water

MDPI

Article

A Preliminary Health Risk Assessment of Heavy Metal Contamination in Chembarambakkam Lake, Tamil Nadu, South India

Prabhu Kolandhasamy [1], Saranya Elumalai [2], Selvam Nandagopal [2], Subriya Senthil Kumaran [3], Rajaram Rajendran [1], Ramachandran Vinayagam [4,*] and Pasiyappazham Ramasamy [5,6,*]

1 Department of Marine Science, Bharathidasan University, Tiruchirappalli 620024, India; drprabhu.marine@gmail.com (P.K.); ajaramdms@bdu.ac.in (R.R.)
2 Department of Biotechnology, Vinayaka Missions Kirupananda Variyar Engineering College, Salem 636308, India; 19bte41@vmkvec.edu.in (S.E.); nandhu04061@gmail.com (S.N.)
3 Department of Food Technology, Mahendra Engineering College, Mallasamudram, Namakkal 637503, India; subriya45@gmail.com
4 Department of Biotechnology, College of Life and Applied Sciences, Yeungnam University, 280 Daehak-ro, Gyeongsan 38541, Gyeongsangbuk-do, Republic of Korea
5 Department of Prosthodontics and Implantology, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha Dental College & Hospitals, Saveetha University, Chennai 600077, India
6 Polymer Research Laboratory (PR Lab), Centre for Marine and Aquatic Research (CMAR), Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai 602105, India
* Correspondence: rambio85@gmail.com (R.V.); ramkanth281@gmail.com (P.R.)

Abstract: Chembarambakkam Lake, an important freshwater reservoir in Chennai that provides drinking water to the city, has noticed a decline in water quality as a result of heavy metal pollution. This study aimed to evaluate the heavy metal contamination in the environment of Chembarambakkam Lake with a health risk assessment. This study involved a comprehensive analysis of toxic heavy metal levels in five waters, sediments, and commercially available freshwater fish samples, considering their bioaccumulation and potential risks to human health. We observed lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) concentrations in water, sediments, and various fish species, including tilapia (*Mozambique Tilapia*), wild carp (*Hemiculter leucisulus*), pearl-spot (*Etroplus maculatus*), spotted barb (*Barbodes binotatus*), and snakehead murrel (*Channa Striate*). The results indicated that, in order of prominence, the metals in the water were Cu > Zn > Pb > Cd, whereas those found in sediments were Zn > Cu > Pb > Cd. The metal concentration in the sediments varied between Cd (0.52–0.82 µg/g), Cu (13.75–38.07 µg/g), Pb (1.30–3.74 µg/g), and Zn (12.60–61.12 µg/g). Similarly, the metal concentrations in the water varied between Cd (0.63–0.72 µg/L), Cu (5.35–55.17 µg/L), Pb (BDL–12.39 µg/L), and Zn (0.62–1.49 µg/L). The order of metals in the fish was Zn > Cd > Cu > Pb. The Cd concentration ranged from 0.3 to 0.60 µg/g, Cu was from BDL to 0.72 µg/g, Pb was from BDL–0.68 µg/g, and Zn was from 13.32–48.48 µg/g. The Cd and Zn concentrations were consistently the highest across the fish, sediment, and water samples. These findings shed light on the health risks associated with heavy metal pollution in Chembarambakkam Lake and suggest the need for potential bioremediation approaches.

Keywords: lake; heavy metal concentration; fish; sediment; water

check for updates

Citation: Kolandhasamy, P.; Elumalai, S.; Nandagopal, S.; Senthil Kumaran, S.; Rajendran, R.; Vinayagam, R.; Ramasamy, P. A Preliminary Health Risk Assessment of Heavy Metal Contamination in Chembarambakkam Lake, Tamil Nadu, South India. *Water* **2024**, *16*, 3517. https://doi.org/10.3390/w16233517

Academic Editor: Grzegorz Nałęcz-Jawecki

Received: 8 October 2024
Revised: 27 November 2024
Accepted: 29 November 2024
Published: 6 December 2024

1. Introduction

Water pollution is a key issue associated with the economic and industrial expansion of any country. Water possesses many qualities that are vital for life and the environment. It is the only naturally occurring inorganic liquid and the only chemical on earth that occurs naturally in all three phases of matter, including solid, liquid, and gas [1,2] (Cuihang et al., 2011 and Govindasamy et al., 2000). Many urban water sources in developing countries, particularly in megacities, are increasingly exposed to contaminants. Untreated sewage is dumped into urban water bodies due to non-existing or poorly enforced laws in several of these nations [3–5]. Under such conditions, heavy metal concentrations may increase in water, sediments, and living organisms due to bioconcentration and biomagnification, representing a significant hazard to human populations in the adjacent vicinity.

India has experienced a fast population increase, notable economic development, and strong industrialization, which is remarkable considering that around 75% of India's surface water supplies are contaminated by biological and chemical pollutants. This issue is particularly severe in developing nations, where increasing population and human activities restrict the availability of safe drinking water [6]. The great amount of pollutants released by urban activity in India has seriously contaminated surface water resources like rivers and lakes [7]. Heavy metal pollution is a phenomenon whereby too-high concentrations of heavy metals and toxicants build up in the surroundings. Living entities might suffer from the presence of toxic heavy metals in sediments and water [8]. Oxidative stress from heavy metal poisoning disturbs normal physiological processes, including protein folding, in invertebrates and vertebrates [9]. The ecological and environmental dynamics of their surroundings depends much on lakes, which both act as a source of aquifer replenishment and change climatic conditions by influencing humidity levels and vegetation. A lake's complex system of plants and animals maintains a varied ecology for aquatic and land life forms, including birds. Many bird sanctuaries depend on lakes and wetlands as essential habitats for maintaining different species in the food chain of the environment [10].

Chembarambakkam Lake, a crucial freshwater reservoir for Chennai, Tamil Nadu, has experienced declining water quality due to heavy metal contamination. This decline poses potential risks to human health, as the lake serves as a major source of drinking water for the city. Heavy metals such as lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) can accumulate in sediments and aquatic organisms, including fish consumed by local populations. Over time, these contaminants bioaccumulate, raising concerns about toxicity levels within the ecosystem and the food chain. This study examines the concentrations of heavy metals in water, sediment, and fish samples, evaluating their potential health risks for humans. The findings also highlight the need for effective bioremediation strategies to address this pollution. However, the rapid growth of industry and urbanization has possibly made lakes contaminated. Untreated dwelling and industrial wastewater discharges [11], garbage disposal, and others adversely impact the biodiversity of an extensive number of water bodies in the city [12]. The bioaccumulation and biomagnification of dangerous metal toxins in humans [13], plants [14], animals, and microbial life are major problems [15]. In aquatic life, these harmful substances can induce various metabolic and physiological disorders [16]. Several studies have revealed the concerning levels of heavy metals in Chennai's drinking water. Water from Chemberambakkam Lake, which is collected for drinking, contains Cd, Pb, Fe, Co, and Ni levels exceeding the WHO guidelines for drinking water [17]. Lakhsmi et al. [18] report that water in south Chennai's lakes has more significant Cu and Pb levels. As revealed by Jayaprakash et al. [19], the sediments of the Pallikaranai Wetland are more highly contaminated with Cd, Hg, Cr, Cu, Ni, Pb, and Zn than in other areas on the southeast coast of India. Therefore, this study aimed to assess the possible toxicity hazards index of Chembarambakkam Lake by analyzing heavy metal contamination in its water, sediments, and freshwater fishes.

2. Materials and Methods

2.1. Description of Study Area

Chembarambakkam Lake, situated in the Chengalpattu district approximately 40 km from Chennai, serves as the origin of the Adyar River, relying on rainwater for its sustenance. It is a vital source of potable water for cities. However, it faces significant challenges, including the proliferation of water hyacinths and pollution from the surrounding catchment areas. Additionally, the proposed industrial developments in the vicinity pose further risks to the ecological balance. To distribute treated water, the lake utilizes a network of canals and two existing pipelines connected to its water treatment plant. Despite having a full tank level of 26.03 m and a total capacity of 108 million m^3, sedimentation has led to a loss of over 40% of its water-holding capacity, exacerbating the strain on its resources. Nevertheless, Chembarambakkam Lake remains a crucial lifeline for Chennai, supplying a significant portion of the city's water demand (Figure 1).

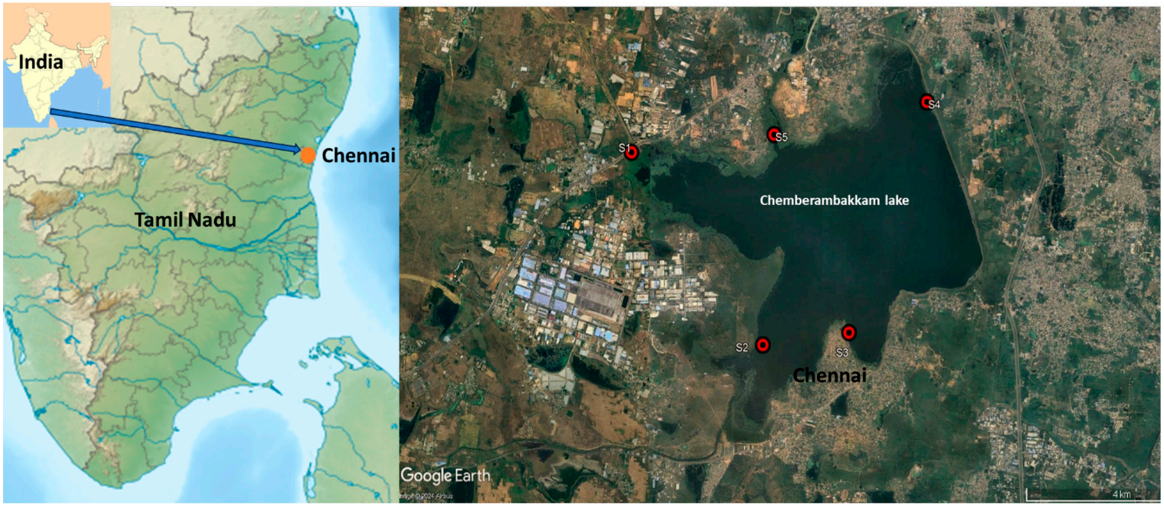

Figure 1. The study area of Chembarambakkam Lake.

2.2. Collection and Sample Preparation

Figure 1 shows the five samples taken from Chemberambakkam Lake in Chennai, consisting of sediment, water, and fish (S1 to S5). The samples were collected from different parts of the lake in plastic bottles to preserve their chemical properties during transportation to the lab. Surface sediment samples (top 2 cm layer) were collected from the intertidal zones at each sampling station using a pre-cleaned PVC pipe with an outer diameter of 3.5 inches, following the procedure outlined in [20]. The sediment samples were placed in zip-lock bags for preservation and transported to the laboratory for further analysis. Subsequently, the sediment samples were dried in a hot air oven at 50 °C until they reached a constant weight and then finely crushed using an agate mortar and pestle [21]. Finally, one gram of the powdered sample was placed into a beaker for acid digestion.

For the acid digestion process, 10mL of a mixture of reagents (HNO_3, $HClO_4$, and H_2SO_4) was added to the sample, and it was heated on a hot plate at 60 °C. After digestion, 5 mL of a 2N hydrochloric acid (HCl) solution was added. The obtained extract was filtered through Whatman Grade 1 filter paper to remove any remaining impurities. The purified extract was then analyzed using an atomic absorption spectrophotometer (AAS), model Shimadzu AA-7000 from Japan, following the procedure described in [20]. The instrument's flame mode yielded the following lower detection limits for several elements: Cu, less than 0.01 mg/kg; Cd, less than 0.01 mg/kg; Pb, 0.01–0.09 mg/kg; and Zn, less than 0.01 mg/kg.

Approximately 1 L of surface water was collected from each sampling location. Two drops of nitric acid (HNO_3) (pH 2) were added to the bottle immediately for preservation and to eliminate cross-contamination, and the samples were stored in an ice-cooled container [22]. The stored water samples were filtered using a Millipore filter unit (0.45 µm) and transferred into a separation funnel. Then, 10 mL of 1% APDC (ammonium pyrrolidine dithiocarbamate) solution was added and shaken well, and 25 mL of MIBK (iso-butyl methyl ketone) was added and subjected to vigorous shaking for 10–15 min. From the two separated layers formed, the upper organic phase was collected. The organic phase obtained was extracted with 50% HNO_3. The organic layer was collected and made up to 25 mL using double-distilled water [20,23]. The resulting sample solution was analyzed using the atomic absorption spectrophotometer (AAS) instrument (Shimadzu AA-7000, Tokyo, Japan).

2.3. Fish Tissue Sample Processing

During March 2023, fish samples were collected using gill nets with the help of local fishermen in Chemberambakkam Lake. A total of 25 individuals, representing five species such as *M. tilapia, C. striata, H. leucisulus, E. maculatus*, and *B. binotatus*, were collected. All the collected fish specimens were identified and stored in an icebox and brought to the laboratory for further analysis. The fish specimens were washed with distilled water before dissection. The concentrations of the metals were assessed following the European Standards. Tissue samples, weighing approximately 20 g, were dehydrated at 70 °C in a hot air oven. After complete drying, the substances were pulverized into a fine powder using a mortar and pestle to prepare them for acid digestion. The acid digestion process involved the use of a mixture of HNO_3, $HCLO_4$, and H_2SO_4 in a ratio of 5:2:1 [21]. A dry powdered sample weighing 1g was subjected to this process, which was carried out by heating it on a hot plate at a temperature of 60 °C until only 2–3 mL of extract remained. Subsequently, 5 mL of a 2N hydrochloric acid solution was introduced into the digestion vessel and heated continuously until the digestion process was fully completed. Following digestion, the samples were diluted by adding distilled water to a final volume of 25 mL. The obtained extract was filtered using Whatman filter paper (grade 1; diameter 125 mm) and then placed in a metal-free container for examination using atomic absorption spectroscopy (AAS) with a Shimadzu AA-7000 device, Tokyo, Japan.

2.4. Health Risk Assessment

To evaluate the extent of metal pollution in the research area, various pollution indices were used. The metal index was employed to quantify the metal concentrations in the water, while a range of indices, including the geo-accumulation index (Igeo), contamination factor (CF), pollution load index (PLI), ecological risk (Er), and enrichment factor (EF), were utilized to evaluate the sediment. These indicators were computed relative to the baseline levels of heavy metals that occur naturally in water and sediments/soils.

2.4.1. Metal Index for Water

The metal index (MI) is a widely adopted method for evaluating the burden of heavy metals in water, and it was benchmarked against the Bureau of Indian Standards (BIS) guidelines 2012 and calculated using the following formula:

$$\text{Metal Index(MI)} = \sum_{i=0}^{n} \frac{\text{C}i}{\text{MAC}i}$$

where Ci represents the concentrations (mean values) of the metals in the analyzed samples, and MAC is the maximum allowed concentration of the heavy metals. The metal index value is categorized into six classes as follows: MI (<0.3) indicates very pure water, MI (0.3 to 1) suggests pure water, MI (1–2) signifies slightly affected water, MI (2–4) denotes moderately affected water, MI (4–6) indicates strongly affected water, and MI (>6) represents seriously affected water.

2.4.2. Metal Indices for Sediment

Geo-Accumulation Index (Igeo)

The geo-accumulation index (Igeo) was used to assess the heavy metal content in the gathered samples against background values (UCC or local soil), providing insight into the contamination level to be addressed. Muller [24] introduced the Igeo. Its calculation is defined by the following equation [25]:

$$\text{Igeo} = \log 2\left(\frac{Cn}{1.5 \times B_n}\right)$$

Cn represents the concentration of metal in the sediment samples, and Bn represents the background value (geochemical) of the relevant metal in the Earth's crust. There is a lack of geochemical background reference values for metals in the study area. Consequently, we decided to use the baseline values of the Earth's crust, as specified [26].

Contamination Factor (C_f) and Degree of Contamination (C_{deg})

Soil contamination assessments can also be conducted using the contamination factor (C_f). This index facilitates the evaluation of soil contamination, considering the presence of heavy metals on the soil surface along with pre-industrial reference levels provided [27]. Cf was computed using the following formula:

$$C_f = \frac{Cm}{C_{p-i}}$$

where Cm represents the mean concentration of heavy metals from the individual samples, and $C_{p–i}$ denotes the pre-industrial reference value for the substances. According to Hakanson [27], the degree of the contamination index, C_{deg}, can be utilized for contamination assessment and is calculated as follows:

$$C_{deg} = \sum_{i=1}^{n} C_f$$

where C_f represents the contamination factor, and n denotes the number of analyzed heavy metals (Table S1).

Pollution Load Index (PLI)

For a comprehensive evaluation of the soil contamination, the pollution load index (PLI) was also employed. This index offers a straightforward method to demonstrate the degradation of soil conditions due to heavy metal accumulation [28]. The *PLI* was computed as the geometric mean of the pollution indices (PI) using the following formula:

$$PLI = \sqrt[n]{C_{f1} \times C_{f2} \times C_{f2} \times \ldots\ldots C_{f\mathrm{n}}}$$

where n is the number of analyzed heavy metals, and PI is the calculated value for the single pollution index (Table S1).

Potential Ecological Risk (PER)

Potential ecological risk (PER) is a metric used to assess the extent of ecological danger arising from the presence of high levels of heavy metals in water, air, and soil. The formula used to calculate this was first introduced in [27].

$$PER = \sum_{i=1}^{n} E_r$$

where n is the number of heavy metals, and E_r is the single index of the ecological risk factor.

The ecological risk factor (Er) is a method used to evaluate soil ecological risk by considering metal toxicity and environmental response factors. As outlined by Hakanson [27], Er was calculated using the following equation:

$$\mathrm{Er} = \mathrm{Tr} \times \mathrm{Cf}$$

The toxicity response coefficient of an individual metal, Tr, was defined according to Hakanson (1980). The contamination factor, PI, was derived based on certain values. Therefore, the initial categorization of the contamination levels was modified accordingly, as displayed in Table S1.

2.4.3. Bioaccumulation Factors

To ascertain the ratio of metal concentrations in the fish and sediment, bioaccumulation factors (BAFs) were computed. The calculation followed the method outlined [29], as follows:

$$\text{BAF} = \frac{C_{(fish\ samples)}}{C_{(sediment)}}$$

where $C_{(fish\ sample)}$ is the measured concentration of heavy metals in the fish (mg/kg dry weight), and $C_{(sediment)}$ is the measured concentration of heavy metals present in the sediment (mg/kg dry weight).

2.4.4. Estimated Daily Intake (EDI)

Fish serves as a primary protein source for many of the human population, so an assessment of the human health risks was conducted using fish muscle tissues. This assessment involved estimating the daily intake of elements and calculating the target hazard quotient (THQ). The formula provided below, as proposed in [30], was used to estimate the daily intake of metals:

$$EDI = \frac{FIR \times C}{BW}$$

where *FIR* is the food ingestion rate, *C* is the metal concentration in the fish samples, and *BW* is the average body weight. According to Siddiqui et al., the recommended daily amount of fish consumption for individuals in the region is 57.5 g/person/day, based on an average body weight of 55.9 kg [31].

2.4.5. Target Hazard Quotients (THQs)

Health hazards associated with consuming fish species were evaluated using target hazard quotients (THQs). These calculations were based on the standard hypothesis stated in an integrated USEPA study [32]. The equations used to calculate the target hazard quotient (THQ) and the resulting hazard index are as follows:

$$\text{THQ} = \frac{\text{EF} \times \text{ED} \times \text{FIR} \times \text{C}}{\text{RfD} \times \text{BW} \times \text{TA}} \times 10^{-3}$$

$$\text{Hazard index(HI)} = \sum \text{THQ}$$

In the formula, EF represents the frequency of exposure (365 days per year), and ED represents the duration of exposure (70 years), based on life expectancy [33]. According to Bennett et al., FIR is the rate of food ingestion (57.5 g/person/day), C is the concentration of the metal in fish tissues in micrograms per gram, RfD denotes the oral reference dose in milligrams per kilogram per day, BW stands for body weight (55.9 kg), and TA indicates the total exposure time (365 days per year multiplied by ED). According to the United States Environmental Protection Agency (USEPA) in 2015 [34], the oral reference dose (RfD) values for the metals are as follows: cadmium (Cd) has a value of 0.001, copper (Cu) has a value of 0.04, lead (Pb) has a value of 0.00357, and zinc (Zn) has a value of 0.3.

2.5. Statistical Analysis

AAS analysis provided essential information on the distribution of metals in the water, sediment, and fish samples obtained from Chemberambakkam Lake in Chennai. The data were analyzed using MS Office Excel and are presented as mean values and corresponding standard deviations. The researchers employed two-way ANOVA to identify significant differences in the levels of heavy metals across the various sampling locations and throughout different seasons. The significance level was set at $p < 0.05$. Statistical analyses were performed using the Origin 2022 software.

3. Results

3.1. Heavy Metal Concentrations in Water and Sediment

Figure 2 displays the concentrations of heavy metals in the water, sediment, and fish samples. The order of the metal concentrations in the sediment was Zn > Cu > Pb > Cd. The metal concentrations ranged from Cd (0.52–0.82 µg/g), Cu (13.75–38.07 µg/g), Pb (1.30–3.74 µg/g), and Zn (12.60–61.12 µg/g). The highest concentration of heavy metals was Zn at S3, followed by Cu at S3, and the lowest concentration of Cd was 0.52 µg/g at S3. One-way ANOVA of the heavy metal levels among the stations indicated a significant disparity in the distribution of metals within Chemberambakkam Lake ($p < 0.05$; F = −9.012). Nevertheless, Tukey's multiple comparison analysis revealed notable differences between Cd and Cu ($p > 0.05$) as well as between Cd, Zn, Pb, and Zn.

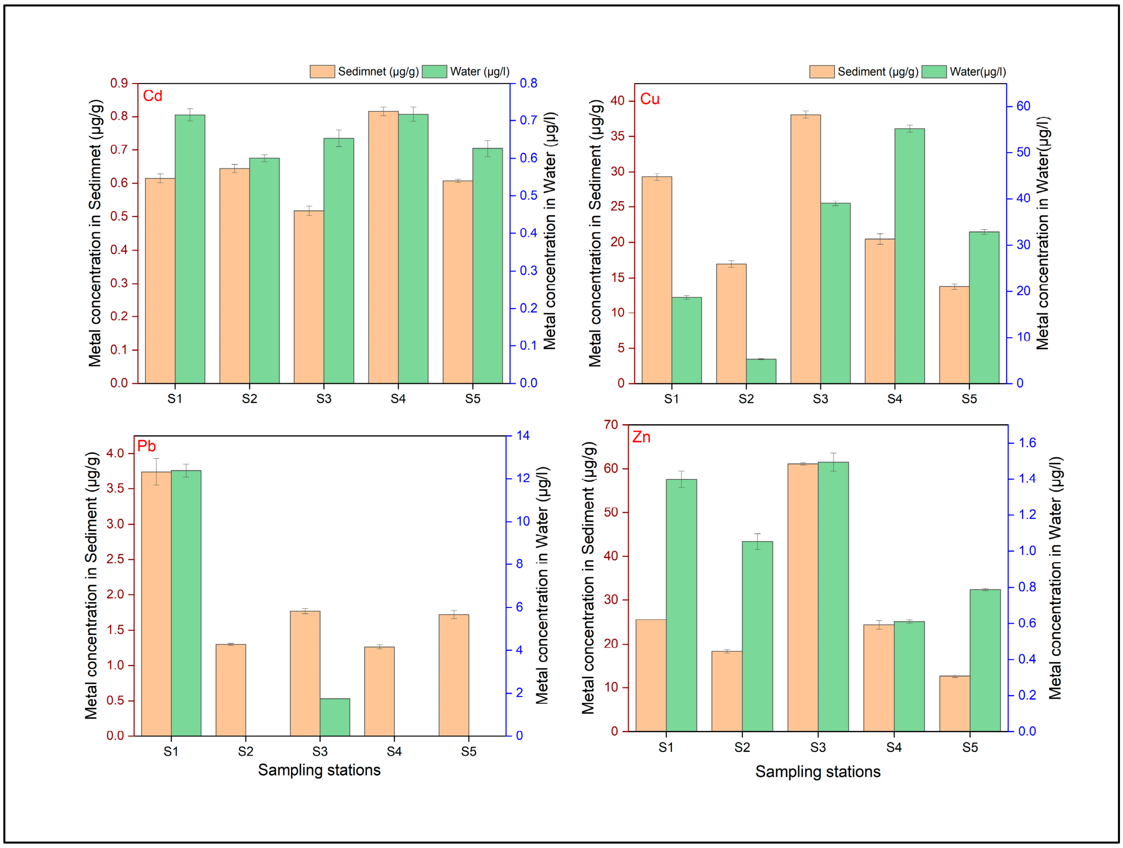

Figure 2. Heavy metal concentration in sediment and water samples of Chemberambakkam Lake.

Similarly, the heavy metal concentrations in the water were in the order of Cu > Zn > Cd > Pb. The concentrations ranged from Cd (0.65–0.74 µg/L), Cu (5.42–55.65 µg/L), Pb (BDL–12.58 µg/L), and Zn (6.2–1.44 µg/L). The highest concentration of the heavy metal Cu was reported at S3 (39.32 µg/L), and the lowest concentration of Cd (0.60 µg/L) was at S2. One-way analysis of the heavy metal distribution in the water samples showed a significant difference among the metals ($p > 0.05$; F = 4.64). Tukey's multiple comparison analysis revealed significant differences between Cd and Cu; Cu and Pb; and Cu and Zn.

The metal concentrations in the freshwater fish collected from the lake are shown in Figure 3. Five freshwater fish were collected from the study area, including *M.tilapia*, *C. striate*, *B. binotatus*, *E. maculatus*, and *H. leucisulus.* Cd and Zn were reported in all fishes, whereas Cu was reported only in *B. binotatus* and *H. leucisulus.* Pb was reported only in *E. maculatus*, while other the fishes were below the detectable limit (BDL). The order of metals in the fish was Zn > Cd > Cu > Pb. The Cd concentration ranged from 0.3 to 0.62 µg/g, Cu ranged from BDL to 0.72 µg/g, Pb ranged from BDL to 0.69 µg/g, and Zn ranged from 13.53 to 48.20 µg/g. One-way analysis of the heavy metal concentrations among the fish species did not show significant differences ($p < 0.05$; F = 0.9529). Furthermore, Tukey's multiple comparison analysis indicated that there was no direct correlation between the fish species and the accumulation of heavy metals.

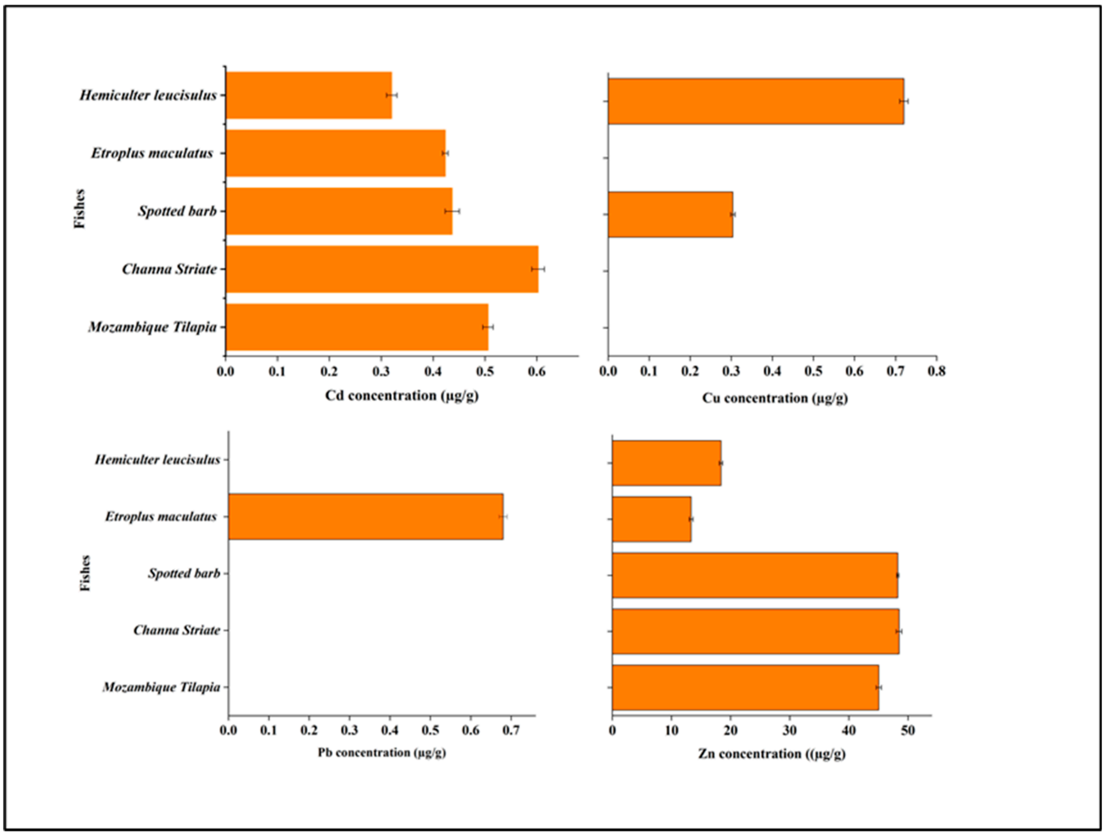

Figure 3. Heavy metal concentration in fish samples of Chemberambakkam Lake.

3.2. Risk Assessment of Heavy Metals

Geo-Accumulation Index

The Igeo values for the heavy metals across the sampling stations are shown in Figure 4. The Igeo classifies the sediment quality into seven classes, as illustrated in S1. The values of the geo-accumulation index for Cu, Pb, and Zn were negative, corresponding to class 0 (uncontaminated). However, Cd showed positive values at all sampling stations, indicating moderate pollution.

3.3. Contamination Factor (C_f) and Contamination Degree (C_{deg})

The classification of the contamination factor (Cf) and contamination degree (Cdeg) is presented in Table S1 and Figure 5a. Cf and Cdeg were divided into four classes, with class 1 representing low contamination, starting from 0 to 1, and class 4 indicating a very high contamination of a degree > 6. In this study, the values of the metal Cd were consistently above 4 at all sampling sites, indicating very high Cd contamination in the area studied. The highest contamination factor values were observed at S4. However, the values of the other metals, Cu, Pb, and Zn, ranged from <1 to 1–3, indicating low-to-moderate contamination levels.

The degrees of contamination of all sampling locations were also calculated and are depicted in Figure 5b. The contamination degrees of S2 (7.69) and S5 (7.09) were classified as category 1, indicating a low degree of contamination. Conversely, S1 (8.15), S3 (8.08), and S4 (9.69) were categorized into category 2, representing moderate degrees of contamination.

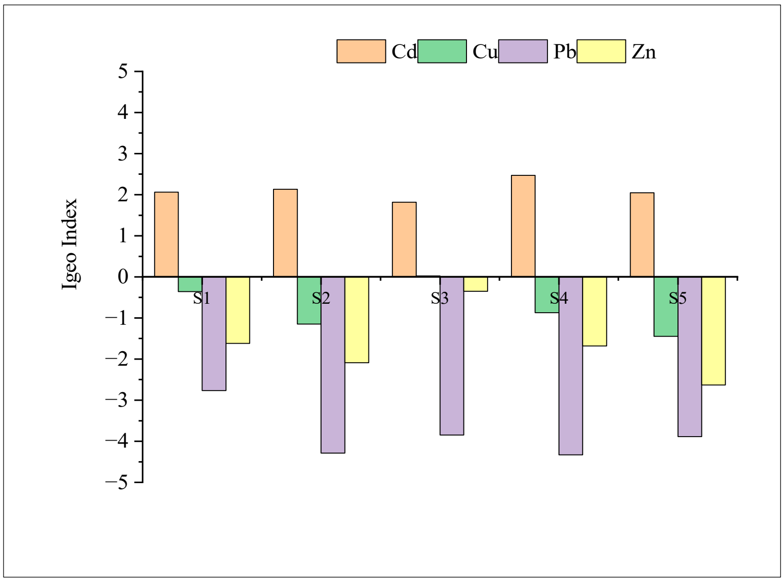

Figure 4. Geo-accumulation index, *Igeo*, of heavy metals.

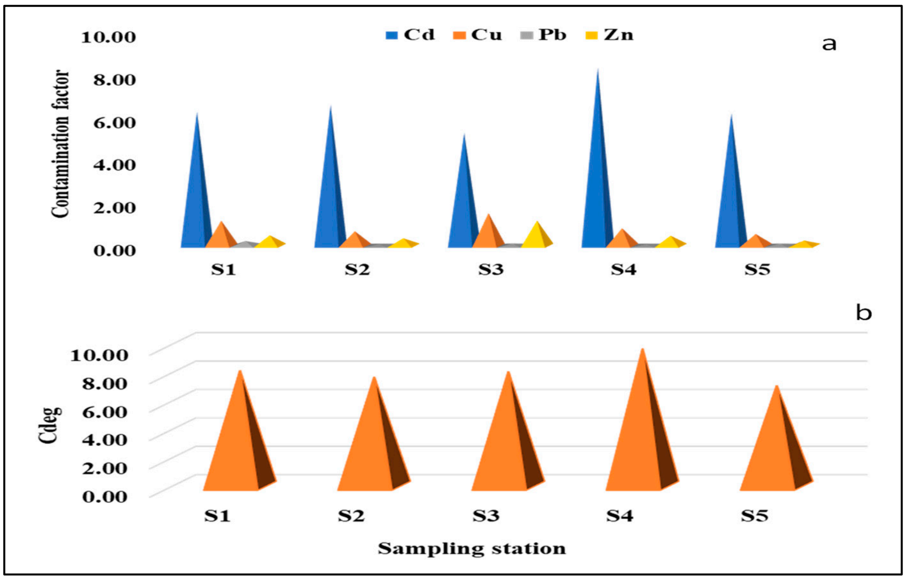

Figure 5. (**a**) Contamination factor (CF) and (**b**) degree of contamination values of heavy metals in Chembarampakkam Lake, south India.

3.4. Pollution Load Index (PLI) and Potential Ecological Risk (PER)

The pollution load index (PLI) was calculated using the assessed contamination factors to determine the combined contamination effect of the various elements across the different locations. Figure 6b displays the results of the PLI values. The PLI values for the various sampling locations within Chembarambakkam Lake were below 1, indicating that there was no significant contamination at the sampling sites. The PLI values ranged from 0.538 to 0.996 across the sampling stations S1–S5.

The ecological risk index (Ei) and potential ecological risk (PER) were used to assess the level of risk posed by the metals found in the research region during different seasons. The ecological risk index results are illustrated in Figure 6b. The ecological risk index of the heavy metals varied from 0.24 to 249.84 among the different locations. However, the indices for the different heavy metals in the S1 range were as follows: Cd, 188.18; Cu, 5.86; Pb, 1.10; and Zn, 0.49. In the S2 range, the indices were: Cd, 197.55; Cu, 3.39; Pb, 0.38; and Zn, 0.35. In the S3 range, the indices were: Cd, 158.23; Cu, 7.61; Pb, 0.52; and Zn, 1.18. In the S4 range, the indices were: Cd, 249.84; Cu, 4.09; Pb, 0.37; and Zn, 0.47. Finally, in the S5 range, the indices were: Cd, 185.84; Cu, 2.75; Pb, 0.51; and Zn, 0.24. The ecological threats varied from minimal to considerable. At sampling point S4, a significant ecological index of Cd was observed, indicating a substantial contamination of Cd.

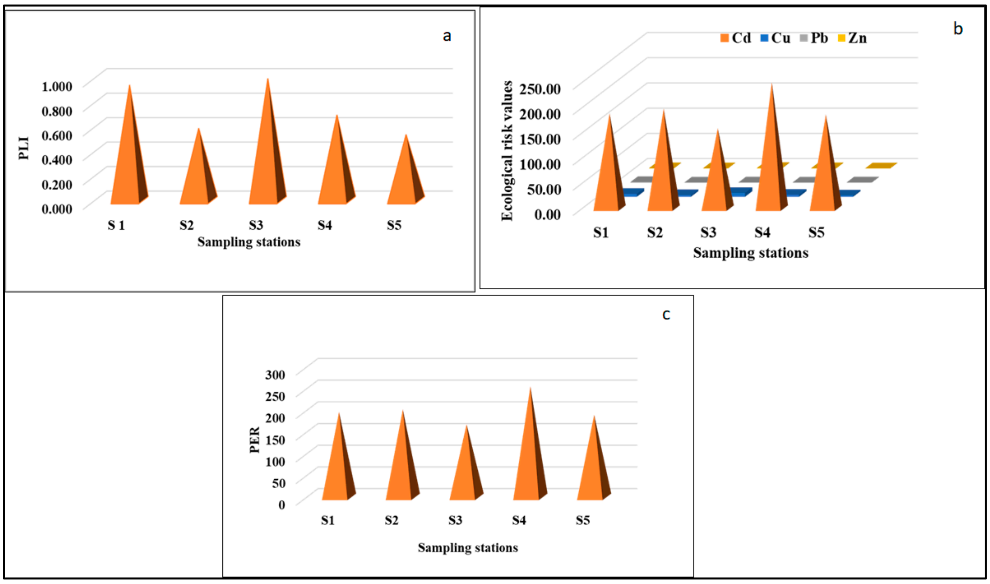

Figure 6. (**a**) Pollution load index, (**b**) ecological risk, and (**c**) potential ecological risk assessment of sediment samples.

The potential ecological risk (PER) was analyzed based on the Ei values, and the resulting PER values are shown in Figure 6c. The PER values ranged from 167.54 to 254.77. The highest PER values were recorded in S4, whereas the lowest values were observed in S3. Overall, the PER values indicated that S1, S2, S3, S5, and S5 were classified in the strong ecological risk category.

3.5. Bioaccumulation Factor (BAF) and Exposure of Daily Intake (EDI)

The bioaccumulation factor (BAF) was determined to improve our understanding of the heavy metal accumulation in the fish tissues, as illustrated in Figure 7. In the freshwater fish, the order of BAF concentrations was Zn > Cd > Pb > Cu. The BAF ranges for the different metals were Cd (0.48–0.91), Cu (0.0–0.02), Pb (0.0–0.24), and Zn (0.58–1.40). *C. striate* exhibited the highest BAF values for Cd (0.91), *H. leucisulus* for Cu (0.02), *E. maculatus* for Pb (0.24), and *C. striate* for Zn (1.40). Similarly, the daily intake ratio exposure in the fish followed the order Zn > Cd > Cu > Pb (Figure 7). The ranges of the estimated daily intake (EDI) for the different metals were Cd (0.33–0.62), Cu (0.0–0.74), Pb (0.0–0.70), and Zn (13.70–49.87). *C. striate* showed the highest EDI value for Cd (0.62), followed by *H. leucisulus* for Cu (0.74) and *C. striate* for Zn (9.87).

3.6. Target Health Quotient (THQ)

The computed target hazard quotient (THQ) for the fish indicated that the overall exposure to heavy metals through the consumption of fish from the investigated freshwater lake was below one (THQ < 1) for the adult population of consumers (Figure 8). The specific concentrations of Cd, Cu, Pb, and Zn were 0.48, 0.01, 0.04, and 0.12, respectively. The hazard index (HI) for the freshwater fish was also below one (HI > 1). The health risk assessments demonstrated a threshold response, where most substances have non-cancerous effects, except for lead, which is considered toxic at any concentration (USEPA 2020). The hazard quotient (HQ) determined for each metal indicated that a 70 kg adult consumer with daily freshwater fish consumption would not experience significant health risks (HQ < 1).

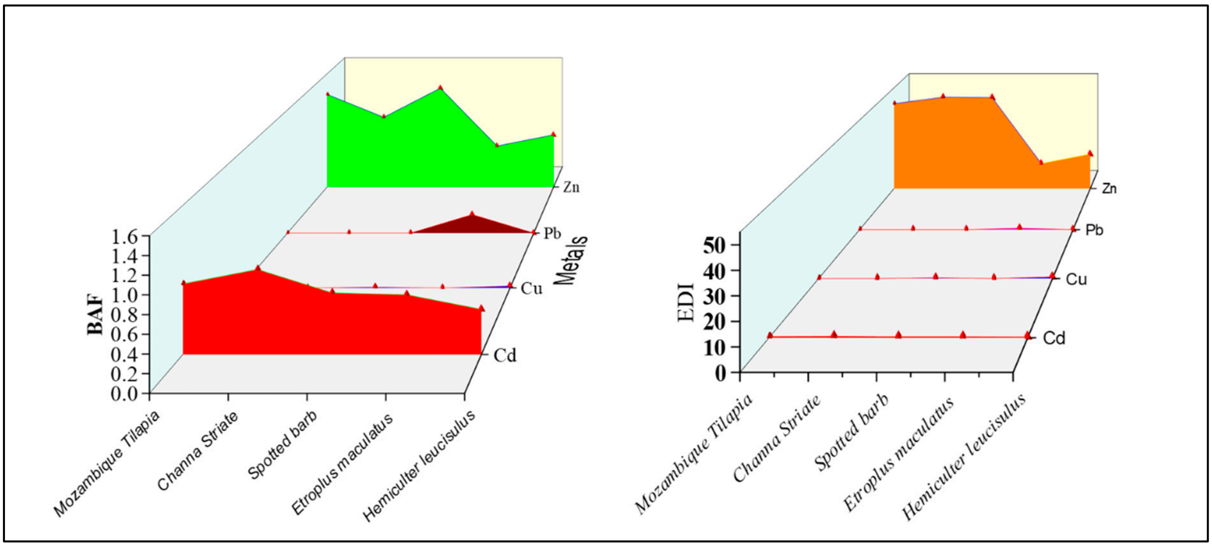

Figure 7. Bioaccumulation and exposure of daily intake of heavy metal concentration in freshwater fishes.

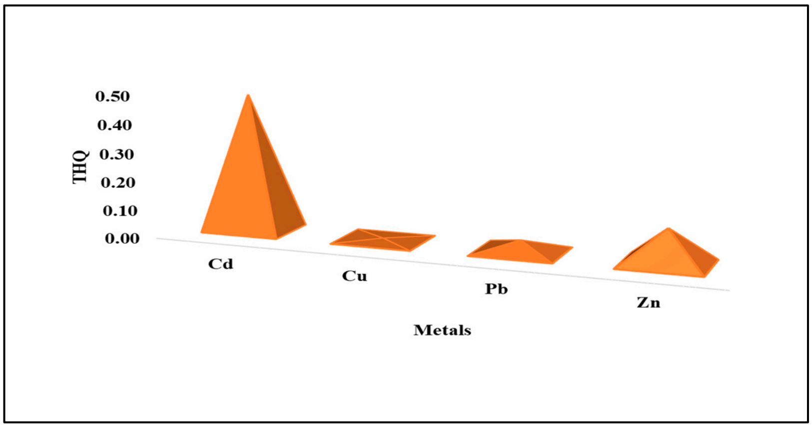

Figure 8. Target health quotient of heavy metals in freshwater fishes from Chembarapakkam Lake, south India.

3.7. Multivariate Analysis of Heavy Metals

Principal Component Analysis

Figure 9 displays the results of the principal component analysis (PCA), revealing eigenvalues of 2.02,0.87, 0.710, and 0.397, respectively. Excluding those with eigen values less than 1, the principal components analysis revealed PC1 and PC2. PC1, contributing 50.25% of the variance, exhibited significant positive loadings of 0.595 (Co), 0.522 (Cu), and 0.388 (Zn). Conversely, PC2, contributing 22.01% of the variance, displayed notable negative loadings for all metals. The association of PC1 with Pb, Cd, and Cu indicated higher levels in the sediment and water, attributed to anthropogenic rather than geogenic sources, such as industrial and various sources, including pesticides, industrial and municipal waste, and agricultural runoff in the lake environment. Additionally, PC2 showed Zn having negative loadings in the fish samples, hinting at a blend of natural and anthropogenic origins like tanneries and agricultural practices.

Cluster analysis (CA) is a statistical technique that groups system items into clusters or categories based on their similarities (Figure 10). The goal is to identify an ideal arrangement where the items or observations within each cluster are similar to each other but the clusters themselves are different from one another. A dendrogram is a visual depiction of how parameters or variables merge to form clusters with similar characteristics. A similarity score of 0 indicates that the cluster areas are as dissimilar as the least similar region.

A similarity score of 100% signifies that there is no gap between the clusters based on their sample readings. Figure 10 illustrates the correlation between the metals and stations, revealing the presence of three primary cluster groupings. Cluster I comprised cadmium (Cd) and copper (Cu), whereas Cluster II encompassed lead (Pb). Zinc produced a solitary cluster associated with Cluster II. The dendrogram displayed a grouping of metals (Cd, Cu, Pb), suggesting a mixture of both natural and human-induced effects on the lake's ecology.

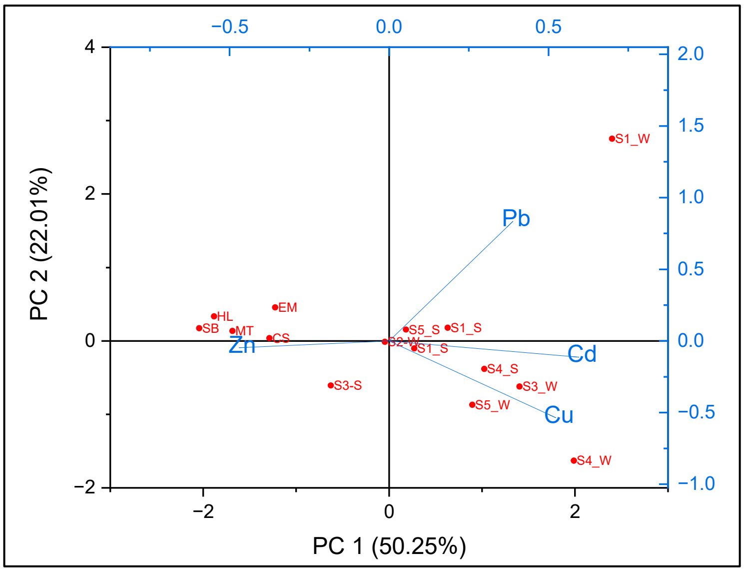

Figure 9. Principal component analysis of the heavy metal distribution in the lake environment.

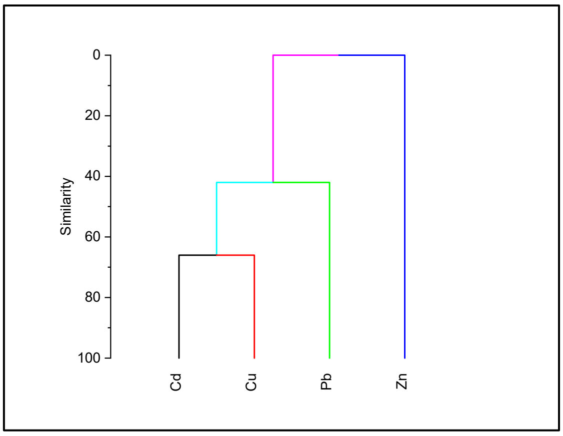

Figure 10. Hierarchical cluster analysis of metal concentration along the Cauvery River.

4. Discussion

4.1. Metal Concentrations in Water, Sediment, and Fish Samples

Heavy metal pollution has increased owing to the rapid growth of industrial and agricultural activities, posing significant hazards to fish, humans, and invertebrates in the environment. Many heavy metals are discharged into rivers, where water, sediment, and aquatic food chains can cause them to build up and undergo biomagnification. In local fish populations, this process may have sublethal consequences or result in death [35,36]. In our study, the heavy metal concentration was higher in the sediment than in the water samples from all the sampling stations in the lake ecosystem, except for station S1 (Cd) and except for Cu. However, the Zn levels were higher in the sediment samples than in the water samples. The sediment samples exhibited a heavy metal concentration ten times greater than that found in the water column [37]. The entry of heavy metals into water bodies leads to their absorption into sediments. Subsequently, these metals may migrate through exchanges between water, sediment, and biota, facilitated by biological and chemical processes. According to Schertzinger et al. [38], heavy metals tend to settle, precipitate, collect, and adhere strongly to sediments, which is why sediments usually contain higher amounts of heavy metals than water. The high concentrations of heavy metals found in the study area are likely due to this phenomenon. In the present study, the Cu and Zn concentrations were higher than those of Cd and Pb in the sediment samples. The levels of zinc observed were consistent with the findings from Pulicat Lake [38,39]. Our research aligns with a study conducted in the Coimbatore Lakes, where the Cd concentrations in the sediment ranged from 0.04 to 0.4 μg/L. These concentrations are well below the recommended limit of 3 μg/L set by the World Health Organization (WHO), as reported in [40]. According to a recent study conducted by Rosado et al. [41], the average concentrations of heavy metals in water measured at Sembakkam Lake were Zn (5.55 μg/L), Cu (2.84 μg/L), and Pb (2.59 μg/L). In comparison, the current investigation suggests that Chemberambakkam Lake has lower concentrations of metals than Sembakkam Lake.

Similarly, the water samples exhibited elevated Cu concentrations. Zhang et al. noted that Cu, Cd, and Zn levels were relatively high in the water of the PRE; however, except for Zn, all the metal concentrations in the water remained within acceptable limits according to water quality standards [42]. For instance, the WHO standards set a permissible limit of 0.05 mg/L for Pb [43], yet the Pb concentration in the water samples ranged from 0.0 to 12.8 mg/L in our findings. Notably, the present results indicate that the concentrations of Pb, Cu, Cd, and Zn in all the water samples did not exceed permissible limits, signifying the state of the water quality (Table 1). Batvari and Surendran [17], previously reported metal concentrations in Chemberambakkam Lake water, with levels ranging between Pb (0.02–0.296 mg/L), Cu (0.02–0.019 mg/L), Cd (0.152–0.187 mg/L), and Zn (0.018–0.026 mg/L). However, our present study revealed a significant increase in the metal load over time, which was attributed to the rapid expansion of industrialization and the growing population in and around the lake ecosystem when compared to earlier research. Untreated domestic wastewater is a major input into Chemberambakkam Lake, and the majority of this discharge occurs on the southern side of the lake. The lake is encircled by farmland and is located next to an abandoned landfill. Moreover, industrial runoff into lakes has great potential to cause heavy metal pollution. According to ATSDR, there is a possibility that the significant sewage flow from nearby communities is connected to the elevated levels of copper (Cu) in the lake [44].

Five fish species—tilapia (*M. tiapia*), wild carp (*H. leucisulus*), pearl-spot (*E. maculatus*), spotted barb (*B. binotatus*), and snakehead murrel *(C. striate*)—were collected in the present study to conduct an assessment of their heavy metal contamination and determine the health risk to higher trophic levels. In fish, Cu reduces survival, development, and reproduction at sub-lethal concentrations and primarily accumulates in the liver and gills [45]. Copper concentrations in various fish species collected from around the world range from 0.5–28 mg/L [46]. Similarly, the Cu concentration in the present study was ranged from −0.07 to 0.72 mg/g. Cu is absorbed rapidly, resulting in increased residue levels and causing retardation in growth and the inhibition of respiratory enzymes in crayfish at 1.0 mg/L [47]. These results are in good accordance with the current investigation, which determined that the levels of copper for the two aquatic fish species *C. punctatus* and *A. aor* were in the ranges of from 0.054 to 0.96 and from 0.78 to 1.2 ppm, respectively. Crayfish and goldfish have very low copper levels. Comparatively, the Cu level was high (BDL to 39 mg/L) in the collected samples in the present study. Fish with Zn buildup die, grow slowly, and develop hypoxia owing to the destruction of the gill epithelium [48,49]. Rajeshkumar and Li [50] reported that the Cu concentration in fish tissues in Lake Taihu was around 0.037–0.316 mg/kg in summer and 0.017–0.144 mg/kg in winter.

Lead (Pb) is considered an element that is not essential for living things to function and is linked to several harmful consequences, such as toxicity to the nervous system and kidneys, rapid behavioral changes, and decreased rates of development, metabolism, and survival. Furthermore, it may cause certain mammals to change their social behavior [51].

According to Rashed et al, a variety of factors, such as significant agricultural practices, poultry farming, textile manufacturing, industrial activities, and other human activities, can have an impact on elevated levels of lead in freshwater fish [52].

Table 1. WHO standards for heavy metals in potable water [53].

Metal	Permissible Limit (mg/L)	Water (µg/L)
Copper	0.003	19.26
Lead	0.05	2.87
Zinc	5.00	1.09
Cadmium	0.05	0.68

4.2. Health Risk Assessment Findings

The geo-accumulation index clearly illustrates the elevated levels of Cd contamination in Chembarambakkam Lake. The Igeo values of all the metals were below zero, indicating a lower degree of contamination, except for Cd, signifying the degree of pollution primarily stemming from industrial and domestic waste discharged into the lake (Figure 4). Notably, station S4 exhibited higher Igeo values for Cd, suggesting the influence of industries in the lake environment. In the study by Gopal et al., Cd emerged as the most environmentally threatening metal among the four studied metals along the coast of Cuddalore [53]. Extensive metal contamination originates from diverse stimuli linked to widespread industrial activities and the improper disposal of metal-laden fluids in the environment. Zhang et al. [54] also asserted that Cd surpassed other heavy metals in terms of toxicity within the surface sediments of the Han River tributaries. Consistent with the Igeo index, the results for the contamination factor reinforce the heightened levels of Cd contamination compared with the other metals. Following Cd, the Cu levels presented a marginally moderate risk in the lake environment. The contamination degree and potential ecological risk assessment indicated a higher contamination level at station S4. Higher PER values could indicate excessive heavy metal loads in this area. The potential ecological risk index (RI) quantifies the overall ecological risk that various heavy metals pose in an ecosystem [55]. Muneer et al. reported historical trends in heavy metal contamination and eutrophication in an aquatic system in the Kashmir Himalayas [56].

The metal index (MI) values in the water ranged from 0.214 to 0.410, as illustrated in Figure 9. The highest MI value was observed at station S1. Across all the sampling stations, the MI values ranged between 0.3 and 1, indicating that the water of Chemberambakkam Lake is of high purity. Conversely, the MI of both surface water and groundwater in the Gudiyattam Region exceeds 1, suggesting that they are unsuitable for drinking purposes [57]. A recent study by Rosado et al. classified the metal index of Chembarambakkam Lake water in Chennai as class I, indicating the absence of anthropogenic pollution [41]. Another study Das Kangabam et al. [58] reported that the water quality index of Loktak Lake in India ranged from 64 to 77, indicating that the water is not suitable for drinking, including for both humans and animals. Additionally, the MI concentrations in the present study area were below the drinking water thresholds established by the Indian Bureau of Standards [58].

The ecological risk index (ERI) values for Pb and Zn have also shown an increasing trend since 1980, indicating the deterioration of the lake ecosystem. Cd can limit the rates of survival, growth, and reproduction in fish. The bioaccumulation factor (BAF) provides a better understanding of how metals accumulate in aquatic organisms for various species (Figure 11). The bioaccumulation factor (BCF) of heavy metals in fish tissues is the ratio of heavy metals in the tissues to the surrounding water [59]. The BAF values of the freshwater fish in the present study were in the order Zn > Cd > Pd > Cu. The highest BAF values were reported for *M. tilapia* and *B. binotatus*. The highest Cd concentration was reported in *C. striate*. The health of those who regularly consume fish and live both inside and outside the fishing site may be directly affected by the accumulation of heavy metals. Therefore, for fish originating from contaminated resources, a health risk evaluation is required. A threshold response is observed in health risk assessments that are carried out with the presumption that the majority of substances have non-cancerous effects [60].

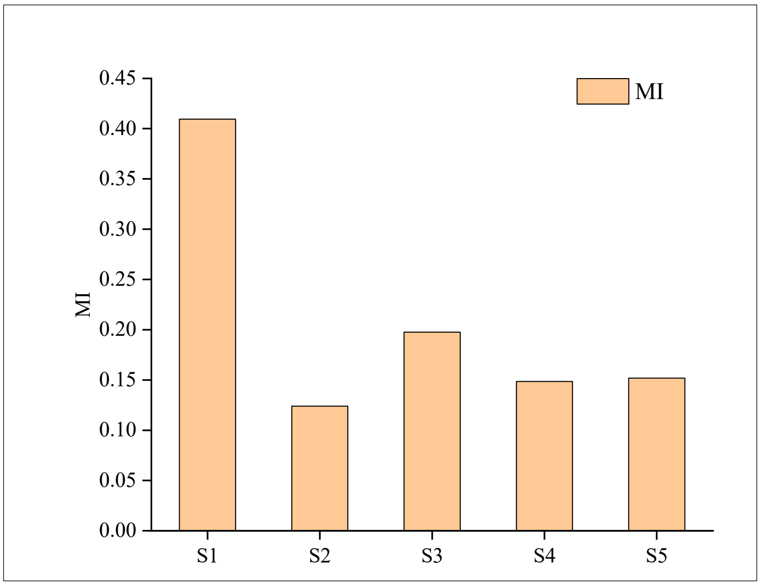

Figure 11. Metal index of water in Chembarambakkam Lake, south India.

The health conditions of customers, including humans, are affected either directly or indirectly by metal deposition in fish. Humans frequently consume fish tissues; therefore, it is critical to evaluate the EDI values of metals. The EDI of the heavy metals via the consumption of the five fish species by people is shown in Figure 11. The results revealed that Cu and Pb showed the lowest daily intake and that Zn and Cd showed the highest daily intake, which agrees with previous studies [61–63]. The current study found that the estimated daily intake (EDI) values of cadmium (Cd) exceeded the recommended daily allowance (0.06 mg/day/person). Similarly, Akila et al., observed the EDI values for copper (Cu), zinc (Zn), chromium (Cr), and lead (Pb) based on their concentration in the muscles of *L. fulviflamma*, *C. chanos*, *Arius* sp., and *T. jarbua* in Pulicat Lake, indicating that these levels do not pose significant health concerns upon consumption [64].

The target hazard quotient (THQ), calculated to assess the risk of individual heavy metals through the consumption of various fish species in Chemberambakkam Lake, is shown in Figure 8. THQ values below 1 were considered acceptable. The findings from this investigation indicate that the THQ for the study area remained below 1, suggesting no significant threats. This observation aligns with a study by Maurya et al. conducted in the Ganga River Basin [65], where concerns were raised regarding the high health risks associated with the daily consumption of heavy-metal-contaminated freshwater fish [50,66]. The estimated daily intakes of Cd, Cu, Pb, and Zn from the fish in Chemberambakkam Lake fell below the guideline reference doses of 0.040, 0.3, 0.0035, 0.001, and 0.003, respectively. Consequently, the presence of these heavy metals in the edible tissues of various fish species from Chemberambakkam Lake is unlikely to pose a significant risk to human health. Similarly, Maurya et al. [65] conducted a comparable study in the Ganga River Basin.

5. Conclusions

The results of this preliminary study highlight the heavy metal contamination in several parts of the lake ecosystem, including in water, sediment, and fish species. The sediment findings indicated that the water had the highest quantities of Cd, Cu, and Zn followed by the sediment. All five fish species, however, showed non-essential metal Cd and essential metal Zn present. Since, the heavy metals are deposited into the fish species from surrounding media and food sources, the metals in the fish species with high Cu and Cd concentrations could have come from industrial waste or garbage disposal in the lake area. Every metal concentration in the organisms fell short of the allowed limit. Still, fish with BAF and EDI readings for Cd over the recommended limits are unfit for human consumption. Rising concentrations of Cd in fish tissues point to possible negative impacts on the species; so, Chemberambakkam Lake should be kept free from metal biomagnification and contamination. If the metal pollution is not taken under control, the HI readings will be above the safe threshold in the not-too-distant future. Therefore, the ingestion of fish from these polluted waters could have negative health consequences for humans if more metal pollution enters Chembarambakkam Lake. To guarantee human safety when consuming these fish, constant observation of the metal levels in the surroundings and the lake is required. These findings underscore the urgent need for monitoring and remediation strategies to reduce the heavy metal levels in Chembarambakkam Lake. Bioremediation, along with stricter pollution controls, could play a key role in managing contamination and safeguarding public health. This study emphasizes the importance of ongoing assessments to track changes in heavy metal concentrations, reduce human exposure risks, and preserve this vital freshwater resource for Chennai's population.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16233517/s1, Table S1: Classification and grading for the values of the contamination degree, potential ecological risk, and pollution load index.

Author Contributions: Conceptualization, methodology, investigation P.K.; software, R.V. and P.K.; validation, P.K. and S.E.; formal analysis, S.S.K.; resources, S.N.; data curation, R.R.; writing—original draft preparation, P.K. and S.E.; writing—review and editing, P.K., R.V. and P.R.; visualization, P.K.; supervision, R.V. and P.R.; project administration, P.K.; funding acquisition, P.R. All authors have read and agreed to the published version of the manuscript.

Funding: Dr. K. Prabhu, Dr. D. S. Kothari post-doctoral fellowship, University Grant commission, New Delhi, for awarding the post-doctoral research grant (No. F.4-2/2006 (BSR)/OT/20-21/0010; date: 14.09.2021 (89th list)).

Data Availability Statement: The raw data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors are thankful to the Department of Prosthodontics and Implantology, Saveetha Dental College and Hospitals, Saveetha University, Chennai, and the Department of Biotechnology, Vinayaka Missions Kirupananda Variyar Engineering College, Salem, for providing the necessary facilities and support to carry out this research work successfully. Author K.P. is also thankful to the University Grants Commission (UGC) for providing financial assistance in the form of a Kothari post-doctoral fellowship. I would like to express the gratitude to Department of Marine Science Bharathidasan University Tiruchirappalli-620024 for providing the AAS facility for analyzing heavy metals.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Govindasamy, C.; Kannan, L.; Jayapaul, A. Seasonal variation in physico–chemical properties and primary production in coastal water biotopes of coromandel coast, India. *J. Environ. Biol.* **2000**, *21*, 1–7.
2. Cuihang, J.; Jiwei, H.; Xianfei, H.; Cuxiong, L.; Jiajun, D.; Zie, Z. Phosphorus speciation in sediments of lake Hongfeng, China. *Chin. J. Oceanol. Limnol.* **2011**, *29*, 53–62.
3. Fraga, R.F.; Rocha, S.M.G.; Lima Neto, I.E. Impact of fow conditions on coliform dynamics in an urban lake in the Brazilian semiarid. *Urban Water J.* **2020**, *17*, 43–53. [CrossRef]
4. Kumar, R.; Parvaze, S.; Huda, M.B.; Allaie, S.P. The changing water quality of lakes—A case study of Dal Lake, Kashmir Valley. *Environ. Monit. Assess.* **2022**, *194*, 228. [CrossRef] [PubMed]
5. Das, R.; Chanakya, H.N.; Rao, L. Study towards understanding foaming and foam stability in urban lakes. *J Env. Manag.* **2022**, *322*, 116111. [CrossRef]
6. Pattanaik, S.; Pattanaik, D.K.; Das, M.; Panda, R.B. Environmental scenario of chromite ore mining at Sukinda valley beyond 2030. *Discov. Sci.* **2012**, *1*, 35–39.

7. Vyas, V.; Bara, S.; Parashar, V.; Damde, D.; Tuli, R.P. Temporal variation in fish biodiversity of River Narmada in Hoshangabad Region. *Fish. Chimes* **2006**, *27*, 49–53.
8. Teles, Y.V.; de Castro, L.M.; Sargentini Junior, É.; Do Nascimento, A.P.; da Silva, H.A.; Costa, R.S.; do Nascimento Souza, R.D.; da Mota, A.J.; Pereira, J.O. Potential of bacterial isolates from a stream in manaus-amazon to bioremediate chromium-contaminated environments. *Water Air Soil Pollut.* **2018**, *229*, 266. [CrossRef]
9. Ishaq, S.; Jabeen, G.; Arshad, M.; Kanwal, Z.; Un Nisa, F.; Zahra, R.; Shafiq, Z.; Ali, H.; Samreen, K.B.; Manzoor, F. Heavy metal toxicity arising from the industrial effluents repercussions on oxidative stress, liver enzymes and antioxidant activity in brain homogenates of Oreochromis niloticus. *Sci Rep.* **2023**, *13*, 19936. [CrossRef]
10. Bassi, N.; Kumar, M.D.; Sharma, A.; Pardha-Saradhi, P. Status of wetlands in India: A review of extent, ecosystem benefits, threats and management strategies. *J. Hydrol. Reg. Stud.* **2014**, *2*, 1–19. [CrossRef]
11. Iyakkam, A. Why Chennai Stinks? Kalachuvadu Publications: Chennai, India, 2017.
12. Lan, T.; Almered Olson, E.; Alpokay, S. *Environmental Stresses and Resource Use in Coastal Urban and Peri-Urban Regions DPSIR Approach to SECOA's 17 Case Studies*; Sapienza Universitá Editrice: Rome, Italy, 2014; pp. 21–32.
13. Hashem, H.A.; Hassanein, R.A.; Bekheta, M.A.; El-Kady, F.A. Protective role of selenium in canola (*Brassica napus* L.) plant subjected to salt stress. *Egypt. J. Exp. Biol.* **2013**, *9*, 199–211.
14. Ogbo, E.M.; Okhuoya, J.A. Bio-absorption of some heavy metals by Pleurotus tuber-regium Fr. Singer (an edible mushroom) from crude oil polluted soils amended with fertilizers and cellulosic wastes. *Int. J. Soil Sci.* **2011**, *6*, 34. [CrossRef]
15. Subroto, M.A.; Priambodo, S.; Indrasti, N.S. Accumulation of zinc by hairy root cultures of Solanum nigrum. *Biotechnology* **2007**, *6*, 344–348. [CrossRef]
16. Bhattacharya, A.K.; Naiya, T.K.; Mandal, S.N.; Das, S.K. Adsorption, kinetics and equilibrium studies on removal of Cr (VI) from aqueous solutions using different low-cost adsorbents. *Chem. Eng. J.* **2008**, *137*, 529–541. [CrossRef]
17. Prabhu, B.; Batvari, D.; Surendran, A. Assessment of heavy metal contamination in Chemberambakkam lake water, Chennai, Tamil Nadu. *J. Chem. Pharm. Res.* **2015**, *7*, 865–869.
18. Lakshmi, D.M.S.R.; Thulasi, M.D.; Ahmad, T.J. Geo-chemical evaluation of heavy metals in the lakes of south Chennai, Tamil Nadu, India. *Int. J. Res. Soc. Sci.* **2018**, *8*, 643–657.
19. Jayaprakash, M.; Urban, B.; Velmurugan, P.M.; Srinivasalu, S. Accumulation of total trace metals due to rapid urbanization in microtidal zone of Pallikaranai marsh, South of Chennai, India. *Environ. Monit. Assess.* **2010**, *170*, 609–629. [CrossRef] [PubMed]
20. Arumugam, G.; Rajendran, R.; Shanmugam, V.; Sethu, R.; Krishnamurthi, M. Flow of toxic metals in food-web components of tropical mangrove ecosystem, Southern India. *Hum. Ecol. Risk Assess. Int. J.* **2018**, *24*, 1367–1387. [CrossRef]
21. Vinothkannan, A.; Charles, P.E.; Rajaram, R. Ecological risk assessment and seasonal variation of heavy metals in water and sediment collected from industrially polluted Cuddalore coast, Southeastern India. *Reg. Stud. Mar. Sci.* **2022**, *49*, 102134. [CrossRef]
22. APHA. *Standard Methods for the Examination of Water and Waste Water*, 20th ed.; American Public Health Association: Washington, DC, USA, 1998.
23. Jonathan, M.P.; Srinivasalu, S.; Thangadurai, N.; Ayyamperumal, T.; Armstrong-Altrin, J.S.; Ram-Mohan, V. Contamination of Uppanar River and coastal waters off Cuddalore, Southeast coast of India. *Environ. Geol.* **2008**, *53*, 1391–1404. [CrossRef]
24. Muller, G. Index of geoaccumulation in sediments of the Rhine River. *Geojournal* **1969**, *2*, 108–118.
25. Khuzestani, R.B.; Souri, B. Evaluation of heavy metal contamination hazards in nuisance dust particles, in Kurdistan Province, western Iran. *J. Environ. Sci.* **2013**, *25*, 1346–1354. [CrossRef]
26. Taylor, S.R.; McLennan, S.M. *The Continental Crust: Its Composition and Evolution*; Blackwell Scientific: Oxford, UK, 1985; p. 312, ISBN 0-632-01148-3.
27. Hakanson, L. An ecological risk index for aquatic pollution control. A sedimentological approach. *Water Res.* **1980**, *14*, 975–1001. [CrossRef]
28. Varol, M.; Şen, B. Assessment of nutrient and heavy metal contamination in surface water and sediments of the upper Tigris River, Turkey. *Catena* **2012**, *92*, 1–10. [CrossRef]
29. Abel, A.B.; Mankiw, N.G.; Summers, L.H.; Zeckhauser, R.J. Assessing dynamic efficiency: Theory and evidence. *Rev. Econ. Stud.* **1989**, *56*, 1–19. [CrossRef]
30. Pal, S.; Mondal, S.; Maity, J.; Mukherjee, R. Synthesis and characterization of ZnO nanoparticles using Moringa oleifera leaf extract: Investigation of photocatalytic and antibacterial activity. *Int. J. Nanosci. Nanotechnol.* **2018**, *14*, 111–119.
31. Siddiqui, E.; Verma, K.; Pandey, U.; Pandey, J. Metal contamination in seven tributaries of the Ganga River and assessment of human health risk from fish consumption. *Arch. Environ. Contam. Toxicol.* **2019**, *77*, 263–278. [CrossRef]
32. US Environmental Protection Agency (USEPA). *Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories*; Risk Assessment and Fish Consumption Limits; USEPA: Washington, DC, USA, 2000; Volume 2, EPA 823-B-00-008.
33. Bennett, D.H.; Kastenberg, W.E.; McKone, T.E. A multimedia, multiple pathway risk assessment of atrazine: The impact of age differentiated exposure including joint uncertainty and variability. *Reliab. Eng. Syst. Saf.* **1999**, *63*, 185–198. [CrossRef]
34. USEPA and USACE (US Environmental Protection Agency and US Army Corps of Engineers). Clean Water Rule: Definition of "Waters of the United States". *Fed. Reg.* **2015**, *80*, 37054–37127.

35. Almeida, J.A.; Diniz, Y.S.; Marques SF, G.; Faine, L.A.; Ribas, B.O.; Burneiko, R.C.; Novelli EL, B. The use of the oxidative stress responses as biomarkers in Nile tilapia (*Oreochromis niloticus*) exposed to in vivo cadmium contamination. *Environ. Int.* **2002**, *27*, 673–679. [CrossRef]
36. Xu, Y.J.; Liu, X.Z.; Ma, A.J. Current research on toxicity effect and molecular mechanism of heavy metals on fish. *Mar. Sci.-Qingdao-Chin. Ed.* **2004**, *28*, 67–70.
37. Barak, N.E.; Mason, C.F. Heavy metals in water, sediment and invertebrates from rivers in eastern England. *Chemosphere* **1989**, *19*, 1709–1714. [CrossRef]
38. Schertzinger, G.; Zimmermann, S.; Sures, B. Predicted sediment toxicity downstream of combined sewer overflows corresponds with effects measured in two sediment contact bioassays. *Environ. Pollut.* **2019**, *248*, 782–791. [CrossRef]
39. Tholkappian, M.; Chandrasekaran, A.; Harikrishnan, N.; Devanesan, E.; Ganeshand, D.; Ravisankar, R. Application of magnetic susceptibility in source identification of heavy metal pollution in sediments of Chennai Coast, Tamilnadu using multivariate statistical analysis. *J. Rad. Nucl. Appl.* **2019**, *4*, 15–23. [CrossRef]
40. Palanisamy, S.; Eswaran, R.; Muniasamy, M. Intensity of Pollution and Heavy Metals Toxicity on Surface Water Bodies of Coimbatore, Tamilnadu, India-A Case Study. *Appl. Ecol. Environ. Sci.* **2021**, *9*, 247–259. [CrossRef]
41. Rosado, D.; Castillo, F.; Nambi, I.; Sadhasivam, R.; Valleru, H.; Fohrer, N. Evaluating heavy metal levels and their toxicity risks in an urban lake in Chennai, India. *Int. J. Environ. Sci. Technol.* **2023**, *21*, 1849–1864. [CrossRef]
42. Zhang, L.; Shi, Z.; Zhang, J.; Jiang, Z.; Wang, F.; Huang, X. Spatial and seasonal characteristics of dissolved heavy metals in the east and west Guangdong coastal waters, South China. *Mar. Pollut. Bull.* **2015**, *95*, 419–426. [CrossRef] [PubMed]
43. Yee, L.T.; Paka, D.D.; Nyanti, L.; Ismail, N.; Emang, J.J. Water quality at Batang Ai hydroelectric reservoir (Sarawak, Malaysia) and implications for aquaculture. *Int. J. Appl.* **2012**, *2*, 23–30.
44. Agency for Toxic Substances and Disease Registry. *ATSDR Toxicological Profile for Di(2-ethylhexyl)phthalate (DEHP)*; U.S. Department of Health and Human Services, Public Health Service: Atlanta, GA, USA, 2002.
45. Beyer, W.N.; Day, D.; Melancon, M.J.; Sileo, L. Toxicity of Anacostia River, Washington DC, USA, Sediment Fed to Mute Swams (Cygnus olor). *Environ. Toxicol. Chem.* **2000**, *19*, 731735. [CrossRef]
46. Brungs, W.A. Effects of residual chlorine on aquatic life. *J. Water Pollut. Control. Fed.* **1973**, *45*, 2180–2193.
47. Hiltibran, R.C. Effects of cadmium, zinc, manganese, and calcium on oxygen and phosphate metabolism of bluegill liver mitochondria. *J. Water Pollut. Control. Fed.* **1971**, *43*, 818–823. [PubMed]
48. Jones, I.; Kille, P.; Sweeney, G. Cadmium delays growth hormone expression during rainbow trout development. *J. Fish. Biol.* **2001**, *59*, 1015–1022. [CrossRef]
49. Plachy, J. Cadmium. In *USGS. US Geological Survey Minerals Yearbook—2003*; Reston: Englewood Cliffs, NJ, USA, 2003; pp. 15.1–15.5.
50. Rajeshkumar, S.; Li, X. Bioaccumulation of heavy metals in fish species from the Meiliang Bay, Taihu Lake, China. *Toxicol. Rep.* **2018**, *5*, 288–295. [CrossRef] [PubMed]
51. García-Lestón, J.; Méndez, J.; Pásaro, E.; Laffon, B. Genotoxic effects of lead: An updated review. *Environ. Int.* **2010**, *36*, 623–636. [CrossRef] [PubMed]
52. Rashed, M.N. Cadmium and lead levels in fish (*Tilapia nilotica*) tissues as biological indicator for lake water pollution. *Environ. Monit. Assess.* **2001**, *68*, 75–89. [CrossRef] [PubMed]
53. Gopal, V.; Shanmugasundaram, A.; Nithya, B.; Magesh, N.S.; Jayaprakash, M. Water quality of the Uppanar estuary, Southern India: Implications on the level of dissolved nutrients and trace elements. *Mar. Pollut. Bull.* **2018**, *130*, 279–286. [CrossRef]
54. Zhang, J.; Li, X.; Guo, L.; Deng, Z.; Wang, D.; Liu, L. Assessment of heavy metal pollution and water quality characteristics of the reservoir control reaches in the middle Han River, China. *Sci. Total Environ.* **2021**, *799*, 149472. [CrossRef]
55. Ke, X.; Gui, S.; Huang, H.; Zhang, H.; Wang, C.; Guo, W. Ecological risk assessment and source identification for heavy metals in surface sediment from the Liaohe River protected area, China. *Chemosphere* **2017**, *175*, 473–481. [CrossRef]
56. Muneer, W.; Behera, D.; Ankit, Y.; Anoop, A.; Mishra, P.K.; Jehangir, A. Historical trends of heavy metal contamination and eutrophication in an aquatic system from Kashmir Himalaya, India. *Environ. Chall.* **2023**, *12*, 100721. [CrossRef]
57. Krishnam Shankar, H.N.; Ponnusamy, P. Investigation of Heavy Metals in the Surface and Groundwater and its Health Risk Assessment in the Parts of Gudiyattam Region, Tamilnadu, India. *Ecol. Eng. Environ. Technol.* **2023**, *24*, 20–29. [CrossRef]
58. Das Kangabam, R.; Bhoominathan, S.D.; Kanagaraj, S.; Govindaraju, M. Development of a water quality index (WQI) for the Loktak Lake in India. *Appl. Water Sci.* **2017**, *7*, 2907–2918. [CrossRef]
59. Bureau of Indian Standards. *Water, B. I. S., & Specification, I. S. D.*; Bureau of Indian Standards: New Delhi, India, 2012; pp. 1–12.
60. El-Azim, A.; Belal, A.; El-Salam, A.; Mourad, F.; Abo Elwafa, S. Water pollution by heavy metals in the western lagoon and its effect on Timsah Lake and consequently on Suez Canal. *Catrina Int. J. Environ. Sci.* **2018**, *17*, 71–76. [CrossRef]
61. Yadav, K.K.; Kumar, V.; Gupta, N.; Kumar, S.; Rezania, S.; Singh, N. Human health risk assessment: Study of a population exposed to fluoride through groundwater of Agra city, India. *Regul. Toxicol. Pharmacol.* **2019**, *106*, 68–80. [CrossRef] [PubMed]
62. Saha, N.; Zaman, M.R. Evaluation of possible health risks of heavy metals by consumption of foodstuffs available in the central market of Rajshahi City, Bangladesh. *Environ. Monit. Assess.* **2013**, *185*, 3867–3878. [CrossRef]
63. Ullah, A.A.; Afrin, S.; Hosen, M.M.; Musarrat, M.; Ferdoushy, T.; Nahar, Q.; Quraishi, S.B. Concentration, source identification, and potential human health risk assessment of heavy metals in chicken meat and egg in Bangladesh. *Environ. Sci. Pollut. Res.* **2022**, *29*, 22031–22042. [CrossRef] [PubMed]

64. Akila, M.; Anbalagan, S.; Lakshmisri, N.M.; Janaki, V.; Ramesh, T.; Merlin, R.J.; Kamala-Kannan, S. Heavy metal accumulation in selected fish species from Pulicat Lake, India, and health risk assessment. *Environ. Technol. Innov.* **2022**, *27*, 102744. [CrossRef]
65. Maurya, P.K.; Malik, D.S.; Yadav, K.K.; Kumar, A.; Kumar, S.; Kamyab, H. Bioaccumulation and potential sources of heavy metal contamination in fish species in River Ganga basin: Possible human health risks evaluation. *Toxicol. Rep.* **2019**, *6*, 472–481. [CrossRef]
66. Ezemonye, L.I.; Enuneku, A.A. Hepatic bioaccumulation of cadmium in the crowned bullfrog, Hoplobatrachus occipitalis and flat backed toad, Bufo maculatus. *Int. J. Aquat. Sci.* **2012**, *3*, 15–22.