the post-monsoon season in most of the datasets, including the Gingee River in Puducherry, India, where overall toxicity is higher in the post-monsoon season compared to the pre-summer season. The justification for this pattern may include factors such as variations in water quality, increased agricultural runoff, and environmental conditions during the post-monsoon season [78]. However, it's essential to note that the season with the highest metal toxicity can vary depending on the specific location and the environmental factors at play. Each dataset and location may have a unique influence on heavy metal accumulation in different seasons. If we look into the scenario of India, pollution due to various contaminants including HMs magnifies during the post-monsoon months. Apart from various factors that we have already covered above, there are some other human and natural phenomena such as festive celebrations: Diwali (Burning of crackers), accidental crop fires, and storms. Another major reason can be the winter inversion (in winter the air near to earth's surface is trapped under the warm layer) which does not allow proper escape of contaminants from the atmosphere and ultimately causes the contaminants to accumulate [79]. On the other hand, in summer the opposite phenomena take place (Vertical mixing) where the atmospheric air moves upward and mixes with the clean air while increasing the distribution of contaminants in a vast area [79].

9. Conclusion

The need for updated information to ensure the level of contamination in various ecosystems is one of the crucial aspects of pollution control and regulatory bodies. Accurate and recent data on the concentration of contaminants like HMs in water and food (Marine) is essential for establishing regulations and safety measures. The availability of authoritative studies in relevant fields is one of the important aspects to be considered. Over the past decade, various research has been conducted in the North-East and South-East regions of India considering major waterbodies, revealing significant contamination levels. However, the same work has not been as pronounced in other parts of the country. A comprehensive discussion was made in the current study considering various aspects of heavy metal bioaccumulation and biomagnification in the food supply, especially fish and major water bodies. This indicates a significant contamination level in water bodies as well as food (HM bioaccumulated in fish and other aquatic organisms). The study also found that post-monsoon periods in India show higher contamination levels. While considering the fish it is found that the liver is often a major site for the accumulation of heavy metals, which can be attributed to the crucial role it plays during detoxification processes. The current review provides comprehensive and updated information on HM contamination in marine food systems. This can be of immense importance to the scientific researchers/communities looking for updated data/findings to carry out further research on developing techniques for the bioremediation of these heavy metals from the marine ecosystem leading to better marine food safety and security.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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