Toxicology Reports 13 (2024) 101727

Contents lists available at ScienceDirect

Toxicology Reports

journal homepage: www.elsevier.com/locate/toxrep

Assessing the risk of consuming fish from Kanyakumari (Tamil Nadu), India: An evaluative study on bioaccumulated heavy metals in different fish species using inductively coupled plasma mass spectrometry

Suryapratap Ray, Rahul Vashishth *

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

ARTICLE INFO

Handling Editor: Prof. L.H. Lash

Keywords:
Heavy metal
Hazard assessment
ICP-MS
Fish
Bioaccumulation

ABSTRACT

Environmental pollutants which are developing an alarming situation in the contemporary world captured attention in the present research. When it comes to food safety and security concerns it becomes an important field to be studied rigorously as food contributes majorly to human and animal health. The pollution of aquatic ecosystems by heavy metals (HMs) ultimately results in adverse effect on the food chain, which is covered in the current study. Fish is considered to be one of the main components of a balanced diet plate due to its high-quality protein, which sets it apart from other dietary sources. On the other hand, it is also susceptible to the absorption and bioaccumulation of HMs at toxic levels. In our study, we have considered three different species (*Nemipterus japonicus, Oreochromis mossambicus,* and *Lates calcarifer*) of fish collected from Kanyakumari, Tamil Nadu (India). Three organs namely liver, gill, and muscle were taken into consideration for the HM profiling using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The Arsenic (As), Cadmium (Cd), Chromium (Cr), Mercury (Hg) and Lead (Pb) were found to be in varied concentrations ranging from 0.1 to 1.13, 0.89–1.45, 9.95–30.66, 0.14–1.62, and 24.69–189.5 μg/kg respectively, in the studied organs of fish. Carcinogenic and noncarcinogenic risk assessments were also done indicating a notable level of Pb and Cr in selected fish species. The Hazard Index (HI) for *Oreochromis mossambicus* was >1 for adults and children, indicating future possibility of probable health hazards on daily consumption of these fish. In *Oreochromis mossambicus*, the cancer risk (CR) values for Cr and As were significantly high, particularly for children, indicating a possible occurrence of acute health risk as it exceeded the threshold of 1×10^{-3} and suggesting a significant concern. Though consumption of fish on daily basis in such significant quantity is practically impossible both for adult and children, rendering these species safe.

1. Introduction

Water is a fundamental element crucial for continuing all life forms that dwell on our planet. Our planet Earth, possesses a water reservoir consisting of approximately 3 % of freshwater resources, while 97 % is derived from the vast bodies of saline water, namely the seas and oceans, that envelop the Earth. Groundwater, accounting for approximately 30.1 % of the freshwater available, only holds a small fraction of 0.3 % within surface water bodies [1,2]. A substantial amount, roughly 68.7 %, is trapped in the icy grips of glaciers and ice caps at the Earth's poles, with the remaining 0.9 % existing in various other forms [1]. Despite the finite nature of freshwater resources on earth, there remains a constant state of uncertainty concerning the quality of these invaluable resources, a concern that has been underscored by the Global Analysis and Assessment of Sanitation. Water serves a pivotal role in preserving ecological balance and functions as a fundamental component within all organisms, serving as a primary element of the biosphere [2]. The absence of water would inevitably result in the unsustainability of life after a mere few days, causing disruptions in the distribution patterns of humans and other living creatures. Extensive pollution, gradual depletion of water reservoirs, and widespread water shortages collectively contribute to the degradation of ecosystems worldwide. The emission of industrial waste into water bodies introduces a variety of dangerous substances such as oils, pesticides, phenols, heavy metals, xenobiotics, and polyaromatic hydrocarbons, further worsening the environmental problems at hand [1,3,4]. The physicochemical attributes of water,

---

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

https://doi.org/10.1016/j.toxrep.2024.101727
Received 11 August 2024; Received in revised form 1 September 2024; Accepted 2 September 2024

encompassing factors like temperature, pH levels, dissolved oxygen content, total solids, dissolved solids, and suspended particles, are significantly altered by these effluents and are frequently employed as essential benchmarks in evaluating water quality standards [5]. As of 2003, global aquaculture production represented a significant 41.9 million tons, making up almost 31 % of the total fishery output on a global scale, which was 132.2 million tons. The aquaculture sector is currently witnessing an annual growth rate of approximately 10 % across most species, reflecting the escalating global demand for fish due to their nutritional value and therapeutic properties [3]. Fishes are typically known for their abundance of essential minerals, unsaturated fatty acids, and vitamins that actively contribute to human well-being, with the American Heart Association advocating for a consumption frequency of twice a week to fulfil omega-3 fatty acid requirements [6–10]. However, the habitats of fish face imminent threats from industrial operations that lead to pollution, particularly prevalent in regions like Bangladesh, India, and Pakistan, where wastewater treatment systems remain inadequate [11]. Occupying higher trophic levels, fish possess the capability to amass harmful heavy metals from their environment, encompassing water sources, sediments, and food supplies, thereby presenting a potential danger that could counteract the positive health advantages linked with fish consumption. Metals of significant mass such as cadmium (Cd), chromium (Cr), arsenic (As), mercury (Hg), and lead (Pb) possess the capacity to induce serious harm to crucial systems within the body, including the nervous, renal, and hepatic systems. Fish polluted with heavy metals have the potential to trigger a variety of health problems in different human organs, resulting in issues such as skin conditions, kidney malfunction, liver problems, heart irregularities, and brain disorders [8]. The increase in industrial operations has significantly raised the levels of heavy metal contamination in the atmosphere, water bodies, sediments, and food supplies, thereby sparking concerns on a global scale regarding environmental health [9,10,12]. The actions of humans such as the disposal of sewage sludge and the utilization of pesticides are identified for their impact on the introduction of heavy metals into ecosystems, which could have consequences for both aquatic organisms and human well-being along the food chain [10,13,14]. Consequently, the ingestion of fish tainted with heavy metals could present serious health risks by impacting various organs and physiological systems in the human body [15–21]. Fish, by virtue of their habitat and feeding habits in polluted environments, are particularly vulnerable to pollution in aquatic ecosystems [22]. A multitude of metals, encompassing cadmium, chromium, lead, nickel, copper, mercury, zinc, and arsenic, can gather in various fish species, with gathering affected by factors like species traits, location, water temperature, and fish size [6].

Our current study aimed to delineate the bioaccumulation of heavy metals in various organs (muscle, liver, and gills) of fish collected from various places in Kanyakumari (Tamil Nadu, India). The Risk assessment was performed for As, Cd, Cr, Hg, and Pb in three fish species namely *Nemipterus japonicus*, *Oreochromis mossambicus*, and *Lates calcarifer* (see Fig. 1: illustration of workflow). The essential parameters to determine the adverse impact of heavy metal contaminated fish were estimated as daily intake (EDI in mg/kg/day), estimated weekly intake (EWI in mg/kg/day), maximum daily intake (MDI in μg/day), maximum weekly intake (μg/week), percentage of provisional tolerable weekly intake (% PTW), daily intake limit (DIL), maximum acceptable daily intake (Kg/day), target hazard quotient (THQ), hazard index (HI) and cancer risk. The results obtained from our study hold immense importance due to the

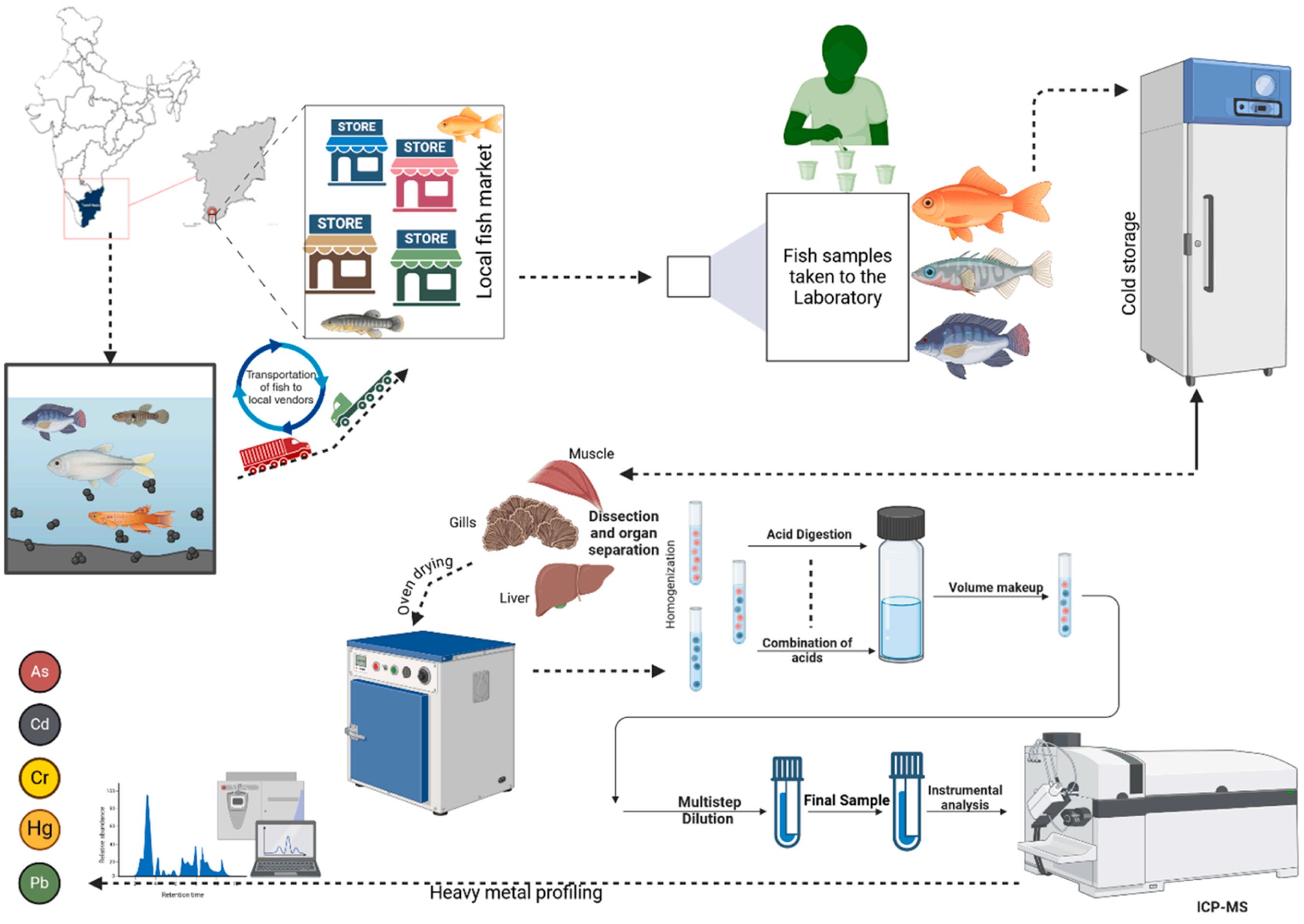

Fig. 1. Diagrammatic representation of the method followed for HM estimation (Created with BioRender.com).

valuable insights they offer regarding the prevalence of heavy metal contamination within the selected fish species collected from Kanyakumari, as they are consumed on regular basis in India (Reference). Furthermore, the findings highlighted the repercussions of such pollution on the intricate web of the food chain. This underscores the urgent requirement for the implementation of robust pollution management strategies aimed at safeguarding the ecosystem and guaranteeing the suitability of fish for human consumption.

2. Materials and methods

2.1. Sampling site

Tamil Nadu, an Indian state, has the district of Kanyakumari. It is known as "The Land's End" in India because it is the southernmost point on the Indian subcontinent and the southernmost city in mainland India. The city is located around 20 kilometers (12 miles) south of Nagercoil, the Kanyakumari district headquarters, and 90 kilometers (56 miles) south of Thiruvananthapuram (Fig. 2). The city, which is located at the point of peninsular India, has the Laccadive Sea to its west, south, and east. Its shoreline stretches along these three sides for a total of 71.5 kilometers (44.4 miles). The city receives 180 cm (71 in) of rain on an average each year from both the northeast and southwest monsoons. Kanyakumari is well-known for being the spot where three oceans converge. The Bay of Bengal, the Indian Ocean, and the Arabian Sea, situated in the east, south, and west regions respectively. Approximately 1.5–4.5 million metric tons of annual fish production has been reported from individual oceans [23–25].

The coastal waters of Kanyakumari are home to a wide diversity of marine life [26]. This contains fish species that sustain the regional fishing economy, such as shrimp, sardines, mackerel, and tuna. An essential component of Kanyakumari's economy is the fishing sector [27]. It is a major fishing hub and has a long history of marine trade. Exploration for offshore oil and gas resources may be possible on the continental shelf close to Kanyakumari.

2.2. Sample processing

Three different species namely *Nemipterus japonicus* (Locally called as Rani fish), *Oreochromis mossambicus* (Locally called as Jalebi fish), and

Fig. 3. Fish species collected for heavy metal analysis from the local, A) *Oreochromis mossambicus,* B) *Nemipterus japonicus,* and C) *Lates calcarifer*.

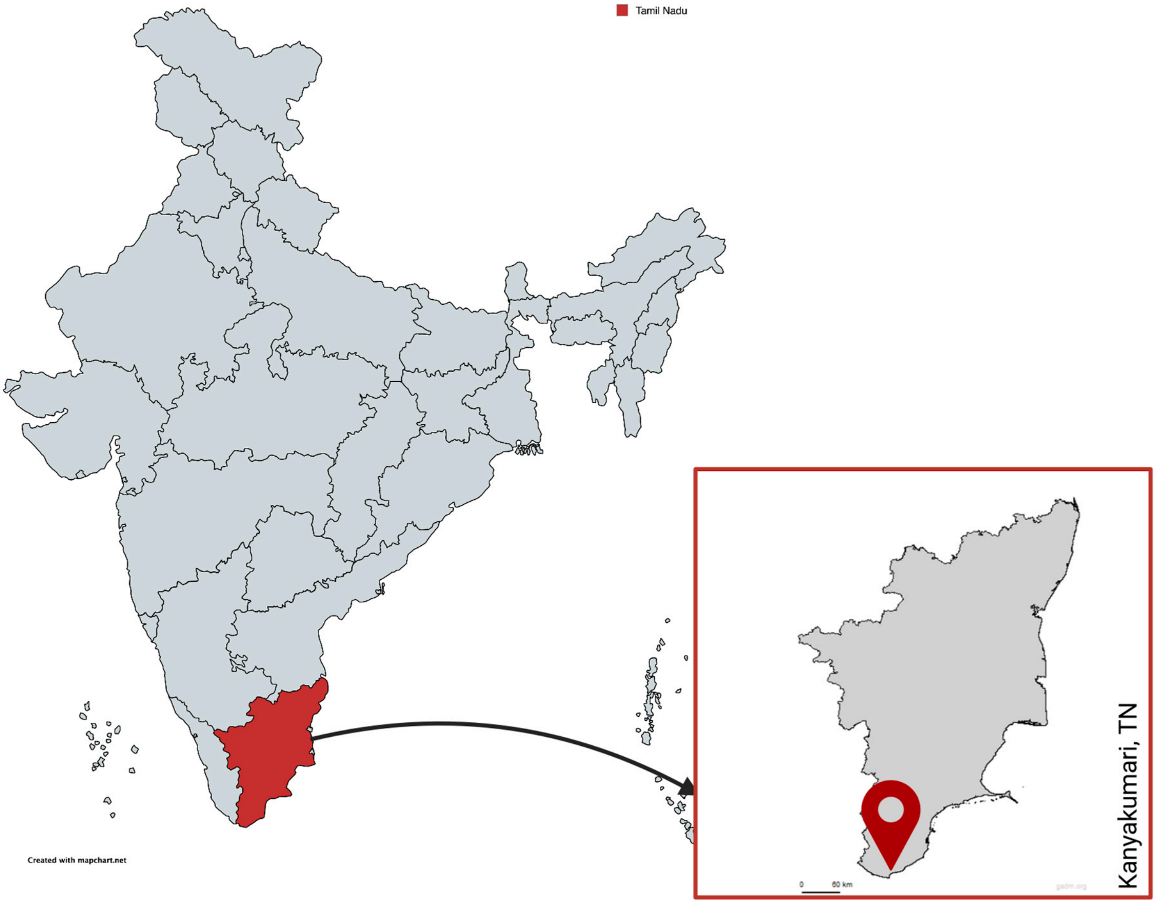

Fig. 2. Location map of the sample collection city (Kanyakumari, India) (Lat. 8° 05' N and Long. 77° 32' E) (Created with BioRender.com).

Lates calcarifer (Locally called as Koduva fish) (Fig. 3) were collected from the local markets of Kanyakumari (Lat. 8° 05' N and Long. 77° 32' E). As per data by Ministry of Fisheries, India, the production and export of these fishes from Tamil Nadu is significantly high and considering the point we have selected these species [28]. The samples were collected from the end of January to February 2024, considering the seasonal variation as a factor that may influence the study and a mixed sampling method was opted considering factors like possible contamination in the city due to industrial, anthropogenic or natural phenomena. The average length of *Nemipterus japonicus, Oreochromis mossambicus,* and *Lates calcarifer* were recorded as 16.2 ± 0.72, 16.07 ± 0.40, and 16.6 ± 0.65 cm respectively. Fish samples were dissected using a sharp, sterile, stainless steel knife. Further, the muscles, liver, and gills were separated. These separated organs were dried in a laboratory oven at 40°C until constant weight. The dried homogenized samples were further grounded into fine powder using mortar and pestle. A total of 6 replicates ($n = 6$) were withdrawn for the analysis.

2.3. Extraction and Analysis

A validated method was used from a recent study to prepare the sample for HM quantification [12]. A closed vessel acid digestion suitable heat-resistant container was used for the digestion process. 1 ml of 30 % hydrogen peroxide (H_2O_2) (ultrapure) and 8 ml of nitric acid (HNO_3) (Analytical grade) was used in combined form to digest 25 mg of the prepared samples. The digestion was carried out at 220°C on a hot plate for a period of 8 hrs approximately. Mineralized samples were then taken into a volumetric flask of 10 ml which was then taken up to 10 ml by adding 2 % HNO_3. A 10-fold dilution was made for the prepared sample and the process was repeated for all the samples in the study.

2.3.1. Analytical Setup

ICP-MS (Inductively Coupled Plasma Mass Spectrometry) system (Perkin Elmer NexION 1000) at Vellore Institute of Technology, supported by the Department of Science and Technology, New Delhi, through the "Promotion of University Research and Scientific Excellence (PURSE)" initiative, was utilized for the analysis of metal concentrations (As, Cr, Hg, Pb, and Cd) in solution samples. This system was equipped with a fixed injector torch featuring a 1.5 mm inner diameter, a spray chamber cooled by a Peltier device to minimize solvent load through the reduction of sample aerosol temperature, and a microflow concentric nebulizer for the introduction of samples. Moreover, an autosampler from Perkin Elmer S23 model was incorporated into the setup. To improve sensitivity and reduce contamination, a pre-installed triple cone interface (consisting of a sampler cone, skimmer cone, and hyper skimmer cone) was employed, with an RF forward power level set at 1600 W. The operational configuration involved the Helium Kinetic Energy Discrimination (KED) mode without collision cell technology (CCT). Prior to conducting the Q-ICPMS analyses, all samples from fish tissue underwent a tenfold dilution with 2 % HNO_3, standards and blanks were prepared using 2 % HNO_3.

2.4. Health risk assessment

To assess potential health risks (non-carcinogenic) linked to the consumption of *Nemipterus japonicus, Oreochromis mossambicus*, and *Lates calcarifer,* calculations were performed for various parameters. These included the EDI, EWI, %PTWI, MDI, MWI, DIL, CRlim, THQ, HI, and CR.

2.4.1. Estimated Daily Intake (EDI)

The Estimated Daily Intake (EDI) is a parameter that characterizes the mean daily ingestion of a specific heavy metal through food that an individual ingests. It serves as a crucial metric for assessing potential health risks associated with exposure to heavy metals. By computing the daily intake, scientists and healthcare professionals can ascertain whether individuals are absorbing heavy metals at levels that could pose health risks. Through the determination of daily consumption, this information plays a pivotal role in formulating strategies to minimize exposure and establishing safe thresholds for heavy metal concentrations in food. The calculation of the Estimated Daily Intake (EDI) value adhered to the prescribed formula outlined by the United States Environmental Protection Agency (USEPA) in 2015.

The procedure for computing EDI commonly entails the multiplication of the heavy metal content in a meal by the average daily intake rate, followed by the summation of all pertinent dietary sources. The levels of metal in fish and the frequency of consumption both influence the Estimated Daily Intake (EDI). The EDI value, expressed in micrograms per kilogram per day (μg/kg/day), was determined for both the adult population and children using the designated equation.

$$\mathbf{EDI = (Mc\ x\ Consumption\ rate)\ /body\ weight} \tag{1}$$

where Mc represents the amount of metal in fish muscle. The rate of consumption was considered as 75 g/day for children and 150 g/day for adults. Adult body weight was considered to be 70 kg, whereas children under the age of seven was considered to be 20 kg [29].

2.4.2. Estimated Weekly Intake (EWI)

The entire quantity of a particular heavy metal that an individual consumes over the course of a week is known as their estimated weekly intake or EWI. It's a metric used to evaluate possible health concerns linked to low-level and prolonged exposure to certain pollutants. Tolerable Weekly Intakes (TWI) were established for different heavy metals by regulatory agencies such as the Joint FAO/WHO Expert Committee on Food Additives (JECFA) [30]. These indicates the weekly intake that an individual may safely consume without suffering from harmful health impacts. The Estimated Weekly Intake (EWI) was calculated using the equation developed by USEPA (2000). Dietary intake of heavy metals through seafood consumption can be calculated using the following equation:

$$\mathbf{EWI = [(C \times IR)/\ BW]\ x\ 7} \tag{2}$$

where C represents the element concentration in seafood; IR is the daily ingestion rate (in grams per day) of seafood and BW is the body weight.

2.4.3. Percent provisional tolerable weekly intake (%PTWI)

Percentage of provisional tolerable weekly intake (%PTWI) has been developed for a few heavy metals. These are the weekly amounts that can be ingested without constituting a significant danger.

The percentage of Provisional Tolerable Weekly Intake (%PTWI) for each heavy metal was calculated using the equation described in Scientific Opinion on Lead in Food by European Food Safety Authority (EFSA), Parma, Italy [15].

$$\%\boldsymbol{PTWI} = \left(\frac{\boldsymbol{Actual\ weekly\ intake}}{\boldsymbol{PTWI}}\right) \times \mathbf{100} \tag{3}$$

Here Actual Weekly Intake is the amount of the contaminant consumed per week and PTWI for Arsenic (inorganic), Cd, Pb, and Hg are 15, 7, 25, and 4 μg/kg body weight per week respectively.

2.4.4. Maximum Daily Intake (MDI)

The maximum daily intake (MDI) of a pollutant, including the quantity of heavy metals, that a person may consume over the course of a lifetime without noticeably endangering their health. It takes body weight into account to guarantee safe intake amounts for various age groups. The establishment of regulatory limitations on the levels of heavy metals in food and drinking water depends heavily on MDIs [5].

The Maximum Daily Intake can be determined on the basis of the equation outlined by

$$MDI = \frac{(PTWI \times Body\ Weight)}{7} \tag{4}$$

2.4.5. Daily Intake Limit (DIL)

The Daily Intake Limit (DIL) for heavy metals in fish relies on the Provisional Tolerable Weekly Intake (PTWI) given by reputable organizations such as the World Health Organization (WHO) or national regulatory bodies. PTWI represents the quantity of a substance, presented based on body weight (e.g., micrograms per kilogram of body weight per week), that can be consumed weekly throughout a lifetime without significant health hazards [31] [32].

$$DIL = \frac{RfD \times BW}{C} \tag{5}$$

Where DIL: Daily Intake Limit of fish (kg/day); BW: Body weight of the individual (in kilograms); RfD: Reference Dose of the heavy metal (mg/kg/day)

2.4.6. Maximum Acceptable Daily Intake (MADI/CRlim)

The maximum acceptable daily intake of fish (CRlim) was determined for the non-carcinogenic risk associated with heavy metal contaminants using the equation described in [32,33].

$$CRlim\ or\ MADI = \frac{\mathrm{RfD\ or\ RfC} \times \mathrm{BW}}{C} \tag{6}$$

Here, RfD or RfC the reference Dose or Reference Concentration for the substance, BW is body weight of the individual (kg), and C is the concentration of the substance in the food, water, or other medium (mg/kg or mg/L).

2.4.7. Target Hazard Quotient (THQ)

The Target Hazard Quotient (THQ) is a measure used in risk assessment to estimate the potential health risks associated with exposure to contaminants such as heavy metals through the consumption of fish or other food items [34].

$$THQ = \frac{\mathrm{EFr} \times \mathrm{ED} \times \mathrm{IR} \times \mathrm{C}}{RfD \times BW \times AD} \tag{7}$$

Where EFr (Exposure Frequency) = 365 days/year (default for daily exposure); ED (Exposure Duration) = 70 years (for a lifetime exposure); IR (Ingestion Rate) = 150 g/day for adults, 75 g/day for children; AT (Averaging Time) = 365 days/year * 70 years = 25550 days for adults and children; BW (Body Weight) = 70 kg for adults, 20 kg for children; RfD (Reference Dose) and C (Concentration of contaminant) values are provided for each contaminant.

If the THQ value is more than 1, this risk index of above 1 indicates that a product that contains a suspected contaminant may have harmful non-carcinogenic consequences on human health. It is advised to use the carcinogenic risk index on the data if THQ is more than or almost equal to 1 [7]. The non-carcinogenic risks were assessed using the Target Hazard Quotient (THQ) calculation, as demonstrated in the equation reported by Naughton, D.P., in 2008 [34].

2.4.8. Hazard Index (HI)

The Hazard Index (HI) was determined by summing all the target hazard quotient values according to the equation defined by Javed, M. (2016) [35]. When evaluating the possible non-carcinogenic health concerns connected to exposure to heavy metal combinations through several environmental channels (ingestion, inhalation, and skin contact), the Hazard Index (HI) is a helpful tool.

$$HI = \sum THQ \tag{8}$$

A HI < 1 is generally considered as a low non-carcinogenic health risk and HI ≥ 1 indicates a potential for adverse health effects, and the severity of the risk increases with increasing HI values. However, it's important to note that HI is a conservative estimate, and exceeding 1 doesn't necessarily guarantee negative health outcomes. HI usually provides a single basement for overall risk assessment, simplifying the interpretation of complex data on multiple heavy metals. It also allows for comparison of health risks across different environmental media (e.g., soil, water, food) contaminated with heavy metals [36,37].

2.4.9. Cancer Risk (CR)

Chronic exposure to certain heavy metals has been linked to an increased risk of developing various cancer cells. Heavy metals can promote cancer development through several mechanisms, including, genotoxicity which makes some of these elements directly resulting in damage to DNA, leading to mutations that can initiate cancer [38]. They can generate free radicals, which damage cells and contribute to DNA alterations. Heavy metals can interfere with cell communication pathways, leading to uncontrolled cell growth, a hallmark of cancer. Prolonged heavy metal exposure can weaken the immune system's ability to identify and eliminate abnormal cells. The CR over a lifetime of HM exposure was calculated following the formula reported by Jianing Gao in 2021 [10].

A formula to estimate the cancer risk for carcinogenic heavy metals (such as arsenic, cadmium, and some types of mercury), needs a cancer slope factor (CSF).

$$CR = EDI \times CSF \tag{9}$$

The CSF values for Cd, Pb, Cr, and As are 5×10^{-5}, 8.5×10^{-3}, 41, and 1.5 mg/kg/day, respectively. CR values between 10^{-6} to 10^{-4} are considered to be in the safe zone and values above 10^{-4} may pose significant health effects [33].

2.5. Statistical analysis

The experiments were performed using six replications and data presented in mean ± SD. The statistical analysis for the samples was analysed using analysis of variance (ANOVA) (SPSS, 2002). The Duncan multiple range test was used to separate the means and accepted at the 95 % level of significance.

3. Results and discussion

3.1. Heavy metal estimation

Table 1 represents the concentrations of five heavy metals namely Arsenic (As), Cadmium (Cd), Chromium (Cr), Mercury (Hg), and Lead (Pb) present in the liver, gills, and muscle tissues of three fish species: *Nemipterus japonicus, Oreochromis mossambicus,* and *Lates calcarifer* collected from Kanyakumari, TN (India).

Arsenic is considered as one of the potent carcinogenic agent and known for its chronic toxicity [39–41]. Occurrence or bioaccumulation of such HM in fish or any other food sources can be a threat to the population frequently consuming these contaminated food [42–45]. In current study the Arsenic levels were measured across various organs of *Nemipterus japonicus*, *Oreochromis mossambicus*, and *Lates calcarifer*. In *Nemipterus japonicus*, The As concentrations were found to be in the range of 0.05 ± 0.01–0.94 ± 0.09 μg/kg. *Nemipterus japonicus* showed relatively low levels of arsenic in the liver and gills. However, significantly higher concentrations in the muscle tissue were observed. In case of *Oreochromis mossambicus*, Arsenic concentrations were slightly higher, ranging from 0.10 ± 0.06–1.13 ± 0.02 μg/kg, indicating a notable accumulation (particularly in the gills and muscles). The arsenic contents were quite high in *Lates calcarifer* as well and observed in the range of 0.08 ± 0.02–1.06 ± 0.02 μg/kg. Overall, arsenic accumulation was found highest in the muscle tissues across all species, with *Oreochromis mossambicus* showing the greatest overall concentrations. Similar results were reported in previous research conducted on the fish samples collected from Subarnarekha River (India) in 2014, exhibited

Table 1
Heavy metal concentration in various organs (Liver, Gills, and Muscle) of Nemipterus japonicus, Oreochromis mossambicus and Lates calcarifer collected from Kanyakumari, TN (in μg kg^{-1}) (Values represented in mean ± standard deviation; n=6).

Fish	Organs	As	Cd	Cr	Hg	Pb
Nemipterus japonicus	**Liver**	0.07 ± 0.02^{a}	0.89 ± 0.60^{a}	16.78 ± 5.10^{a}	1.62 ± 1.43^{a}	44.81 ± 3.70^{a}
	Gills	0.05 ± 0.01^{a}	1.45 ± 0.05^{b}	11.92 ± 0.9^{a}	0.35 ± 0.06^{b}	37.09 ± 3.03^{a}
	Muscle	0.94 ± 0.09^{b}	1.09 ± 0.04^{a}	28.58 ± 1.38^{b}	0.36 ± 0.06^{b}	170.48 ± 5.3^{c}
Oreochromis mossambicus	**Liver**	0.10 ± 0.06^{a}	1.06 ± 0.07^{c}	9.95 ± 1.14^{a}	0.15 ± 0.01^{c}	24.69 ± 1.83^{b}
	Gills	0.79 ± 0.52^{b}	1.08 ± 0.12^{c}	30.55 ± 1.35^{b}	0.20 ± 0.01^{c}	187.72 ± 2.46^{d}
	Muscle	1.13 ± 0.02^{c}	1.19 ± 0.03^{d}	32.12 ± 0.87^{c}	0.25 ± 0.02^{c}	189.50 ± 3.39^{d}
Lates calcarifer	**Liver**	0.08 ± 0.02^{a}	1.11 ± 0.03^{c}	10.08 ± 0.33^{a}	0.14 ± 0.02^{c}	26.20 ± 1.01^{b}
	Gills	0.12 ± 0.10^{a}	1.04 ± 0.03^{c}	10.09 ± 1.42^{a}	0.18 ± 0.01^{c}	26.06 ± 5.3^{b}
	Muscle	1.06 ± 0.02^{c}	1.14 ± 0.01^{c}	30.66 ± 0.46^{b}	0.27 ± 0.01^{d}	180.26 ± 3.5^{c}

notably high arsenic (As) concentrations, while cadmium (Cd) and lead (Pb) displayed a varied levels across all species of fish selected [46]. Similar study in 2021 at the Gulf of Guinea also reported As levels at 8.46 ± 2.42 μg/g in *Penaeus notialis* [47].

Cadmium which has various reported adverse effect on human and other animals is associated majorly to the reproductive dysfunction and developmental disorders [45,48–51]. Cd was quantified in the organs of all three fish species and found to be present in varying concentrations. In *Nemipterus japonicus*, cadmium levels ranged from 0.89 ± 0.60–1.09 ± 0.04 μg/kg. The gills showed the highest cadmium concentration in these species (1.45 ± 0.05 μg/kg). *Oreochromis mossambicus* showed cadmium levels ranging from 1.06 ± 0.07–1.19 ± 0.03 μg/kg, with relatively consistent distribution across different organs. In *Lates calcarifer*, cadmium concentrations were in the range of 1.11 ± 0.03–1.14 ± 0.01 μg/kg. The cadmium levels in *Lates calcarifer* were almost uniformly distributed, showing no significant tissue-specific accumulation. Similar results for the Cadmium contamination were reported by Lakshmanasenthil S (2013), who reported higher levels of Cadmium in *O. mossambicus* from the Bay of Bengal at 26.25 ± 0.06 μg/g [52].

Chromium has well documented reports and long history for causing various toxicities in human and found to be involved in the carbohydrate, protein, fat and various other nutrient metabolism process causing toxic metabolite formation. It is also said to be associated with various blood related diseases such as anemia, lymphocytosis, eosinophilia etc [43,44,53–62]. In current study the concentrations of Cr varied significantly among the different fish species and tissues. In *Nemipterus japonicus*, the chromium levels were in the range of 16.78 ± 5.10–28.58 ± 1.38 μg/kg, with the highest accumulation in the muscle tissue. *Oreochromis mossambicus* exhibited chromium levels of 9.95 ± 1.14 μg/kg to 32.12 ± 0.87 μg/kg, indicating a substantial accumulation in the gills (30.55 ± 1.35 μg/kg) and muscles (32.12 ± 0.87 μg/kg). In *Lates calcarifer*, chromium concentrations were found in range of 10.08 ± 0.33–30.66 ± 0.46 μg/kg. The muscle tissues in all species consistently showed the highest chromium levels, with *Oreochromis mossambicus* having the greatest overall chromium concentration.

Mercury, one of the common environmental contaminants reported to cause various adverse effects in human including nervous system dysfunction and developmental disorder [63]. In our study Hg levels were also measured across the organs of fish species. In *Nemipterus japonicus*, mercury concentrations were in the range of 0.35 ± 0.06–1.62 ± 1.43 μg/g, with the liver showing the highest accumulation (1.62 ± 1.43 μg/kg). *Oreochromis mossambicus* had mercury levels of 0.15 ± 0.01–0.25 ± 0.02 μg/kg, with highest concentration in the muscles. The Hg levels were observed to be relatively low and uniform distributed across tissues. *Lates calcarifer* showed mercury concentrations of 0.14 ± 0.02–0.27 ± 0.01 μg/kg. Among the three species, *Nemipterus japonicus* had the highest mercury levels, particularly in the liver, while *Oreochromis mossambicus* and *Lates calcarifer* exhibited lower and more consistent mercury distribution. A similar study conducted in 2021 at the Gulf of Guinea by Botwe B, reported contamination of Hg in *D. angolensis* (0.14 ± 0.03 μg/g) [47]. However, the concentration of Hg present in the samples were lower than the concentrations observed in our study, indicating the relative need of continuous research around the Indian coastal area with respect to the heavy metal contamination.

Lead which is associate to hepatotoxicity, developmental retardation and, adverse behavioural changes was evaluate for contamination levels in the current research. High concentrations level across all organs of considered species was observed (Figs. 4,5, and 6). In *Nemipterus japonicus*, lead concentration levels were in the range of 37.09 ± 3.03–170.48 ± 5.3 μg/kg, with the highest accumulation observed in the muscle tissue. *Oreochromis mossambicus* showed lead concentrations of 24.69 ± 1.83–189.50 ± 3.39 μg/kg, indicating significant accumulation in the gills as well as in muscles. In *Lates calcarifer*, lead levels were in the range of 26.06 ± 5.3–180.26 ± 3.5 μg/g. The muscle tissues consistently exhibited the highest lead concentrations across all three considered species, with *Oreochromis mossambicus* showing the greatest overall lead accumulation. The results obtained were found in concordance with the study conducted at Ennore Creek (Tamil Nadu, India) in 2013 by Kumar C, the lead contamination level was found to be significantly higher which aligns with our findings. The study revealed the concentration of lead in *Penaeus monodon, Perna viridis, Crossostrea madrasensis, Mugil cephalus, Terapon jarbua,* and *M. cephalus* was 4.37 ± 0.33, 3.42 ± 0.29, 4.00 ± 0.29, 2.59 ± 0.31, and 3.42 ± 0.29 μg/g respectively [64]. The lead contamination level obtained in current study are significantly higher than the previous reports exhibiting the increased levels of alarming concern related to lead contamination in aquatic resources.

From the observed data we can conclude that out of three selected species *Oreochromis mossambicus* accumulated a significant amount of HMs (especially As, Cr, and Pb) as compared to *Nemipterus japonicus* and *Lates calcarifer* (Figs. 4–7). Also, our study suggests varied concentration of HM across organs and a significantly higher accumulation in the muscle tissues. There can be various factors that can affect the accumulation process of such contaminants [65–68]. Muscles are less exposed to the detoxification process of the body as compared to liver and gills as liver and gills are more actively involved in the metabolism processes. Over the period accumulation may show an elevation in muscle tissue for this reason [68]. Various fish muscle composition may vary in terms of lipid content or binding site location etc. A higher lipid content is associated to higher binding efficiency of HMs in such tissues [69]. The rate of detoxification or excretion of such contaminants from body also varies with the species (individually) and between the species as well. This bioprocess has impact on the bioaccumulation level as well. Although the accumulation may vary in organs as per previous reported studies, still various studies are in alignment of our findings [70–74].

3.2. Risk assessment

The risk assessment was done for As, Cd, Cr, Hg, and Pb in selected fish species. Estimation of various parameters such as estimated daily intake (EDI in μg/kg/day), estimated weekly intake (EWI in mg/kg/

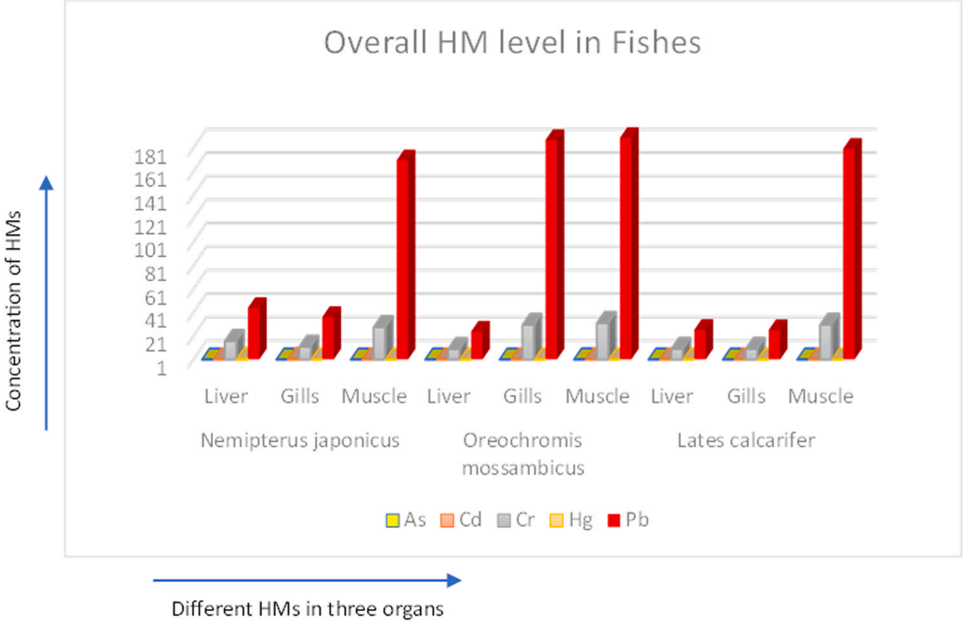

Fig. 4. - Chart representing overall HMs level (μg kg^{-1}) in various organs of collected fishes.

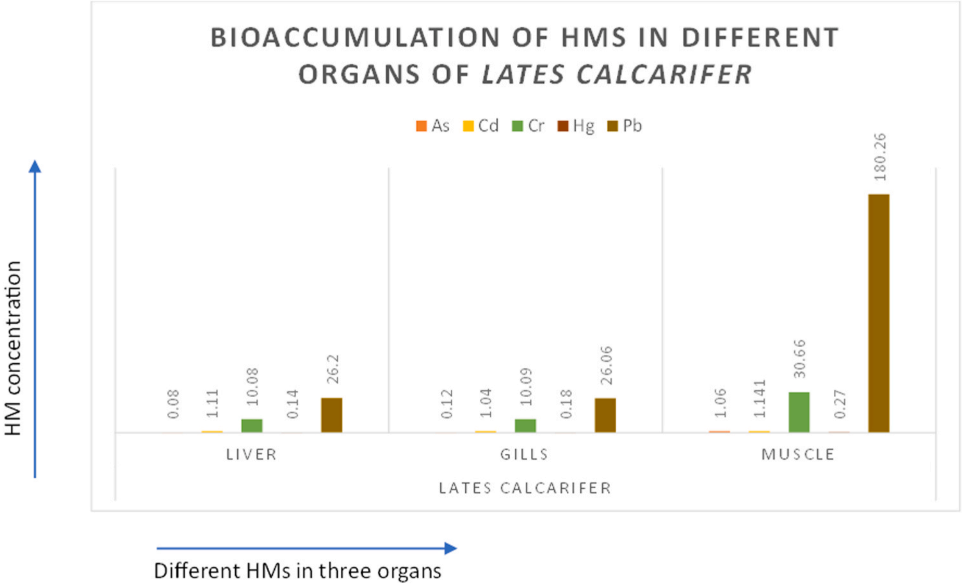

Fig. 5. - Level of HMs in various organs of Lates calcarifer (in μg kg^{-1}).

day), maximum daily intake (MDI in μg/day), maximum weekly intake (μg/week), percentage of provisional tolerable weekly intake (%PTWI), daily intake limit (DIL), maximum acceptable daily intake (Kg/day), target hazard quotient (THQ), hazard index (HI) and cancer risk was performed (Tables 2-4). The given safety levels for the heavy metals concerning the maximum daily intake (MDI) of As, Cd, Hg, and Pb are limited to 42.86, 20, 71.4, and 11.4 μg/day for children and 150, 70, 249.9, and 39.9 for the adults respectively [36]. The Provisional Tolerable Weekly Intake (PTWI) for Arsenic (inorganic), Cd, Pb, and Hg are 15, 7, 25, and 4 μg/kg body weight per week respectively [36].

In the case of *Nemipterus japonicus,* the EDI was calculated for children and adults considering the following HMs: As, Cd, Cr, Hg, and Pb. For children, it was found to be 0.0035, 0.004, 0.107, 0.001, and 0.0639 μg/kg/day respectively whereas for adults, it was 0.002, 0.0023, 0.061, 0.0007, and 0.36 μg/kg/day respectively. Similarly, in the case of *Oreochromis mossambicus*, the recorded EDI for children was 0.0042, 0.0044, 0.12, 0.0009, and 0.71 μg/kg/day and for adults, it was recorded as 0.0024, 0.0025, 0.068, 0.00053, and 0.406 μg/kg/day respectively. In the case of *Lates calcarifer,* the EDI for children were 0.0039, 0.0041, 0.11, 0.0001, and 0.67 μg/kg/day and for adults, it was recorded as 0.0022, 0.0023, 0.065, 0.0005, and 0.386 μg/kg/day. For *Nemipterus japonicus*, children had higher EDI values compared to adults, particularly for Cr and Pb. Similarly, *Oreochromis mossambicus* and *Lates calcarifer* showed higher EDI values for children, with notable figures for Cr and Pb.

In the case of *Nemipterus japonicus,* the EWI was calculated for children and adults considering the following HMs As, Cd, Cr, Hg, and Pb. The MDI values reflect the maximum quantity of each heavy metal that can be ingested daily without causing adverse health effects. For children, it was found to be 0.0245, 0.028, 0.749, 0.007, and 4.473 μg/kg/day respectively. For adults, it was found to be 0.014, 0.0161, 0.427, 0.00539, and 2.52 μg/kg/day respectively. Similarly, in the case of

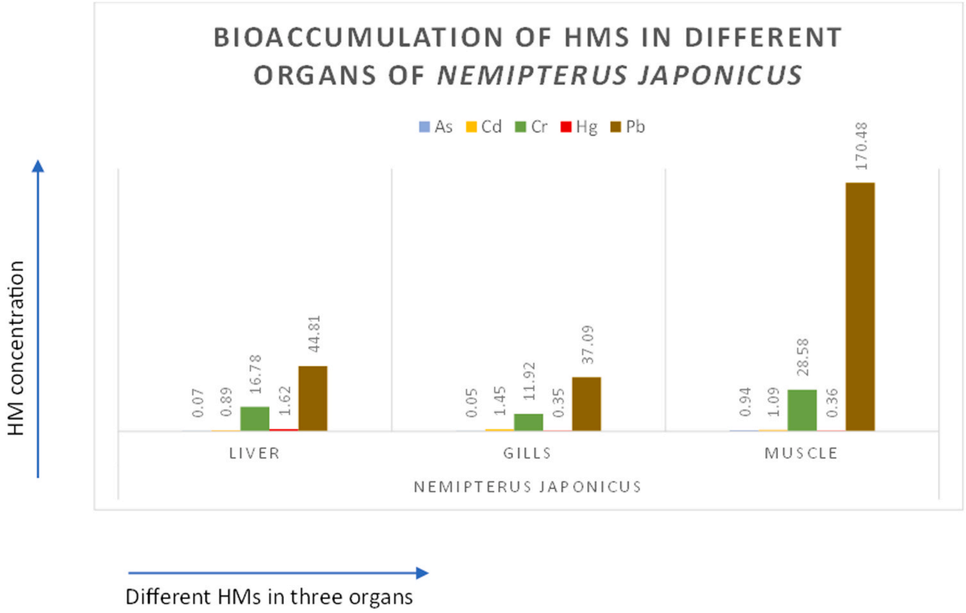

Fig. 6. - Level of HMs in various organs of Nemipterus japonicus (in μg kg^{-1}).

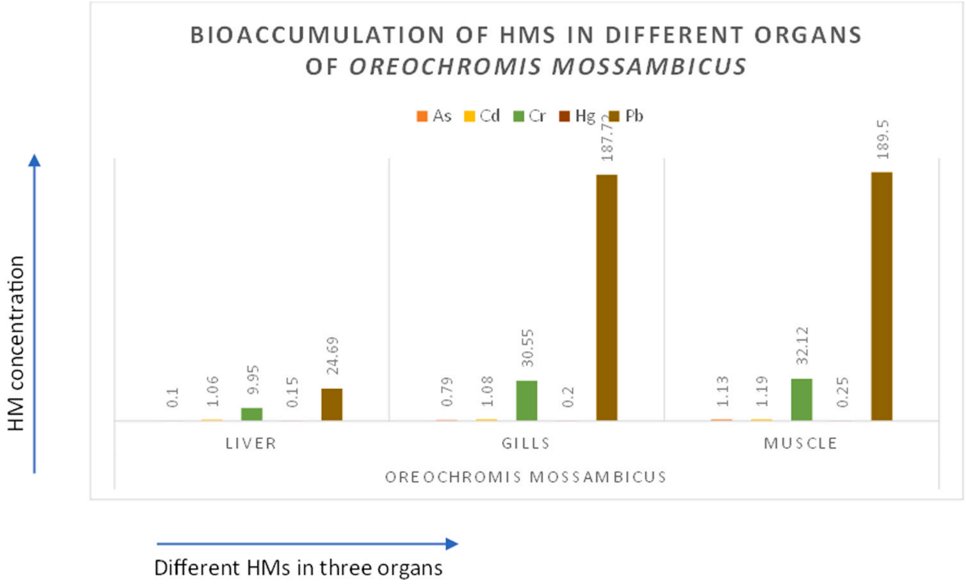

Fig. 7. - Level of HMs in various organs of Oriochromis mossambicus (in μg kg^{-1}).

Oreochromis mossambicus, the recorded EWI for children was 0.0294, 0.0308, 0.84, 0.0063, and 4.97 μg/kg/day respectively. For adults, it was recorded as 0.0168, 0.0175, 0.476, 0.00371, and 2.842 μg/kg/day respectively. In the case of *Lates calcarifer,* the EWI for children was 0.0273, 0.0287, 0.77, 0.0007, and 4.69 μg/kg/day respectively. For adults, it was recorded as 0.0154 0.0161 0.455 0.0035, and 2.702 μg/kg/day respectively. Here we found out that children generally had higher EDI and EWI values, indicating a higher risk of exposure compared to adults. This finding is in favor of various studies conducted so far [75,76]. The reason can possibly be the weight which is less in the case of children than adults. Since EDI and EWI are often calculated per unit of body weight, the same exposure level results in a higher intake with respect to body weight in children. In addition, Children are often more sensitive to contaminants due to their developing organs and immune systems [77]. This is critical as children are more susceptible to the toxic effects of HMs due to their developing bodies and higher consumption rates relative to their body weight. Also, as per our study, the EWI values for children in some of the cases approached or exceeded the PTWI, particularly for Pb, indicating a significant possible health risk.

CRlim/Maximum acceptable Daily Intake (kg/day) was estimated for As, Cd, Cr, Hg, and Pb considering children and adults. The CRlim value for children in case of *Nemipterus japonicus* was found to be 6.38, 18.35, 2.1, 5.56, and 0.41 respectively. For adults, it was found to be 22.34, 64.22, 7.35, 19.44, and 1.44 respectively. Similarly, in the case of *Oreochromis mossambicus*, the recorded CRlim for children was 7.59, 18.52, 1.96, 10, and 0.37. For adults it was recorded as 26.58, 64.81, 6.87, 35, and 1.31 respectively. In the case of *Lates calcarifer,* the Crlim for children were 5.66, 17.51, 1.96, 3.7, and 1.09 respectively. For adults, it is 21.13, 61.39, 2.78, 25.93, and 5.45 respectively.

The target hazard quotient (THQ) values were presented for both children and adults (Table 4). The Target Hazard Quotient (THQ) is a

Table 2
EDI, EWI, DIL and CRlim data (RfD of As, Cd, Cr(III), Cr(VI), Hg, and Pb are 0.0003, 0.001, 1.5, 0.003, 0.0001, 0.0003, and 0.0035 respectively in mg/kg/day) [36,37].

Fish Species	HMs	Estimated Daily Intake (EDI) in µg/kg/day		Estimated Weekly Intake (EWI) in µg/kg/day		Daily Intake Limit for fish in Kg per day [29]		CRlim/Maximum acceptable Daily Intake (kg/day)	
		Children	Adult	Children	Adult	Children	Adult	Children	Adult
Nemipterus japonicus	**As**	0.0035	0.002	0.0245	0.014	6.38	21.34	6.38	22.34
	Cd	0.004	0.0023	0.028	0.0161	18.35	64.22	18.35	64.22
	Cr	0.107	0.061	0.749	0.427	2.1 [Cr (VI)]	7.35 [Cr (VI)]	2.1	7.35
	Hg	0.001	0.00077	0.007	0.00539	5.56	19.44	5.56	19.44
	Pb	0.639	0.36	4.473	2.52	0.035	0.123	0.41	1.44
Oreochromis mossambicus	**As**	0.0042	0.0024	0.0294	0.0168	5.31	18.58	7.59	26.58
	Cd	0.0044	0.0025	0.0308	0.0175	16.81	58.82	18.52	64.81
	Cr	0.12	0.068	0.84	0.476	1.87	6.54	1.96	6.87
	Hg	0.0009	0.00053	0.0063	0.00371	8	28	10	35
	Pb	0.71	0.406	4.97	2.842	0.032	0.111	0.37	1.31
Lates calcarifer	**As**	0.0039	0.0022	0.0273	0.0154	5.66	19.81	5.66	21.13
	Cd	0.0041	0.0023	0.0287	0.0161	17.53	61.34	17.51	61.39
	Cr	0.11	0.065	0.77	0.455	1.96	6.85	1.96	2.78
	Hg	0.0001	0.0005	0.0007	0.0035	7.41	25.93	3.7	25.93
	Pb	0.67	0.386	4.69	2.702	0.116	0.033	1.09	5.45

Table 3
MDI, MWI and PTWI [PTWI for Arsenic (inorganic), Cd, Pb, Hg are 15, 7, 25, 4 µg/kg body weight per week] [36].

HMs	Maximum Daily Intake (in µg/day)		Maximum Weekly Intake (µg/week)		Percentage of Provisional Tolerable Weekly Intake (PTW)	
	Children	Adult	Children	Adult	Children	Adult
As	42.86	150	300	1050	100	100
Cd	20	70	140	490	20	70
Cr	-	-	-	-	-	-
Hg	71.4	249.9	500	1750	20	70
Pb	11.4	39.9	80	280	20	70

risk assessment parameter used to evaluate the potential health risk associated with long-term exposure to a chemical contaminant through dietary intake. A THQ value below 1 indicates that the exposure level is unlikely to cause adverse health effects, while a THQ above 1 suggests potential health risks [43,53,55,57,78]. For *Nemipterus japonicus*, children's THQ for As, Cd, Cr, Hg, and Pb were 0.011, 0.0056, 0.0071, 0.0135, and 0.182 respectively. Adult's THQ was found to be 0.006, 0.003, 0.000041, 0.0077, and 0.104 respectively. Similarly, for *Oreochromis mossambicus* children's THQ for As, Cd, Cr, Hg, and Pb were 0.0112, 0.0043, 0.0081, 0.0093, and 2.0148 respectively. Adult's THQ were 0.0064, 0.0025, 0.0046, 0.0054, and 1.1534 respectively. for *Lates calcarifer* children's THQ for As, Cd, Cr, Hg, and Pb were 0.00132, 0.000405, 0.000783, 0.0101, and 0.0192 respectively. Adult's THQ were 0.0007, 0.0002, 0.000435, 0.0058, and 0.0109 respectively.

For *Nemipterus japonicus*, THQ values for both children and adults concerning all contaminants fall below the threshold of 1, indicating that the likelihood of significant health risks from these contaminants due to the consumption of this fish is minimal [47,57]. On the other hand, it was observed that the THQ values for lead (Pb) were noticeably higher when compared to other contaminants, with children showing a value of 0.182 and adults 0.104. Even though these values remain below the threshold, they do point towards a relatively higher risk of exposure to Pb, especially among children. In the case of *Oreochromis mossambicus*, the THQ values related to lead (Pb) were notably higher than 1 for both children (2.0148) and adults (1.1534), signifying a potential health hazard associated with the consumption of this fish due to lead exposure. Conversely, the THQ values for other pollutants such as As, Cd, Cr, and Hg are under 1, pointing to reduced hazards from these particular substances. Nevertheless, the elevated Pb values raised concerns and imply that the consumption of this fish should be subjected to careful monitoring, particularly considering the obtained values for children. Moving on to *Lates calcarifer*, the THQ values for all contaminants in both children and adults were significantly lower than 1, suggesting that the consumption of this fish poses minimal health risks from the contaminants under examination. Furthermore, the THQ values for *Lates calcarifer* were the most modest among the three fish species, highlighting it as a comparatively safer choice in terms of exposure to chemical contaminants.

The significantly higher THQ values for Pb in *Oreochromis mossambicus* surpassed the safety threshold, indicating a pressing need for

Table 4
Calculated values of THQ, HI, and CR ('-' represents Not determined).

Fish Species	HMs	Target Hazard Quotient (THQ)		Hazard Index		Cancer Risk	
		Children	Adult	Children	Adult	Children	Adult
Nemipterus japonicus	As	0.011	0.006	0.21281	0.120741	5.288×10^{-7}	3.021×10^{-7}
	Cd	0.0056	0.003			2.044×10^{-11}	1.168×10^{-11}
	Cr	0.00071	0.000041			4.395×10^{-4}	2.513×10^{-4}
	Hg	0.0135	0.0077			-	-
	Pb	0.182	0.104			5.443×10^{-8}	3.103×10^{-8}
Oreochromis mossambicus	As	0.0112	0.0064	2.0477	1.1723	6.356×10^{-3}	3.642×10^{-3}
	Cd	0.0043	0.0025			2.231×10^{-7}	1.278×10^{-7}
	Cr	0.0081	0.0046			4.93	2.816
	Hg	0.0093	0.0054			-	-
	Pb	2.0148	1.1534			7.968×10^{-6}	4.553×10^{-6}
Lates calcarifer	As	0.00132	0.0007	0.031808	0.018085	5.962×10^{-3}	3.407×10^{-3}
	Cd	0.000405	0.0002			2.139×10^{-7}	1.220×10^{-7}
	Cr	0.000783	0.000435			4.757	2.697
	Hg	0.0101	0.0058			-	-
	Pb	0.0192	0.01095			8.606×10^{-6}	4.915×10^{-6}

monitoring and potentially restricting the consumption of this fish, especially among vulnerable demographics like children. The escalated Pb levels could potentially stem from sources of environmental pollution that require thorough investigation and effective mitigation strategies. In the case of *Nemipterus japonicus*, although the Pb values were elevated, they still fall below the established threshold, suggesting a moderate level of risk. Conversely, *Lates calcarifer* exhibits minimal exposure risk to Pb. It is worth noting that children generally display higher THQ values compared to adults across all fish species and contaminants. This discrepancy can be attributed to the lower body weight of children and their elevated consumption rates relative to their body size, rendering them more susceptible to exposure to contaminants.

The Hazard Index (HI) aggregates the THQ values of multiple contaminants to provide an overall risk assessment (Table 4). It was estimated considering all three species and was found to be 0.2128, 2.0477, and 0.0318 in *Nemipterus japonicus, Oreochromis mossambicus,* and *Lates calcarifer respectively* for children. Similarly, for adults, it was found to be 0.1207, 1.1723, and 0.01808 respectively. The HI values above 1 indicates a significant combined risk from multiple contaminants [36].

The Health Index (HI) values pertaining to *Nemipterus japonicus* indicated levels that are considerably below 1 for both juveniles and adults, pointing towards a low overall risk arising from the presence of various contaminants within this specific species. As a result, the likelihood of encountering significant health hazards related to the analyzed contaminants through the consumption of this fish appears to be minimal [35]. On the contrary, when examining the HI values associated with *Oreochromis mossambicus*, it becomes evident that they were significantly higher and surpassed 1 for individuals of all age groups. This observation highlights a notable combined risk stemming from a variety of contaminants, with a particular emphasis on the increased risks posed to children [35]. The escalated HI values highlighted the fact that the act of consuming such fish carries substantial health risks, primarily attributed to the heightened Target Hazard Quotient (THQ) values pertaining to lead (Pb) [79–81]. To address these concerns, it is imperative to implement public health measures such as consumption advisories and the implementation of strategies aimed at controlling and reducing the sources of contamination. *Lates calcarifer*, in contrast, exhibits HI values that are markedly below 1 for both children and adults, indicating a minimal collective risk originating from the presence of multiple contaminants. This species of fish emerges as the safest option among the trio under scrutiny, based on the assessment of the contaminants analyzed, thereby presenting negligible health risks. The species *Oreochromis mossambicus* stands out due to its elevated combined risk, particularly concerning the well-being of children [80,81]. The HI values associated with this species surpass the established safety threshold, primarily due to amplified levels of lead. Consequently, there arises a pressing necessity for the implementation of regulatory measures aimed at managing the sources of contamination and restricting the consumption of this particular species.

Cancer risk assessment evaluates the probability of an individual developing cancer over a lifetime due to the exposure against carcinogenic contaminants [10]. The risk is generally expressed in terms of probability, where a risk value of 1×10^{-6} implies an one in a million chance of developing cancer due to the exposure [10]. A cancer risk assessment was done considering the three selected species. In *Nemipterus japonicus,* the cancer risk due to As, Cd, Cr, and Pb was found to be 3.021×10^{-7}, 1.168×10^{-11}, 2.513×10^{-4}, and 3.103×10^{-8} for adults. For children, the values were 5.288×10^{-7}, 2.044×10^{-11}, 4.395×10^{-4}, and 5.443×10^{-8} respectively. Similarly, in the case of *Oreochromis mossambicus* it was found to be 3.642×10^{-3}, 1.278×10^{-7}, 2.816×10^{0}, and 4.553×10^{-6} respectively for adults. For children, the values were found to be 6.356×10^{-3}, 2.231×10^{-7}, 4.93, and 7.968×10^{-6} respectively. In case of *Lates calcarifer* it was found to be 3.407×10^{-3}, 1.220×10^{-7}, 2.697, and 4.915×10^{-6} respectively for adults. For children, the values were found to be 5.962×10^{-3}, 2.139×10^{-7}, 4.757, and 8.606×10^{-6} respectively. For *Nemipterus japonicus*, chromium (Cr) showed the highest cancer risk for both adults and children. These values were significantly higher than those for arsenic (As), cadmium (Cd), and lead (Pb), indicating that Cr is the primary concern for carcinogenic risk in this species. However, even the highest values for Cr are still below the threshold of 1×10^{-3}, suggesting a relatively low cancer risk from this species. In *Oreochromis mossambicus*, the cancer risk values for chromium (Cr) were extremely high, particularly for children, indicating a severe risk. The risk from arsenic (As) is also notably high for adults and for children, as the values were exceeding the threshold of 1×10^{-3} and suggesting a significant concern. The values for cadmium (Cd) and lead (Pb) were lower but still contribute to the overall cancer risk, especially given the high values for Cr and As.

Constant surveillance or monitoring of pollutants (including heavy metals, microplastics, pesticides, industrial waste, anthropogenic sources, domestic pollutants, etc.) is imperative considering the numerous significant issues associated with them. Analyzing reviews, spanning a decade of published research and reports indicates that heavy metal contamination not only possesses substantial magnitude but also has evolved into a critical concern involving human activities [82,83]. The noteworthy fluctuations in heavy metal levels across seasons and over time underscore the necessity for regular scientific assessments of heavy metal contamination in marine species to uphold continuous monitoring of aquatic health and food security [83]. Additionally, having access to up-to-date information can facilitate the formulation of efficient solutions while fostering research and development aimed at ameliorating the deteriorating environmental conditions. Furthermore, updated data can enhance the precision of future studies and support various entities (both governmental and non-governmental organizations) in establishing guidelines or safety protocols that prioritize public health considerations. Addressing the persistence of toxicity emerges as a crucial focal point. Several pollutants exhibit non-biodegradable characteristics or degrade at an exceedingly slow pace, resulting in the accumulation of significant pollutant quantities in specific geographical regions. Such scenarios may lead to uncontrolled toxicity seeping into the ecosystem, potentially infiltrating the food chain and adversely impacting various organisms, including human health [84].

4. Conclusion

The current study efficiently analyzed the HMs bioaccumulated in *Nemipterus japonicus, Oreochromis mossambicus,* and *Lates calcarifer* considering various organs. Overall, the muscle was found to accumulate relatively higher levels of HMs, particularly Pb and Cr. HMs (As, Cd, Cr, Hg, and Pb) were found to be in varied concentrations ranging from 0.1 to 1.13, 0.89–1.45, 9.95–30.66, 0.14–1.62, and 24.69–189.5 μg/kg respectively in different organs of fish. Carcinogenic and noncarcinogenic risk assessment suggested notable levels of Pb and Cr in considered fish species, wherein the THQ values related to lead (Pb) were notably higher than 1 for both children (2.0148) and adults (1.1534), signifying a potential health hazard associated with the consumption of selected fish due to lead exposure. Conversely, the THQ values for other pollutants such as As, Cd, Cr, and Hg were under 1, pointing to a reduced hazard possibilities from these particular substances. The Hazard Index (HI) was above 1 for adults and children in case of *Oreochromis mossambicus* which is indicating a significantly higher risk associated with the consumption. In *Oreochromis mossambicus,* the cancer risk values for chromium (Cr) were extremely high, particularly for children, indicating a severe health risk. The risk values for Arsenic (As) were also notably high for adults and children, exceeding the threshold of 1×10^{-3} and suggesting a significant concern. The elevated cancer risk values for Pb and Cr across all species suggest a need for strict monitoring and development of rigorous regulation of these contaminants in fish to protect public health. Further, it can be stated that the *Oreochromis mossambicus* can only be consumed with caution due to its high cancer risk values for multiple contaminants and must be studied further as prior literature also suggested higher contamination levels in the same species in southern India. However, the risk assessment that has been conducted here considered the consumption frequency as 365 days and various other parameters such as body weight, ingestion rate etc., are subjective in nature. Considering these circumstances subjective, all the selected fish species in our study from Kanyakumari can be categorized as safe to consume in moderation when thorough cleaning and cooking method is followed.

CRediT authorship contribution statement

Suryapratap Ray: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rahul Vashishth:** Writing – review & editing, Visualization, Supervision, Resources, Formal analysis.

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.

Data availability

Data will be made available on request.

Acknowledgement

The authors are grateful to the Department of Science and Technology, New Delhi, India for providing financial support to acquire “Inductively Coupled Plasma Mass Spectrometry (ICP-MS)” through “Promotion of University Research and Scientific Excellence (PURSE)” under Grant No. SR/PURSE/2020/34 (TPN 56960) and carry out the work.” Further, we thank VIT Management, with special mention to Sponsored Research and Industrial Consultancy (SpoRIC) office, VIT for supporting the research through preliminary research grant (Seed Grant). The authors also wish to extend their heartfelt thanks to all their colleagues who put forward their expertise and to family members for their constant support.

References

[1] R.H. Piedrahita, Reducing the potential environmental impact of tank aquaculture effluents through intensification and recirculation, Aquaculture 226 (2003) 35–44, https://doi.org/10.1016/S0044-8486(03)00465-4.

[2] P. Edwards, Aquaculture environment interactions: Past, present and likely future trends, Aquaculture 447 (2015) 2–14, https://doi.org/10.1016/J.AQUACULTURE.2015.02.001.

[3] R.H. Piedrahita, Reducing the potential environmental impact of tank aquaculture effluents through intensification and recirculation, Aquaculture 226 (2003) 35–44, https://doi.org/10.1016/S0044-8486(03)00465-4.

[4] M. Javed, N. Usmani, An overview of the adverse effects of heavy metal contamination on fish health, Proc. Natl. Acad. Sci. India Sect. B - Biol. Sci. 89 (2019) 389–403, https://doi.org/10.1007/S40011-017-0875-7/METRICS.

[5] WHO. Guidelines for drinking-water quality, 4th edition, incorporating the 1st addendum. Geneva: World Health Organization. Geneva, Switzerland. World Health Organization 2017.

[6] Y.-J. Yi, S.-H. Zhang, Heavy metal (Cd, Cr, Cu, Hg, Pb, Zn) concentrations in seven fish species in relation to fish size and location along the Yangtze River, Environ. Sci. Pollut. Res. 19 (2012) 3989–3996, https://doi.org/10.1007/s11356-012-0840-1.

[7] J. Rahmani, Y. Fakhri, A. Shahsavani, Z. Bahmani, M.A. Urbina, S. Chirumbolo, et al., A systematic review and meta-analysis of metal concentrations in canned tuna fish in Iran and human health risk assessment, Food Chem. Toxicol. 118 (2018) 753–765, https://doi.org/10.1016/J.FCT.2018.06.023.

[8] G. Barone, A. Storelli, R. Garofalo, V.Pietro Busco, N.C. Quaglia, G. Centrone, et al., Assessment of mercury and cadmium via seafood consumption in Italy: estimated dietary intake (EWI) and target hazard quotient (THQ), Food Addit. Contam. Part A Chem. Anal. Control Expo. Risk Assess. 32 (2015) 1277–1286, https://doi.org/10.1080/19440049.2015.1055594.

[9] D.S. Malik, P.K. Maurya, Heavy metal concentration in water, sediment, and tissues of fish species (Heteropneustis fossilis and Puntius ticto) from Kali River, India, Toxicol. Environ. Chem. 96 (2014) 1195–1206, https://doi.org/10.1080/02772248.2015.1015296.

[10] J. Gao, D. Zhang, R. Proshad, E. Uwiringiyimana, Z. Wang, Assessment of the pollution levels of potential toxic elements in urban vegetable gardens in southwest China, Sci. Rep. 11 (1) (2021), https://doi.org/10.1038/s41598-021-02069-6, 2021;11:1–13.

[11] B. London, C. Albert, M.E. Anderson, W.R. Giles, D.R. Van Wagoner, E. Balk, et al., Omega-3 fatty acids and cardiac arrhythmias: prior studies and recommendations for future research, Circulation 116 (2007), https://doi.org/10.1161/CIRCULATIONAHA.107.712984.

[12] J. Griboff, D.A. Wunderlin, M.V. Monferran, Metals, As and Se determination by inductively coupled plasma-mass spectrometry (ICP-MS) in edible fish collected from three eutrophic reservoirs. Their consumption represents a risk for human health? Microchem. J. 130 (2017) 236–244, https://doi.org/10.1016/J.MICROC.2016.09.013.

[13] S.S. Habib, S. Naz, F. Fazio, C. Cravana, M. Ullah, K.H. Rind, et al., Assessment and Bioaccumulation of Heavy Metals in Water, Fish (wild and Farmed) and Associated Human Health Risk, Biol. Trace Elem. Res 202 (2024) 725–735, https://doi.org/10.1007/s12011-023-03703-2.

[14] A.A. Zorpas, J.N. Pedreño, M.B.A. Candel, Heavy metal treatment and removal using natural zeolites from sewage sludge, compost, and agricultural soils: a review, Arab. J. Geosci. 14 (2021) 1098, https://doi.org/10.1007/s12517-021-07443-2.

[15] Scientific, Opinion on lead in food, EFSA J. (2010) 8, https://doi.org/10.2903/J.EFSA.2010.1570.

[16] Kh.M. El-Moselhy, A.I. Othman, H. Abd El-Azem, M.E.A. El-Metwally, Bioaccumulation of heavy metals in some tissues of fish in the Red Sea, Egypt, Egypt. J. Basic Appl. Sci. 1 (2014) 97–105, https://doi.org/10.1016/j.ejbas.2014.06.001.

[17] S. Zhao, C. Feng, W. Quan, X. Chen, J. Niu, Z. Shen, Role of living environments in the accumulation characteristics of heavy metals in fishes and crabs in the Yangtze River Estuary, China, Mar. Pollut. Bull. 64 (2012) 1163–1171, https://doi.org/10.1016/j.marpolbul.2012.03.023.

[18] M.I. Castro-González, M. Méndez-Armenta, Heavy metals: Implications associated to fish consumption, Environ. Toxicol. Pharmacol. 26 (2008) 263–271, https://doi.org/10.1016/j.etap.2008.06.001.

[19] H. Ali, E. Khan, Trophic transfer, bioaccumulation, and biomagnification of non-essential hazardous heavy metals and metalloids in food chains/webs—Concepts and implications for wildlife and human health, Hum. Ecol. Risk Assess.: Int. J. 25 (2019) 1353–1376, https://doi.org/10.1080/10807039.2018.1469398.

[20] D.P. Häder, A.T. Banaszak, V.E. Villafañe, M.A. Narvarte, R.A. González, E. W. Helbling, Anthropogenic pollution of aquatic ecosystems: emerging problems with global implications, Sci. Total Environ. 713 (2020) 136586, https://doi.org/10.1016/J.SCITOTENV.2020.136586.

[21] M.S. Sankhla, M. Kumari, M. Nandan, R. Kumar, P. Agrawal, Heavy metals contamination in water and their hazardous effect on human health-a review, Int J. Curr. Microbiol Appl. Sci. 5 (2016) 759–766, https://doi.org/10.20546/ijcmas.2016.510.082.

[22] S. Tasleem, S. Masud, S.S. Habib, S. Naz, F. Fazio, M. Aslam, et al., Investigation of the incidence of heavy metals contamination in commonly used fertilizers applied to vegetables, fish ponds, and human health risk assessments, Environ. Sci. Pollut. Res. 30 (2023) 100646–100659, https://doi.org/10.1007/s11356-023-29480-y.

[23] L. Rainville, C.M. Lee, K. Arulananthan, S.U.P. Jinadasa, H.J.S. Fernando, W.N. C. Priyadarshani, et al., Water Mass Exchanges between the Bay of Bengal and Arabian Sea from Multiyear Sampling with Autonomous Gliders, J. Phys. Oceano 52 (2022) 2377–2396, https://doi.org/10.1175/JPO-D-21-0279.1.

[24] S.S. Shetye, M. Sudhakar, R. Mohan, B. Jena, Contrasting productivity and redox potential in Arabian Sea and Bay of Bengal, J. Earth Sci. 25 (2014) 366–370, https://doi.org/10.1007/S12583-014-0415-9/METRICS.

[25] S. Kay, J. Caesar, T. Janes, Marine dynamics and productivity in the Bay of Bengal, Ecosyst. Serv. Well-Being Delta.: Integr. Assess. Policy Anal. (2018) 263–275, https://doi.org/10.1007/978-3-319-71093-8_14/FIGURES/2.

[26] N. Vineesh, P. Divya, A. Kathirvelpandian, C. Mohitha, C. Shanis, V. Basheer, et al., Four evolutionarily significant units among narrow-barred Spanish mackerel (Scomberomorus commerson) in the Indo-West Pacific region, Mar. Biodivers. 48 (2018) 2025–2032, https://doi.org/10.1007/S12526-017-0714-3/METRICS.

[27] C.E. Delgado-Ramírez, Y. Ota, A.M. Cisneros-Montemayor, Fishing as a livelihood, a way of life, or just a job: considering the complexity of “fishing communities” in research and policy, Rev. Fish. Biol. Fish. 33 (2023) 265–280, https://doi.org/10.1007/S11160-022-09721-Y/METRICS.

[28] Handbook on Fisheries Statistics 2020 Department of Fisheries Ministry of Fisheries, Animal Husbandry & Dairying Government of India, New Delhi. 2020.

[29] Integrated Risk Information System | US EPA 2004. ⟨https://www.epa.gov/iris⟩ (Accessed 16 July 2024).

[30] Evaluation of certain contaminants in food: eighty-third report of the Joint FAO/WHO Expert Committee on Food Additives 2011. ⟨https://iris.who.int/handle/10665/254893⟩ (Accessed 16 July 2024).

[31] Guidelines for Carcinogen Risk Assessment | US EPA 1989. ⟨https://www.epa.gov/risk/guidelines-carcinogen-risk-assessment⟩ (Accessed 16 July 2024).

[32] Evaluation of certain food additives and contaminants: seventy-fourth [↱74th]↱ report of the Joint FAO/WHO Expert Committee on Food Additives 2011. ⟨https://iris.who.int/handle/10665/44788⟩ (Accessed 16 July 2024).

[33] US EPA NATIONAL CENTER FOR ENVIRONMENTAL ASSESSMENT WDIO. Exposure Factors Handbook 2011 Edition (Final Report) 2011.

[34] D.P. Naughton, A. Petróczi, Heavy metal ions in wines: Meta-analysis of target hazard quotients reveal health risks, Chem. Cent. J. 2 (2008) 1–7, https://doi.org/10.1186/1752-153X-2-22/COMMENTS.

[35] M. Javed, N. Usmani, Accumulation of heavy metals and human health risk assessment via the consumption of freshwater fish Mastacembelus armatus inhabiting, thermal power plant effluent loaded canal, Springerplus 5 (2016) 1–8, https://doi.org/10.1186/S40064-016-2471-3/TABLES/3.

[36] Evaluationof certain contaminants in food: eighty-third report of the Joint FAO/WHO Expert Committee on Food Additives n.d. 〈https://iris.who.int/handle/10665/254893〉(Accessed 15 July 2024).

[37] Final I. Risk Assessment Guidance for Superfund Volume I Human Health Evaluation Manual (Part A) SW-A-005613. 1989.

[38] Y. Wang, Z. Lin, H. Huang, H. He, L. Yang, T. Chen, et al., AMPK is required for PM2.5-induced autophagy in human lung epithelial A549 cells, Int J. Clin. Exp. Med 8 (2015) 58.

[39] P. Balakumar, J. Kaur, Arsenic exposure and cardiovascular disorders: an overview, Cardiovasc Toxicol. 9 (2009) 169–176, https://doi.org/10.1007/S12012-009-9050-6.

[40] M.K. Ahmed, M. Habibullah-Al-Mamun, E. Parvin, M.S. Akter, M.S. Khan, Arsenic induced toxicity and histopathological changes in gill and liver tissue of freshwater fish, tilapia (Oreochromis mossambicus), Exp. Toxicol. Pathol. 65 (2013) 903–909, https://doi.org/10.1016/j.etp.2013.01.003.

[41] Md.K. Ahmed, Md Habibullah-Al-Mamun, E. Parvin, M.S. Akter, M.S. Khan, Arsenic induced toxicity and histopathological changes in gill and liver tissue of freshwater fish, tilapia (Oreochromis mossambicus), Exp. Toxicol. Pathol. 65 (2013) 903–909, https://doi.org/10.1016/j.etp.2013.01.003.

[42] J.A. Kim, S.H. Lee, S.H. Choi, K.K. Jung, M.S. Park, J.Y. Jeong, et al., Heavy metal risk management: case analysis, Toxicol. Res. 28 (2012) 143–149, https://doi.org/10.5487/TR.2012.28.3.143/METRICS.

[43] J. Briffa, E. Sinagra, R. Blundell, Heavy metal pollution in the environment and their toxicological effects on humans, Heliyon 6 (2020) e04691, https://doi.org/10.1016/J.HELIYON.2020.E04691.

[44] M. Al osman, F. Yang, I.Y. Massey, Exposure routes and health effects of heavy metals on children, Biometals 32 (2019) 563–573, https://doi.org/10.1007/S10534-019-00193-5.

[45] S. Das, K.W. Sultana, A.R. Ndhlala, M. Mondal, I. Chandra, Heavy metal pollution in the environment and its impact on health: exploring green technology for remediation, Environ. Health Insights 17 (2023), https://doi.org/10.1177/11786302231201259.

[46] S. Giri, A.K. Singh, Assessment of human health risk for heavy metals in fish and shrimp collected from Subarnarekha river, India, Int. J. Environ. Health Res 24 (2014) 429–449, https://doi.org/10.1080/09603123.2013.857391.

[47] B.O. Botwe, Heavy metal concentrations in five fish species from the Gulf of Guinea and their human health implications, Reg. Stud. Mar. Sci. 44 (2021), https://doi.org/10.1016/j.rsma.2021.101763.

[48] M.R. Rahimzadeh, M.R. Rahimzadeh, S. Kazemi, A.A. Moghadamnia, Cadmium toxicity and treatment: an update, Casp. J. Intern Med 8 (2017) 135–145, https://doi.org/10.22088/cjim.8.3.135.

[49] S. MNH, M. BC, Z R. Heavy Metals (Lead, Cadmium and Nickel) concentration in different organs of three commonly consumed fishes in Bangladesh, Fish. Aquac. J. 08 (2017), https://doi.org/10.4172/2150-3508.1000207.

[50] G. Fatima, A.M. Raza, N. Hadi, N. Nigam, A.A. Mahdi, Cadmium in human diseases: it's more than just a mere metal, Indian J. Clin. Biochem 34 (2019) 371–378, https://doi.org/10.1007/S12291-019-00839-8.

[51] K.T. Eriksen, J. Halkjær, M. Sørensen, J.R. Meliker, J.A. McElroy, A. Tjønneland, et al., Dietary cadmium intake and risk of breast, endometrial and ovarian cancer in danish postmenopausal women: a prospective cohort study, PLoS One 9 (2014), https://doi.org/10.1371/JOURNAL.PONE.0100815.

[52] Lakshmanasenthil S., Vinothkumar T., Thankappan Ajithkumar T., Marudhupandi T., Kottila Veettil D., Ganeshamurthy R., et al. Harmful metals concentration in sediments and fishes of biologically important estuary, Bay of Bengal. 2013.

[53] Farid M., Bharwana S.A., Hannan F., Ahmad R. Effect of Different Heavy Metal Pollution on Fish. 2014.

[54] V. Kumar, R.D. Parihar, A. Sharma, P. Bakshi, G.P. Singh Sidhu, A.S. Bali, et al., Global evaluation of heavy metal content in surface water bodies: a meta-analysis using heavy metal pollution indices and multivariate statistical analyses, Chemosphere 236 (2019) 124364, https://doi.org/10.1016/j.chemosphere.2019.124364.

[55] M. Jaishankar, T. Tseten, N. Anbalagan, B.B. Mathew, K.N. Beeregowda, Toxicity, mechanism and health effects of some heavy metals, Interdisp. Toxicol. 7 (2014) 60, https://doi.org/10.2478/INTOX-2014-0009.

[56] H. Ali, E. Khan, I. Ilahi, Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation, J. Chem. 2019 (2019), https://doi.org/10.1155/2019/6730305.

[57] Garai P., Banerjee P., Mondal P., Mahavidyalaya N., Arambagh H. Effect of Heavy Metals on Fishes: Toxicity and Bioaccumulation. 2021.

[58] T. Bera, S.V. Kumar, M.S. Devi, V. Kumar, B.K. Behera, B.K. Das, Effect of heavy metals in fish reproduction: a review, J. Environ. Biol. 43 (2022) 631–642, https://doi.org/10.22438/jeb/43/5/MRN-4042.

[59] Morales D.V. Behavioral and Physiological Effects of Heavy Metals on Fish: A Review and Preliminary Results. 2022.

[60] K. Taslima, M. Al-Emran, M.S. Rahman, J. Hasan, Z. Ferdous, M.F. Rohani, et al., Impacts of heavy metals on early development, growth and reproduction of fish – a review, Toxicol. Rep. 9 (2022) 858–868, https://doi.org/10.1016/j.toxrep.2022.04.013.

[61] K.J. Elnabris, S.K. Muzyed, N.M. El-Ashgar, Heavy metal concentrations in some commercially important fishes and their contribution to heavy metals exposure in palestinian people of Gaza Strip (Palestine), J. Assoc. Arab Univ. Basic Appl. Sci. 13 (2013) 44–51, https://doi.org/10.1016/j.jaubas.2012.06.001.

[62] D. Witkowska, J. Słowik, K. Chilicka, Heavy metals and human health: possible exposure pathways and the competition for protein binding sites, molecules (2021), https://doi.org/10.3390/molecules26196060.

[63] A. Carocci, N. Rovito, M.S. Sinicropi, G. Genchi, Mercury toxicity and neurodegenerative effects, Rev. Environ. Contam. Toxicol. 229 (2014) 1–18, https://doi.org/10.1007/978-3-319-03777-6_1.

[64] C.S. Kumar, M. Jaikumar, R.S. Robin, P. Karthikeyan, 192-201the-journal-of-toxicology-and-health Original Research Article, ISJN: 2294–7439 J. Toxicol. Health Cit. vol. 103 (2013).

[65] M. Ture, M.B. Kilic, I. Altinok, Relationship between heavy metal accumulation in fish muscle and heavy metal resistance genes in bacteria isolated from fish, Biol. Trace Elem. Res 199 (2021) 1595–1603, https://doi.org/10.1007/S12011-020-02246-0/METRICS.

[66] Kh.M. El-Moselhy, A.I. Othman, H.A. El-Azem, M.E.A. El-Metwally, Bioaccumulation of heavy metals in some tissues of fish in the Red Sea, Egypt, Egypt. J. Basic Appl. Sci. 1 (2014) 97–105, https://doi.org/10.1016/J.EJBAS.2014.06.001.

[67] G.Y. Zaghloul, H.A. Eissa, A.Y. Zaghloul, M.S. Kelany, M.A. Hamed, K.M. E. Moselhy, Impact of some heavy metal accumulation in different organs on fish quality from Bardawil Lake and human health risks assessment, Geochem Trans. 25 (2024) 1–20, https://doi.org/10.1186/S12932-023-00084-2/FIGURES/11.

[68] G.M.M. Anwarul Hasan, M.A. Satter, A.K. Das, M. Asif, Detection of heavy metals in fish muscles of selected local fish varieties of the Shitalakshya River and probabilistic health risk assessment, Meas.: Food 8 (2022) 100065, https://doi.org/10.1016/J.MEAFOO.2022.100065.

[69] M. Balali-Mood, K. Naseri, Z. Tahergorabi, M.R. Khazdair, M. Sadeghi, Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic, Front. Pharm. 12 (2021) 643972, https://doi.org/10.3389/FPHAR.2021.643972/BIBTEX.

[70] Bhattacharya A.K., Mandal S.N., Das S.K. Heavy Metals Accumulation in Water, Sediment and Tissues of Different Edible Fishes in Upper Stretch of Gangetic West Bengal 2008. 〈https://scialert.net/abstract/?doi=tasr.2008.61.68〉.

[71] B. Jezierska, M. Witeska, The metal uptake and accumulation in fish living in polluted waters, Soil Water Pollut. Monit., Prot. Remediat. (2006) 107–114, https://doi.org/10.1007/978-1-4020-4728-2_6.

[72] S. Bakhshalizadeh, R. Mora-Medina, F. Fazio, V. Parrino, N. Ayala-Soldado, Determination of the Heavy Metal Bioaccumulation Patterns in Muscles of Two Species of Mullets from the Southern Caspian Sea, 2022;12:2819, Animals Vol 12 (2022) 2819, https://doi.org/10.3390/ANI12202819.

[73] S. Bakhshalizadeh, R. Mora-Medina, F. Fazio, V. Parrino, N. Ayala-Soldado, Determination of the heavy metal bioaccumulation patterns in muscles of two species of mullets from the Southern Caspian Sea, 2022;12:2819, Animals Vol 12 (2022) 2819, https://doi.org/10.3390/ANI12202819.

[74] N. Majed, M.K. Alam, M.I.H. Real, M.S. Khan, Accumulation of copper and zinc metals from water in anabus testudineus fish species in Bangladesh, Aquac. Stud. 19 (2019) 91–102, https://doi.org/10.4194/2618-6381-v19_2_02.

[75] P.O. Ukaogo, J. Tang, A.A. Ahuchaogu, O.U. Igwe, A.I. Obike, P.O. Emole, et al., Evaluation of concentrations of trace metal(loid)s in indigenous crab species and human health risk implications, Emerg. Contam. 8 (2022) 371–380, https://doi.org/10.1016/J.EMCON.2022.07.001.

[76] M.A. Noman, W. Feng, G. Zhu, Mb.B. Hossain, Y. Chen, H. Zhang, et al., Bioaccumulation and potential human health risks of metals in commercially important fishes and shellfishes from Hangzhou Bay, China, Sci. Rep. 12 (1) (2022), https://doi.org/10.1038/s41598-022-08471-y, 2022;12:1–15.

[77] M.J. Carroquino, M. Posada, P.J. Landrigan, Environmental toxicology: children at risk, Environ. Toxicol. (2013) 239, https://doi.org/10.1007/978-1-4614-5764-0_11.

[78] River K., Hashim R., Han Song T., Zuhartini Md Muslim N., Peck Yen T. Determination of Heavy Metal Levels in Fishes from the Lower Reach of the. vol. 25. 2014.

[79] N. Singh, A. Kumar, V.K. Gupta, B. Sharma, Biochemical and molecular bases of lead-induced toxicity in mammalian systems and possible mitigations, Chem. Res Toxicol. 31 (2018) 1009–1021, https://doi.org/10.1021/ACS.CHEMRESTOX.8B00193.

[80] T.I. Lidsky, J.S. Schneider, Lead neurotoxicity in children: basic mechanisms and clinical correlates, Brain 126 (2003) 5–19, https://doi.org/10.1093/BRAIN/AWG014.

[81] M. Boskabady, N. Marefati, T. Farkhondeh, F. Shakeri, A. Farshbaf, M. H. Boskabady, The effect of environmental lead exposure on human health and the contribution of inflammatory mechanisms, a review, Environ. Int. 120 (2018) 404–420, https://doi.org/10.1016/J.ENVINT.2018.08.013.

[82] J.F. Artiola, M.L. Brusseau, The Role of Environmental Monitoring in Pollution Science. Environmental and Pollution Science, Elsevier, 2019, pp. 149–162, 10.1016/B978-0-12-814719-1.00010-0.

[83] Md.S. Bhuyan, M.A. Bakar, Md Rashed-Un-Nabi, V. Senapathi, S.Y. Chung, Md. S. Islam, Monitoring and assessment of heavy metal contamination in surface water and sediment of the Old Brahmaputra River, Bangladesh, Appl. Water Sci. 9 (2019) 125, https://doi.org/10.1007/s13201-019-1004-y.

[84] S. Das, S.S. Choudhury, Analysis of heavy metals from water, sediment, and tissues of Labeo angra (Hamilton, 1822), from an Ox-box lake-an wetland site from Assam, India, J. Environ. Sci. Health A Tox Hazard Subst. Environ. Eng. 51 (2016) 21–33, https://doi.org/10.1080/10934529.2015.1079102.