

Toxicity and Human Health Risk Assessment of Heavy Metals in the sediments of the Korle Lagoon Using Fish Bioassay

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Abstract

This study evaluated the toxicity of sediments from the Korle Lagoon, a heavily polluted water body, by assessing the bioaccumulation of heavy metals in *Sarotherodon galilaeus* through a 10-day fish bioassay. Sediment heavy metal concentrations were analyzed using USEPA Method 3050B, while heavy metals in fish tissues were assessed before and after exposure using USEPA Method 200.11. The results revealed an alarming mortality rate of 90–100% in fish exposed to the sediments, compared to only 10% in the control group. This high mortality correlated with elevated heavy metal concentrations in the sediments. The geoaccumulation index of heavy metals in sediments showed that the Korle Lagoon is moderately polluted with Cd (0-1.85), Pb (0.37-1.56) and Zn (1.14); moderately to strongly polluted with As (0.03-2.88); and extremely polluted with Fe (9.90-13.10). Post-exposure analysis showed significant accumulation of heavy metals in fish tissues, with recorded concentrations of Cu (103.75 mg/kg), Cd (0.31 mg/kg), As (13.95 mg/kg), Cr (16.02 mg/kg), Ni (7.97 mg/kg), Pb (5.83 mg/kg), and Hg (0.72 mg/kg). Most values exceeded WHO guideline limits, except for Ni and Cd. The estimated hazard index values for adults (328.52) and children (191.63) suggest a severe risk of non-carcinogenic health effects from consuming exposed fish. Additionally, lifetime cancer risk values (LCR > 0.0006) indicated potential carcinogenic threats. These findings confirm the toxicity of Korle Lagoon sediments and highlight significant ecological and public health risks, particularly for local communities dependent on fish from the lagoon as a dietary staple. Urgent mitigation measures are necessary to address heavy metal contamination and protect aquatic and human health.

Introduction

The Korle Lagoon, once a thriving freshwater ecosystem teeming with aquatic life such as crabs and fish, played a crucial role in ensuring food security for local communities (Squire, 2018). On the other hand, it is now widely acknowledged as being among the most contaminated water bodies worldwide (Osae et al., 2022). The land surrounding the lagoon has been significantly altered by rapid, unplanned urbanization, and is now home to slums, informal settlements, and a concentration of industrial activities. Various sources of pollution, including textile factories, breweries, vehicle repair shops,

material recovery sites, and electronic waste dumping at Agbogbloshie, contribute heavily to the contamination of the lagoon (Aglanu and Appiah, 2014).

Effluents from industrial, household, and agricultural activities, both treated and untreated, are discharged into the lagoon, resulting in alarming concentrations of metals in its waters and surrounding lands (Clotley, 2018; Aboagye, 2012; Fosu-Mensah et al., 2017). For instance, Clotley (2018) reported extremely high concentrations of cadmium (1.10-54.50 mg/kg), lead (42.92-112.45 mg/kg), and copper (5.15-29.38 mg/kg) in the lagoon's sediments. While the heavy pollution makes the Korle Lagoon generally not suitable

for fish survival, the lagoon is part of the open sea; fish periodically enters the lagoon and may bioaccumulate heavy metals. Moreover, fishing occurs at the estuary of the lagoon suggesting that edible fish can be exposed to contaminants.

Fosu-Mensah et al. (2017) documented heavy metal pollution in the surrounding soil, including elevated levels of lead, cadmium, and copper, well beyond acceptable limits. The presence of these metals poses serious risks to human health, as shown by Aboagye (2012), who found that fish from the lagoon's estuary had cadmium and lead levels exceeding World Health Organization (WHO) guidelines, making them hazardous for consumption.

Sediments in aquatic environments serve as reservoirs for heavy metals, playing a vital role in their storage and distribution (Abdallah and Mohamed, 2019). Under shifting environmental circumstances, pollutants that are deposited in sediments can build up to quantities that are far greater than those in the water itself. These pollutants may re-enter the water column, causing secondary contamination (Algül and Beyhan, 2020; Huang et al., 2020). Aquatic organisms exposed to contaminated sediments can bioaccumulate these toxic substances, introducing them into the food chain and posing risks to human and environmental health.

Even though the Korle Lagoon has been shown to be impacted by heavy metals in several studies, there has not yet been a comprehensive assessment of the sediments' toxicity to aquatic and terrestrial organisms. Furthermore, the potential for these metals to bioaccumulate in fish, which could then be consumed by humans, remains largely unexplored. Addressing this gap is crucial to understanding the broader ecological and

public health risks associated with the lagoon's contamination.

Toxicity testing is an essential tool for assessing the biological effects of environmental pollutants on both aquatic and terrestrial organisms. The Whole Sediment Toxicity Bioassay, which measures the response of aquatic organisms to sediments in controlled environments, is particularly useful for evaluating the overall toxic impact of all pollutants present (DeIValis et al., 2004). This method provides a more comprehensive picture of sediment toxicity compared to other approaches, as it captures the combined effects of multiple contaminants (Bat, 2005; Morales-Caselles et al., 2008).

Given the high levels of heavy metals previously reported in the Korle Lagoon, it is critical to assess the toxicity of its sediments and the potential health risks associated with consuming fish exposed to these sediments. This study aims to assess the toxicity of sediments from the Korle Lagoon using a whole sediment fish bioassay and evaluate the associated health risks for consumers of fish exposed to the contaminated sediments. The findings will contribute to understanding the hazardous impacts of toxic sediments, both in aquatic ecosystems and when stored on land, offering insights for mitigation strategies.

Methodology

Study location

The research examines the Korle Lagoon and its surrounding catchment region in Accra, the capital of Ghana. The lagoon, situated at coordinates 05°35'N, 00°6'W, has a catchment area of approximately 400 km², falling within the Accra Metropolitan Assembly. It spans

an area of approximately 0.6 km², rendering it a notable element in the city's topography (Aglanu and Appiah, 2014).

Sediment sampling and processing

Three surface sediments (1–15 cm) were randomly selected from each of the four quadrants that made up the sampling site (Figure 1), for a total of 12 samples. Using a Van Veen grab, the sediments were gathered in plastic bags and brought to the lab in refrigerators with ice packs. In the laboratory, sediment from each site was fully homogenized into four samples and subsampled for the analysis of heavy metals, organic matter, and pH. Samples were analyzed in triplicates and reported as the mean \pm standard deviation. Sediment samples for Bioassay were kept at 4°C in the dark until needed. Similarly, sediments were gathered from the Labadi beach to serve as control. Labadi beach is about 14km from the Korle lagoon. Labadi Beach was selected as the control site due to its relative distance from the Korle Lagoon and its lower degree of direct industrial and domestic effluent influence compared to the Lagoon. While both areas are within the

same coastal stretch, Labadi Beach provides a baseline for background coastal sediment conditions in Accra. The heavy metals in sediments from the Labadi beach were tested prior to the experiment and low concentration were observed. Labadi was considered the most practical and representative control site given accessibility, environmental setting, and its reduced exposure to direct discharges from the Korle Lagoon.

Analysis of Heavy metals in sediments

An aliquot of dried sediment samples (<2 mm sieve size) weighing 2g was digested following the USEPA Method 3050B. To the sediment sample, 1 mL of concentrated HCl and 1 mL of HNO₃ were added and digested for 40 minutes on a digestion block preheated to 110 \pm 4°C. After the initial digestion, the tube was removed from the block, 10 mL of deionized water was added, and digestion continued for another 20 minutes. The samples were then cooled and brought up to a final volume of 50 mL with deionized water. A millilitre of 1:1 HNO₃ was added to the digested samples to further dilute them. As, Cu, Cd, Cr, Pb, Hg, Ni, Zn, and Fe were among the heavy

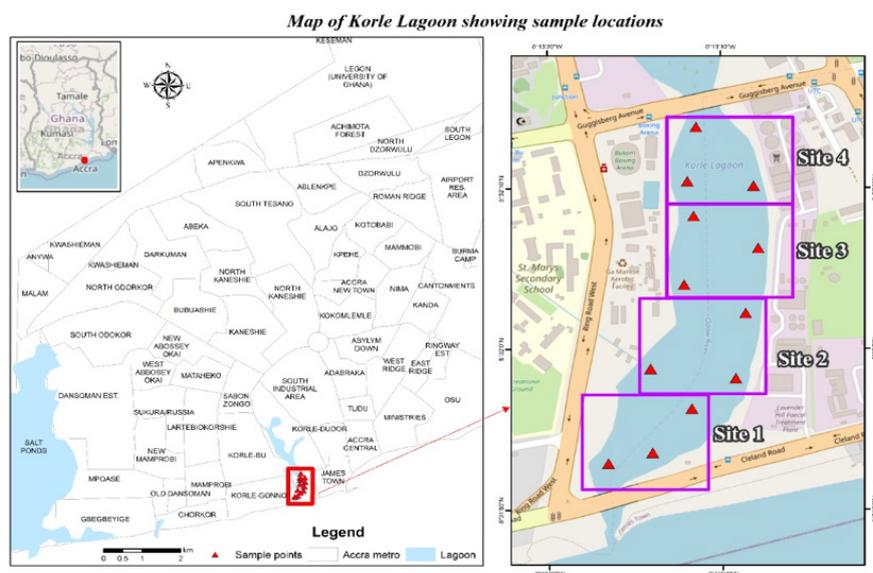


Figure 1 Map showing the study location and sample location

metals that were measured with a Nexion 2000 ICPMS, which has a spray chamber and a micro mist nebuliser. Iron (Fe) is not typically classified as a heavy metal in the context of environmental pollution. However, it was included in our study because Fe can influence the mobility and bioavailability of other heavy metals in sediments through geochemical interactions such as adsorption and redox reactions. Monitoring Fe content helps provide a more complete understanding of sediment geochemistry and the potential behavior of toxic metals, even though it is not considered a pollutant in itself. The following dwell periods were established for each metal: Hg takes 100 ms, As takes 60 ms, Pb takes 50 ms, Cu takes 25 ms, Zn takes 25 ms, Cd takes 25 ms, and Cr takes 25 ms. For repeated samples, all relative standard deviations were less than 20%. Duplicates, reagent blanks, and certified reference material (Enviromat-contaminated soil SS-2) were used for quality control, and findings were considered valid if recovery rates were higher than 90%.

Organic matter

A little over one- third (0.35) g of dried sediment was weighed and treated with 6 M HCl in a carbon-free combustion boat until effervescence ceased. Following a 24-hour drying period at 40°C, the samples were further dried at 105°C. After drying, the boats were

put in a LECO Analyzer's autosampler rack to be analysed for total organic carbon (TOC). The organic matter content was calculated by multiplying the TOC value by a conversion factor of 1.724, as outlined by Walkley and Black (1934).

$$\text{Organic matter (\%)} = \text{TOC (\%)} \times 1.724 \quad (1)$$

2.5 pH

A 10 g sample of sediment was placed into a 50 mL tube, and 40 mL of deionized water was added. The mixture was then shaken mechanically at room temperature for 30 minutes. After one hour, the pH of the solution was determined using a TPS Smartchem electrode probe and meter.

Geo-accumulation index

The Igeo index was applied to evaluate soil pollution by comparing the concentration of heavy metals in the soil to the background levels, as described by Equation 2:

$$I_{geo} = \log_2 \frac{C_n}{1.5B_n} \quad (2)$$

where B_n is the background concentration of heavy metals in the soil and C_n is the concentration of each heavy metal (mg/kg) (Taylor, 1964). Table 1 presents the categorisation for the Geo Accumulation Index (Müller, 1981) and Table 2 presents the baseline amounts of heavy metals in the

TABLE 1

Classification criteria for Geo-accumulation index (Igeo). (Müller, 1981)

Igeo level	Class	Contamination status
Igeo<0	0	Unpolluted
0<Igeo<1	1	Unpolluted to moderately polluted
1<Igeo<2	2	Moderately polluted
2<Igeo<3	3	Moderately to strongly polluted
3<Igeo<4	4	Strongly polluted
4<Igeo<5	5	Strongly polluted
5<Igeo	6	Extremely polluted

TABLE 2
Background levels of heavy metals in the continental crust (Taylor, 1964)

Element	Background level(mg/kg)
Cu	55
Cd	0.2
As	1.8
Cr	100
Ni	75
Pb	12.5
Hg	0.08
Zn	70
Fe	5.63

continental crust (Taylor, 1964).

Toxicity test procedure

The toxicity test was conducted following the sediment toxicity test procedure for fish bioassays proposed by Jiménez-Tenorio *et al.* (2006). In this study, *Sarotherodon galilaeus* was selected over *Sparus aurata* and *Solea senegalensis*, as the former is more readily available and exhibits a greater tolerance for a wide range of habitats and conditions.

Juvenile *S. galilaeus* were sourced from an aquaculture farm and transported to the laboratory in sealed polyethylene bags with headspace filled with oxygen. Upon arrival, the fish samples were analyzed for baseline concentrations of heavy metals. The remaining fish were placed in an aquarium equipped with an air filter and aerator to maintain optimal water quality while they acclimatized to laboratory conditions over a 10-day period. The fish were fed twice daily with a commercial fish ration. The water used during acclimatization was tap water that had been aerated for 48 hours to remove any chlorine residues. Prior to the experiment, the tap water was tested for heavy metals and found to be free of detectable contaminants.

Following the acclimation phase, a 2 cm layer of sediments from the Korle Lagoon

and a control sediment sample from Labadi Beach was placed separately in 5-liter glass aquariums, along with the previously aerated tap water. Each aquarium was fitted with a biofilter to maintain water quality and a pump to ensure adequate oxygen levels. Twenty juveniles were introduced into each test aquarium 24 hours after adding the sediments. A 12-hour light photoperiod was maintained throughout the experiment.

Dissolved oxygen (DO), pH, ammonia (NH₃), and nitrite (NO₂) levels were measured twice weekly in each aquarium to ensure they remained within acceptable limits. The fishes were fed twice daily with fish ration. The survival of the fishes was visually monitored daily in each aquarium. At the end of the experiment, the fishes were collected using an aquarium net, and the sediments were washed through the net to recover any surviving specimens. The effects of the sediments on fish survival and the bioaccumulation of heavy metals were evaluated after the 10-day exposure period.

Analysis of heavy metals in fish

Before and after the whole sediment bioassay, fish samples were analyzed using whole fish samples according to USEPA Method 20.11, which describes the determination

of heavy metals in fish tissues by ICP. A 2 g whole fish samples were dissociated with tetramethylammonium hydroxide by frequent mixing over low heat and vortexing for 2 hours. The samples were partially oxidized by adding 5 ml of hydrogen peroxide and left overnight at room temperature. One (1) ml of HNO₃ was added and heated at 100° C for 1 hour. Samples were allowed to cool and adjusted to final volume with deionized water. Samples were analyzed for their heavy metal content using ICPMS according to the procedure described in section 2.3.

Potential ecological risk

The potential ecological risk of heavy metals contamination in the sediments of the Korle Lagoon was characterized using sediment quality guidelines, ERL (Effect range low) and ERM (effect range median). The ERL represents the contaminant concentration that is likely to rarely cause adverse biological effects, and the ERL-ERM interval represents the range of contaminant concentrations that are likely to occasionally cause adverse biological effects. ERM represents the probability of contaminants to frequently cause adverse biological effects. Based on the ERL and ERM values, ERMQ and ERLQ were calculated using Equations 3 and 4.

$$ERMQ = \frac{\text{Concentration of heavy metal}}{ERM \text{ of the same heavy metal}} \quad (3)$$

$$ERLQ = \frac{\text{Concentration of heavy metal}}{ERL \text{ of the same heavy metal}} \quad (4)$$

If the ERLQ exceeded 1.0, a corresponding ERMQ was derived instead, and three potential risk levels associated with the measured metal concentrations were defined as follows: ERLQ ≤ 1.0 low risk, ERLQ > 1 but ERMQ < 1.0 moderate risk and ERMQ ≥ 1.0 high risk.

Bioconcentration factor (BCF)

The bioaccumulation of heavy metals in fish tissues was evaluated using the bioconcentration factor as shown in equation 5 (USEPA, 2003).

$$BCF = \frac{\text{Concentration of metals in fish}}{\text{concentration of metals in water}} \quad (5)$$

Health risk assessment

The evaluation of human health risks seeks to evaluate the potential adverse health consequences on humans exposed to metals in contaminated environments. This process encompasses exposure assessments along with evaluations of both non-carcinogenic and carcinogenic risks. Considering the physiological and behavioral differences, the health risk assessment was performed separately for adults and children.

Exposure assessment

The Estimated Daily Intake (EDI) was employed to assess human exposure to heavy metals by direct intake, utilizing the formula presented in Equation 6. (USEPA methods, 1992). The calculations were carried out for two groups: children (as a vulnerable group) and adults (representing the general population).

$$EDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (6)$$

where C is the metal content in the food (mg/kg), IR is the intake rate (kg/day), EF is the exposure frequency, ED is the exposure duration, BW (kg) is body weight, AT is the average exposure time, and EDI (mg/kg/day) is the estimated daily intake. Table 3 provides specifics on the EDI calculation parameters.

Non carcinogenic health risk

Assessing the likelihood that exposure to a certain chemical may result in detrimental health consequences over a predetermined

TABLE 3
Parameters for assessment of estimated daily intake

Parameter	Value	Reference
IR	0.1g/day for children and 0.2 g/day for adults	USEPA, 2012
EF	180 days/year	USEPA, 2012
ED	6years for children and 24 years for adults	USEPA, 2012
BW	70kg for adults and 15kg for children	USEPA, 2012
AT	365 *ED	

time is known as non-carcinogenic health risk assessment. The Hazard Quotient and Hazard Index were used to evaluate the non-carcinogenic health risk.

Hazard quotient

Equation 7 was used to calculate the Hazard Quotient (HQ). HQ is the ratio of a substance's possible exposure to the amount at which no negative effects are expected (USEPA, 1989). The reference doses (RD) for the different heavy metals, along with their cancer slope factors (CSF), are provided in Table 4 (USEPA, 2012).

$$HQ = \frac{EDI}{RD} \quad (7)$$

Hazard Index

Multiple pollutants' cumulative non-carcinogenic health hazards were evaluated using the Hazard Index (HI) technique (USEPA, 1989). Equation 8 is used to determine the HI for a combination of contaminants (USEPA, 1989).

$$HI = \sum HQ \quad (8)$$

If the HI value is below 1, the exposed population is unlikely to face significant adverse health effects. However, HI values above 1 could indicate potential harmful health impacts (USEPA, 1989).

Carcinogenic risk assessment

By calculating the possibility of getting cancer over the course of one's lifespan because of exposure to possible carcinogens, carcinogenic risk was evaluated. Equation 9's cancer slope factor was utilized for estimating the carcinogenic health risk (USEPA, 1989). The cancer slope factor represents the estimated likelihood that an individual will develop cancer after a lifetime of exposure (70 years) to a chemical substance

$$LCR = EDI \times CSF \quad (9)$$

Where LCR is the lifetime cancer risk and CSF is the cancer slope factor (mg/kg/day).

A lifetime cancer risk (LCR) greater than 1×10^{-4} is considered unacceptable, risks lower than 1×10^{-6} are regarded as insignificant, and risks falling between 1×10^{-4} and 1×10^{-6} are

TABLE 4
Reference dose and cancer slope factor (CSF) for heavy metals

	Ref Dose (mg/kg/day)	CSF(mg/kg/day)
Cd	0.001	0.0061
Cr	1.5	0.041
Pb	0.004	0.0085
Fe	0.7	
Zn	0.3	
Cu	0.04	
Ni	0.02	0.00084
As	0.0003	1.5
Hg	0.0001	

considered acceptable (USEPA, 1989).

Ethical consideration

Strict ethical guidelines were followed in this study, which was approved by the University of Ghana's College of Basic and Applied Sciences Ethics Committee (Ref No. ECBAS 087/21-22). Procedures were designed to minimize discomfort to animal participants, ensuring humane treatment throughout the study. Physicochemical parameters, including dissolved oxygen (DO), nitrate (NO₃), ammonia (NH₃), and pH, were monitored continuously to maintain optimal experimental conditions. All waste products generated during the study were treated appropriately prior to disposal, following environmental safety standards.

Statistical analysis

Exploratory Data Analysis (EDA) was conducted to calculate the mean and standard deviation of the measured parameters, with replicate results expressed as mean ± standard deviation. To assess significant differences between parameters, Analysis of Variance (ANOVA) was performed at significance levels of 0.01 and 0.05. Principal Component Analysis (PCA) was applied to reduce the dimensionality of the dataset and improve interpretability. Correlation analysis was also carried out to examine relationships between variables. All statistical analyses, including EDA, PCA, and correlation, were performed

using SPSS version 24. Prior to analysis, the normality of the data was confirmed using the Shapiro-Wilks test.

Results

*Mortalities of *Sarotherodon galilaeus* in whole sediments bioassay and the physicochemical parameters of overlying water during the bioassay experiment*

The mortalities for *S. galilaeus* recorded at sites 1, 2,3,4 and control's bioassay were 90, 100, 100, 95 and 10% respectively (Table 5). The mortalities of *S. galilaeus* for the Korle lagoon's bioassay and the control's bioassay were significantly different. The mortality trend recorded was in the order Control<Site 1<site 4< Site 2=Site 3 (Table 5). The results for the physicochemical parameters for the overlying water body during the bioassay experiment is presented in Table 6 which shows that there was no buildup of Nitrite and NH₃ during the bioassay experiment. The DO was also within the normal ranges.

pH and organic matter contents of sediments before toxicity assessment

Table 7 presents the pH and organic matter (OM) content of sediments from both the Korle Lagoon and the control site. The sediments exhibited an alkaline nature, with pH values ranging from 8.24 to 8.70. In the Korle Lagoon,

TABLE 5

Mortalities of *S. galilaeus* in 10 days bioassay test with whole sediments from different sampling sites of the Korle Lagoon (Site 1,2,3,4) and Sediments from the Labadi beach (Control)

Sampling site	Number	Number of deaths	% Mortality
1	20	18	90
2	20	20	100
3	20	20	100
4	20	19	95
Control	20	2	10

TABLE 6

Physicochemical parameters of overlying water during the whole sediment bioassay test

Sampling site	pH	Nitrite	DO	NH ₃
1	8.24	ND	7.42±0.02	ND
2	8.69	ND	7.04±0.01	ND
3	8.48	ND	7.13±0.03	ND
4	8.70	ND	6.94±0.02	ND
Control	8.15	ND	7.01±0.02	ND

ND= Not detected

TABLE 7

pH and organic matter content of sediments and control site before bioassay experiment

Sampling site	pH	Organic matter
1	8.24	5.89±0.08
2	8.69	6.01±0.05
3	8.48	7.12±0.06
4	8.70	6.05±0.04
Control	8.16	1.24±0.02

a statistically significant difference in pH values across the four sites was found ($P = 0.001$; $P < 0.05$). However, the pH of the sediments from the Korle Lagoon and those from the control location did not change significantly ($P = 0.05$; $P = 0.05$). In the same way, there was a statistically significant variation in the amount of organic matter at each of the Korle Lagoon's locations ($P = 0.001$; $P < 0.05$). Furthermore, the organic matter composition of the sediments from the Korle Lagoon and the control site differed statistically significantly ($P = 0.001$; $P < 0.05$).

Total concentration of heavy metals in sediments from the Korle lagoon and control site before the bioassay experiment

The concentrations of heavy metals in the sediments before the bioassay experiment

are presented in Table 8. Results ranged from 3.81-43.64 mg/kg, ND-1.08 mg/kg, 2.76-19.93 mg/kg, 2.09-62.95 mg/kg, 6.70-26.17 mg/kg, 2.64-55.44 mg/kg, ND-0.12 mg/kg, 16.55-98.8 mg/kg and 15409-74155 mg/kg for Cu, Cd, As, Cr, Ni, Pb, Hg, Zn and Fe respectively. A statistically significant difference ($P=0.001$; $P<0.05$) was observed between the heavy metals in the sediments from the different sites of the Korle lagoon with Fe recording the highest concentration (15409.43 mg/kg-71155.71 mg/kg). Similarly, a statistically significant difference ($P=0.001$; $P<0.05$) was observed between the heavy metal content of the sediments from the Korle lagoon and the control sediment. The sediments from the control site recorded relatively lower concentration of heavy metals compared to that of the Korle lagoon. The sediments from the

TABLE 8

Heavy metals concentration (mg/kg) in sediments from the Korle Lagoon and control site before the bioassay experiment

Site	Cu	Cd	As	Cr	Ni	Pb	Hg	Zn	Fe
1	3.81±0.08	ND	2.76±0.05	2.09±1.09	26.17±	2.64±0.06	ND	16.55±3.33	74155.71±100.32
2	17.47±1.26	0.32±0.02	16.45±3.01	26.78±3.32	8.84±	18.12±3.54	0.02±0.01	87.02±16.68	15409.43±72.15
3	43.64±6.32	1.08±0.03	19.93±1.63	62.95±12.02	20.00±	55.44±12.28	0.12±0.04	231.50±18.13	59059.92±22.68
4	23.00±7.01	0.30±0.04	4.15±1.22	22.22±6.33	6.70±	24.24±5.18	0.01±0.07	98.80±18.61	19179.02±62.19
Control	3.13±0.08	ND	1.16±0.08	14.53±2.65	3.06±0.04	3.15±1.12	ND	38.23±3.67	8083.02±43.05
ERL	34	1.2	8.2	81	20.9	46.7	0.15	150	-
ERM	270	9.6	70	370	51.6	218	0.71	410	-

control site recorded 3.13mg/kg, 1.16 mg/kg, 14.53 mg/kg, 3.06 mg/kg, 3.15 mg/kg, 38.23 mg/kg, 8083.02 mg/kg for Cu, As, Cr, Ni, Pb, Zn and Fe respectively. Cd and Hg were not detected in sediments from the control site.

Geoaccumulation index of heavy metals in sediments before the toxicity assessment

Table 9 presents the geoaccumulation index of heavy metals in sediments of the Korle Lagoon and control site. The results showed that the sediments from the Korle Lagoon is moderately polluted with Cd (0-1.85), Pb (0.37-1.56) and Zn (1.14), moderately to strongly polluted with As (0.03-2.88), and extremely polluted with Fe (9.90-13.10). The sediments from the control site shows no contamination of heavy metals except Fe which was found to be extremely polluted.

Potential ecological risk of sediments from the Korle Lagoon and control site

The results for Effect range low quotient (ERLQ) and Effect range median quotient (ERMQ) are shown in Table 10. The results showed that some of the heavy metals from the sediments of the Korle Lagoon may pose

potential ecological risk in the environment. Particularly, Cu at sampling site 3, As at site 2 and 4, Ni at site 1, Pb at site 3 and Zn at site 3 pose moderate ecotoxicological risk. All other metals have ERLQ valued <1 indicating low ecological risk.

Concentration of heavy metals in fish samples before the toxicity experiment

Table 11 present the concentration of heavy metals in *S. galilaeus* before the bioassay experiment. The results recorded are 4.57 mg/kg, 0.03 mg/kg, 1.76 mg/kg, 0.49 mg/kg, 0.84 mg/kg, 0.02 mg/kg and 44 mg/kg for Cu, Cd, Cr, Ni, Pb, Hg, Zn respectively. Arsenic was not detected in the fish sample. All the results were below the reference guidelines limits for fish implying that the heavy metal content of fish was low before the bioassay experiment.

The concentration of heavy metals in fish after the bioassay experiment is also shown in Table 11. High concentration of Heavy metals was found in fish from the Korle Lagoon’s bioassay compared to the control. The results for the fish from the Korle sediment toxicity test was 103.75 mg/kg, 0.31 mg/kg, 13.95 mg/kg, 16.02 mg/kg, 1.83 mg/kg, 5.83 mg/kg for Cu, Cd, As,

TABLE 9

Geoaccumulation index of heavy metals in sediments from the Korle lagoon and control site

	Cu	Cd	As	Cr	Ni	Pb	Hg	Zn	Fe
1	-4.44	0	0.03	-6.17	-2.10	-2.83	0	-2.67	13.10
2	-2.24	0.09	2.61	-2.49	-3.67	-0.05	-2.58	-0.27	10.83
3	-0.92	1.85	2.88	-1.25	-2.49	1.56	0.00	1.14	12.77
4	-1.84	0.00	0.62	-2.76	-4.07	0.37	-3.58	-0.09	11.15
Control	-4.72	0	-1.22	-3.37	-5.20	-2.57	0	-1.46	9.90

TABLE 10

Derived risk quotient for potential ecological risk

	Cu	Cd	As	Cr	Ni	Pb	Hg	Zn
1	0.11	0.00	0.34	0.03	0.51	0.06	0.00	0.11
2	0.51	0.27	0.24	0.33	0.42	0.39	0.13	0.58
3	0.13	0.90	0.28	0.78	0.96	0.25	0.80	0.56
4	0.68	0.25	0.51	0.27	0.32	0.52	0.07	0.66
Control	0.09	0.00	0.14	0.18	0.15	0.07	0.00	0.25

Bold-ERMQ and unbold-ERLQ

TABLE 11

Concentration of heavy metals in fish before and after the bioassay experiment and their bioconcentration factors

Metal	Metals Before	Control After (mg/kg)	Korle After (mg/kg)	Reference guideline (mg/kg)	Reference
Cu	4.57 ± 0.27	3.35 (1.07)	103.75 (4.7)	30	WHO, 1995
Cd	0.03 ± 0.001	0.03 (0.00)	0.31 (0.73)	0.5	FAO, 1983
As	ND	0.06 (0.52)	13.95 (1.28)	1	FAO/WHO, 2002
Cr	1.76 ± 0.09	0.37 (0.25)	16.02 (0.56)	13	USFDA 1993
Ni	0.49 ± 0.07	0.19 (0.06)	1.83 (0.12)	80	USFDA 1993
Pb	0.84 ± 0.08	0.22 (0.07)	5.83 (0.23)	2	WHO, 1995
Hg	0.02 ± 0.002	0.01 (0.00)	0.67 (0.32)	0.005	WHO, 1995
Zn	19.23 ± 2.49	27.01 (0.71)	390 (3.59)	30	FAO, 1983
Fe	36.8±1.25	43.01(0.005)	231(0.007)		

Cr, Ni, Pb, Hg, and Zn respectively. That of the control was 3.35 mg/kg, 0.03 mg/kg, 0.06 mg/kg, 0.37 mg./kg, 0.19 mg/kg, 0.22 mg/kg, 0.01 mg/kg and 27.01 mg/kg for Cu, Cd, As, Cr, Ni, Pb, Hg, Zn and Fe respectively. Similarly, the Fish from the Korle sediment bioassay recorded very high bioconcentration factor (0.32-4.7) compared to those from the control sediments bioassay (0.00-1.07).

Sources of Heavy metals in tissues of the fish after the bioassay experiment

Correlation of heavy metals

Pearson correlation was used to identify the relationship between the heavy metals in sediments and mortality. Significant correlation was observed between all the heavy metals except for Fe and Ni which did not correlate

with the other metals but correlated with each other (Table 12). Similarly, significant correlation was observed between the heavy metals and mortality except for Fe and Ni. Also, a correlation analysis was performed for the heavy metals found in the fish tissues after the bioassay experiment to determine the relationship between the metals. There was a high correlation between the heavy metals Cu, Cd, Cr, Pb, Hg and Zn (Table 13). Similarly, Fe and Ni did not correlate with the other metals but correlated with each other.

Principal component analysis (PCA)

PCA identified two principal components with eigen values greater than 1 which explained 90% of the total variance. PC1 explained 70% of the total variance and was highly loaded

TABLE 12

Correlation between heavy metals in sediments and mortality

	Cu	Cd	As	Cr	Ni	Pb	Hg	Zn	Fe	Mortality
Cu	1									
Cd	.974**	1								
As	.675*	.758*	1							
Cr	.973**	.991**	.818**	1						
Ni	-0.13	0.039	-0.157	-0.075	1					
Pb	.996**	.987**	.681*	.978**	-0.045	1				
Hg	.914**	.979**	.731*	.950**	0.237	.945**	1			
Zn	.993**	.993**	.727*	.990**	-0.053	.998**	.952**	1		
Fe	-0.042	0.102	-0.203	-0.022	.986**	0.04	0.289	0.022	1	
Mortality	.678*	.678*	.923**	.770*	-0.52	0.649	0.575	.690*	-0.544	1

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2tailed)

TABLE 13

Correlation between heavy metals in fish tissues after the bioassay experiment

	<i>Cu</i>	<i>Cd</i>	<i>Cr</i>	<i>Ni</i>	<i>Pb</i>	<i>Hg</i>	<i>Zn</i>	<i>Fe</i>
Cu	1							
Cd	1.00	1.00						
Cr	0.99**	0.99**	1.00					
Ni	0.53	0.52	0.39	1.00				
Pb	0.92**	0.92	0.97**	0.14	1.00			
Hg	0.86**	0.87**	0.93**	0.03	0.99**	1.00		
Zn	1.00**	1.00**	0.99**	0.51	0.93**	0.87**	1.00	
Fe	-0.95	-0.95	-0.89	-0.77	-0.75	-0.66	-0.94	1

TABLE 14

Loading of Principal components

	<i>Cu</i>	<i>Cd</i>
	1	2
Cu	0.966	
Cd	0.997	
As	0.807	
Cr	0.997	
Ni		0.972
Pb	0.978	
Hg	0.972	
Zn	0.989	
Fe		0.995
Mortality	0.73	-0.612
%	70.4	20.1

with Cu (0.966), Cd (0.997), As (0.807), Cr (0.997), Pb (0.978), Hg (0.972), Zn (0.9890), and Mortality (0.73) (Table 14). Similarly, PC2 explained 20% of the total variance and was highly loaded with Ni (0.972) and Fe (0.995).

Health risk assessment of fish exposed to the sediments of the Korle Lagoon and the control site

Non carcinogenic health risk (Estimated Daily intake (EDI), Hazard Quotient (HQ), Hazard Index (HI))

The noncarcinogenic health risk assessment because of consumption of fish exposed to sediments of the Korle Lagoon and control site are presented in Table 15. The estimated daily intake (EDI) for fish exposed to the control site

was below the acceptable daily intake for all metals except for As for adults (Table 15a). On the other hand, fish exposed to the sediments of the Korle lagoon exceeded the acceptable daily intake for all metals for both adults and children except for Cr and Pb. Similarly, the HQ for all Heavy metals for the control were all below the acceptable limit of 1 except As for adults. The HQ for both adults and children for the Korle Lagoon exceeded the recommended HQ for all metals except Cr and Pb for both adults and children (Table 15b). The HI for both the control and Korle lagoon all exceeded the acceptable limit. The HI of the Korle lagoon was significantly higher than that of the control site.

TABLE 15

Non carcinogenic health risk a: EDI, b: HQ and HI, associated with the consumption of fish exposed to the Korle Lagoon sediment and control site sediment.

a: Estimated daily intake

Metal	Children		Adults		ADI
	EDI Control	EDI Korle	EDI Control	EDI Korle	
Cu	0.011	0.341	0.019	0.585	0.04
Cd	0.000	0.001	0.000	0.002	0.001
As	0.0002	0.046	0.0003	0.079	0.0003
Cr	0.001	0.053	0.002	0.090	1.5
Ni	0.001	0.026	0.001	0.045	0.02
Pb	0.001	0.019	0.001	0.033	0.04
Hg	0.000	0.002	0.000	0.004	0.0001
Zn	0.089	1.282	0.152	2.198	0.3
Fe	0.141	0.759	0.242	1.302	0.7

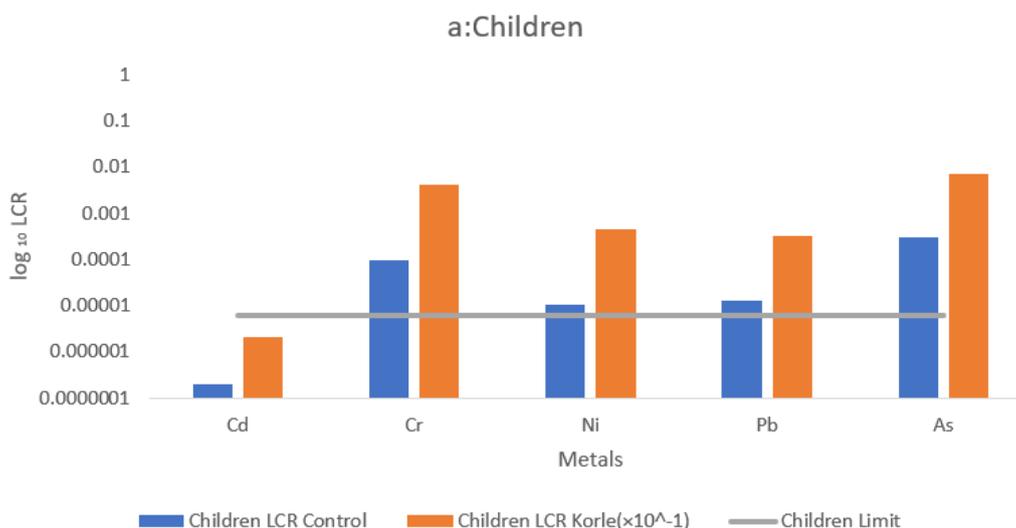
b: Hazard quotient and Hazard index

	Children		Adults	
	HQ Control	HQ Korle Lagoon	HQ Control	HQ Korle Lagoon
Cu	0.275	8.527	0.472	14.618
Cd	0.099	1.019	0.169	1.747
As	0.658	152.877	1.127	262.074
Cr	0.001	0.035	0.001	0.060
Ni	0.031	1.310	0.054	2.246
Pb	0.018	0.479	0.031	0.821
Hg	0.329	22.027	0.564	37.761
Zn	0.296	4.274	0.507	7.327
Fe	0.202	1.085	0.346	1.860
HI	1.908	191.634	3.271	328.515

Carcinogenic health risk

Figure 3 shows the LCR for both children (a) and adults (b). Generally, the LCR for the control site was lower than that of the Korle

Lagoon. The LCR for Cr, As, Ni, Pb in fish from the Korle Lagoon exceeded the maximum allowable limit of 0.0006 for both children and adults.



a: LCR for children

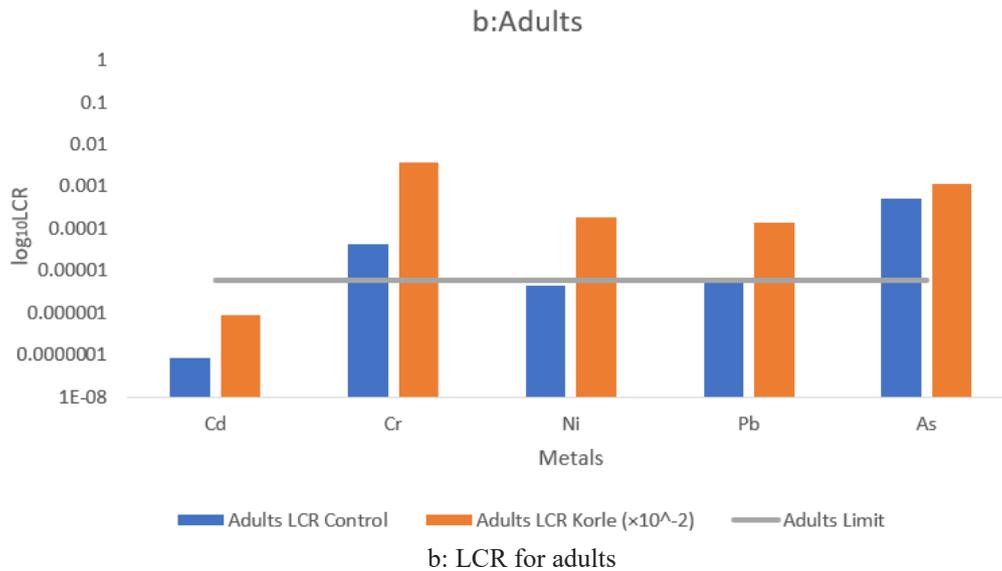


Figure 3. 1 Lifetime cancer risk for A: Adults and B: Children

Discussion

Heavy metal pollution in aquatic environments is widely recognized for its detrimental effects on biota (Yilmaz, 2011; Zaynab et al., 2022; Ouma et al., 2022). The toxicity of these metals is influenced by their concentrations in the environment, as they can displace essential metals from their binding sites in organisms, leading to cellular malfunctions (Mahdi et al., 2021; Jaishankar et al., 2014). One notable consequence of heavy metal exposure is growth inhibition among aquatic species (Sarnowski and Jezierska, 2006). Additionally, heavy metals that accumulate in sediments can adversely impact benthic organisms, exposing crustaceans, worms, insects, and other fauna to these toxic substances (Mussa et al., 2019). Sediment-bound heavy metals may also desorb into the water column, where they can be ingested directly by higher trophic levels (Olusegun et al., 2020; Sazon and Migo, 2020). Furthermore, when higher animals consume benthic species that have accumulated heavy metals, these contaminants can enter the food chain, posing risks to human health (Olusegun et al., 2020; Sazon and Migo, 2020). For

example, Begum et al. (2009) reported elevated heavy metal concentrations in the kidneys and livers of various fish species from contaminated water bodies, highlighting the potential for bioaccumulation and biomagnification, leading to varying degrees of toxicity.

In the Korle Lagoon, sediment analysis revealed significant contamination with heavy metals, categorized from moderately to highly polluted using the Geoaccumulation Index. Historically, the lagoon was a vibrant ecosystem supporting abundant fish populations, crucial for the livelihoods of local residents (Boadi and Kuitunen, 2002; Osae et al., 2022). However, heavy metal pollution has severely impacted fish populations, with current concentrations posing potential health risks for human consumption (Osae et al., 2022; Osae et al., 2023). A bioassay experiment indicated high toxicity in the lagoon's sediments, resulting in a mortality rate of 90–100% for juvenile *S. galilaeus*, compared to only 10% in the control group. Continuous monitoring of the overlaying water during the experiment showed that physicochemical parameters, such as dissolved oxygen, NO_2^- , and NH_3 levels, remained within acceptable limits, suggesting

that the high mortality rate was solely due to sediment toxicity. These findings align with previous studies, such as Jiménez-Tenorio *et al.* (2006), who reported elevated mortality rates in fish exposed to contaminated sediments, although their sediments had lower heavy metal concentrations, potentially leading to increased survival times.

The mortality rates observed in juvenile *S. galilaeus* exposed to the Korle Lagoon sediments exceeded 20% above the control group mean, qualifying the sediments as toxic (USEPA, 1993). Furthermore, the heavy metals exhibited significant bioaccumulation in aquatic organisms. Table 11 illustrates the concentration of heavy metals in *S. galilaeus* following the bioassay, alongside their bioconcentration factors. Notably, Cu, As, and Zn displayed bioconcentration factors greater than one, indicating substantial bioaccumulation and toxicity. Previous studies (Osae *et al.*, 2022) have reported high mobility and bioavailability of these metals in the lagoon's sediments, contributing to their elevated concentrations in fish. This study observed a significant increase in heavy metal concentrations in *S. galilaeus* post-bioassay, which was not mirrored in the control group. The consistently higher bioconcentration factors in the Korle Lagoon sediments suggest a potential source for heavy metal accumulation in aquatic organisms. As benthic organisms frequently interact with sediments and their pore waters, they may accumulate even greater concentrations of heavy metals (Feng *et al.*, 2020). This is supported by Feng *et al.* (2020), who found significantly higher trace metal concentrations in fish species inhabiting sediment layers compared to pelagic or sub-benthic fish.

Comparisons with similar recent studies, further highlight the severity of heavy metal

accumulation in the Korle Lagoon. For instance, Wang *et al.* (2021) and Ali *et al.* (2022) reported bioconcentration factors for Cu, Zn, and Pb ranging between 0.8 and 1.5 in polluted lakes. In this study, Cu and Zn showed similar bioconcentration factors, indicating significantly higher accumulation potential. Additionally, Ni and Fe, which displayed lower bioconcentration factors in this study, have been similarly reported as having limited bioaccumulation potential due to strong geogenic influences (Rahman *et al.*, 2020). These comparisons reinforce the hypothesis that the Korle Lagoon sediments contribute significantly to bioaccumulation risks, surpassing the levels found in other urban water bodies. The low bioconcentration factors for Fe and Ni can be attributed to their geogenic origin, strong binding affinity in sediments, and potential homeostatic regulation in fish.

Correlation analysis and Principal Component Analysis (PCA) demonstrated that the heavy metals in the Korle Lagoon sediments were the primary source of metal accumulation in fish tissues, correlating with the observed high mortality rates. The significant correlation between heavy metal concentrations agrees with findings from Bat & Raffaelli (1998), which highlighted the link between metal bioaccumulation and sediment concentrations. However, no correlation was found between Fe and Ni with other heavy metals, potentially due to their lower toxicity levels for *S. galilaeus*. The lack of correlation may also be attributed to their geogenic origin, as Fe and Ni are often present in sediments from natural weathering processes rather than anthropogenic pollution sources. Additionally, Fe plays an essential physiological role in fish, which could result in homeostatic regulation mechanisms preventing excessive accumulation (Jaishankar *et al.*,

2014).

PCA results provided insights into the possible sources of heavy metals in the Korle Lagoon. The first principal component (PC1) accounted for 70% of the total variance, with high loadings for Cu, Cd, Cr, Pb, Hg, and Zn. These metals are often associated with industrial discharges, urban runoff, untreated sewage, and electronic waste (e-waste) disposal, indicating anthropogenic pollution as their primary source. The presence of Cu and Zn in elevated concentrations suggests contamination from industrial processes such as metal plating, battery manufacturing, and electronic waste recycling, which are common sources of these metals in urban environments (Ali et al., 2022; Wang et al., 2021). Additionally, Pb and Cd are frequently linked to vehicular emissions, lead-acid battery waste, and the leaching of paints and coatings into water bodies (Gong et al., 2018, Osaie et al., 2023).

One of the significant sources of heavy metal pollution in the Korle Lagoon is e-waste, as parts of Accra, particularly Agbogboshie, are known for informal e-waste dismantling and processing activities (Grant & Oteng-Ababio, 2019). The dismantling and burning of electronic components release hazardous substances, including Pb from solder, Cd from batteries, Cu from circuit boards, and Hg from switches and fluorescent lamps (Bakhiyi et al., 2018). These heavy metals are transported into nearby water bodies through surface runoff, leaching, and atmospheric deposition, significantly contributing to contamination in the lagoon. In particular, Hg contamination in the area is associated with e-waste. The burning of electronic components containing Hg, such as switches and compact fluorescent bulbs, releases Hg vapors that eventually settle in sediments and water, leading to

bioaccumulation and potential ecological risks (Sepúlveda et al., 2010).

In contrast, Fe and Ni had weak loadings on PC1 and were more associated with PC2, which suggests a natural geogenic origin from weathering and erosion of underlying geological formations. Ni is typically derived from ultramafic and mafic rocks, while Fe occurs naturally in sediments due to weathering processes (Rahman et al., 2020). Their lower bioavailability and mobility, compared to Cu and Cd, suggest that they are largely bound to sediment particles in stable mineral forms, making them less likely to contribute significantly to bioaccumulation in aquatic organisms (Feng et al., 2020). Previous studies have shown that geogenic Fe and Ni tend to be less toxic to biota unless influenced by changes in redox conditions, which can enhance their solubility and availability in the water column (Bat & Raffaelli, 1998).

The differentiation between anthropogenic and geogenic sources is crucial for developing targeted pollution control measures. Identifying anthropogenic hotspots allows for the implementation of stricter industrial discharge regulations, improved waste management systems, and wastewater treatment enhancements to mitigate further contamination (Ali et al., 2019). In particular, the regulation and proper management of e-waste disposal should be prioritized, as informal recycling practices contribute significantly to heavy metal pollution in urban environments (Grant & Oteng-Ababio, 2019). Meanwhile, understanding geogenic contributions helps in predicting natural background levels and assessing potential mobilization risks due to environmental changes such as acidification or sediment resuspension (Jaishankar et al., 2014). These findings align with global

research on urban water pollution, where PCA has been effectively used to distinguish pollution sources and guide remediation efforts (Olusegun *et al.*, 2020). For instance, studies on industrially impacted rivers in China and India have similarly identified Cu, Cd, and Pb as key indicators of anthropogenic contamination, particularly from e-waste processing hubs (Gong *et al.*, 2018).

Ecological risk assessments using the Effects Range Median Quotient (ERMQ), and Effects Range-Low Quotient (ERLQ) indicate that heavy metals in the Korle Lagoon sediments pose significant ecological threats. The Effects Range-Low (ERL) represents pollutant concentrations that are unlikely to cause adverse biological effects, while the ERL-ERM interval denotes concentrations that may occasionally induce negative impacts. The Effects Range-Median (ERM), on the other hand, corresponds to concentrations that are likely to have regular and severe effects on aquatic organisms (DeValls *et al.*, 2004; Zabihollah *et al.*, 2020; Farzingohar *et al.*, 2020).

Findings from the current study suggest that Cu, Cr, Ni, and Zn levels in the sediments exceed ERL values, signaling potential biological risks. These results align with the correlation analysis, which links elevated heavy metal concentrations to increased mortality rates in *Sarotherodon galilaeus*. Chronic exposure to Cu and Zn, commonly associated with industrial discharge and electronic waste leaching, can impair fish gill function, disrupt enzymatic activity, and compromise overall aquatic health (Hanna *et al.*, 2021). Similarly, Cr and Ni have been shown to induce genotoxic effects in benthic organisms, leading to reduced reproductive success and population decline (Zhao *et al.*, 2019).

More concerningly, ERMQ values for Cu,

Pb, and Cd exceeded the ERM threshold, indicating that these metals pose frequent and severe ecological risks. Exceeding ERM levels suggests a high probability of adverse effects on sediment-dwelling organisms, which can lead to trophic transfer of contaminants through the aquatic food web (Liao *et al.*, 2023). Pb and Cd, both known for their high toxicity, can bioaccumulate in fish tissues, leading to oxidative stress, developmental anomalies, and immunosuppression in exposed populations (Akan *et al.*, 2021). The persistent presence of these metals may also contribute to alterations in microbial community structure and function, further affecting sediment nutrient cycling and ecosystem stability (Shen *et al.*, 2022).

The bioaccumulation of heavy metals in *S. galilaeus* from the Korle Lagoon presents significant health concerns due to the potential risks of heavy metal toxicity from contaminated fish. As shown by the hazard quotient (HQ) values exceeding one, there is a clear indication of a non-carcinogenic health risk, highlighting the impact of anthropogenic activities on the local aquatic ecosystem. This is especially alarming considering that the Korle Lagoon, like many urban water bodies, is influenced by multiple pollution sources, including those from electronic waste (e-waste) disposal.

When comparing the findings of this study to similar research focused on e-waste areas, we can look at studies such as those by Zabihollah *et al.* (2020) and Shen *et al.* (2022). Zabihollah *et al.* (2020) examined the pollution from e-waste activities along the coast of Bandar Abbas in Iran, where they found elevated levels of heavy metals, particularly lead and mercury, in fish species near e-waste recycling sites. The study highlighted that these fish species exhibited significant bioaccumulation of toxic metals, with the potential to harm local

populations that consumed them. Similarly, Shen et al. (2022) in their review on microbial community shifts and heavy metal pollution in estuarine sediments, indicated that e-waste contamination could cause profound changes in microbial communities and lead to increased metal bioavailability, exacerbating the risk to aquatic life. These studies align with the findings from the Korle Lagoon, suggesting that e-waste contamination can contribute to the observed high HQ values for fish in polluted water bodies.

Moreover, research by Simon et al. (2022) on chronic toxicity of uranium and other heavy metals in benthic organisms found that aquatic organisms near e-waste recycling areas often accumulate metals from the sediment in concentrations that are hazardous for human consumption. The results from these studies reinforce the concern raised in the Korle Lagoon, where high HQ values suggest widespread contamination in the ecosystem. Unlike some studies that found variability in HQ values across different species, the consistently high values point to a pervasive contamination issue, likely influenced by e-waste-derived pollutants in the environment. This is consistent with the findings from Zabihollah et al. (2020), where fish in e-waste-affected areas displayed elevated levels of metals, and the risk to human health remained significant even across distinct species. This further emphasizes the importance of not only controlling e-waste disposal but also monitoring aquatic organisms in these areas to protect both biodiversity and public health.

Conclusion

This study provides compelling evidence of the significant toxicity of sediments from the

Korle Lagoon, as demonstrated by the elevated mortality rate of *S. galilaeus* in the 10-day fish bioassay. The presence of heavy metals, including Cu, Cd, Cr, Ni, Pb, Hg, and Zn, at concentrations exceeding ecological safety thresholds presents a serious environmental threat. Ecological risk assessments using ERLQ and ERMQ indicate that these metals pose substantial risks to aquatic life, leading to potential disruptions in the lagoon's ecological balance. Furthermore, the bioaccumulation of these contaminants in aquatic organisms raises major concerns for human health, particularly for communities that rely on the lagoon's seafood as a primary food source. Continuous exposure to such heavy metal-laden sediments can have long-term consequences, including biomagnification through the food chain, leading to increased health risks such as heavy metal poisoning.

Addressing this environmental challenge requires urgent and sustained intervention. Strict enforcement of environmental regulations governing waste discharge is necessary to curb further contamination. Additionally, given the toxicity of the sediments, proper management and disposal of dredged materials must be prioritized to minimize secondary pollution. Future research should focus on long-term monitoring, remediation strategies, and public health risk assessments to safeguard both the ecosystem and local communities dependent on the lagoon's resources.

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