Assessment of Comprehensive Pollution, Trophic Transfer, Bioaccumulation Patterns and Human Health Risks of Heavy Metals from Sediments through Seagrasses to Fish in Chukwani Bay, Zanzibar

Abstract

This study assessed the comprehensive pollution status, trophic transfer, and human health risks associated with heavy metals through seagrasses in the marine ecosystem of Chukwani Bay, Zanzibar. Sediment, seagrass, and fish samples were collected and analyzed for selected heavy metals (Pb, As, Cu, Ti, Al, Mg, Mn, Fe, Hg, Cd, and Zn) using Agilent 5900 Inductively Coupled Plasma–Optical Emission Spectrometry (ICP–OES). The Comprehensive Pollution Index (CPI) was applied to evaluate overall metallic contamination in fish, while bioaccumulation and trophic transfer factors were used to trace metal movement from sediments through seagrasses to fish.

Among the eleven metals analyzed, sediment samples exhibited the highest mean concentrations from Fe: 121.45 ppm; Ti: 210.05 ppm; Mg: 188.37 ppm, etc., followed by seagrasses and fish tissues, indicating a distinct trophic transfer of metals across the benthic food web. Notably, Fe, Mn, and Zn demonstrated strong bioaccumulation tendencies, while elevated levels of Pb (up to 3.88 ppm) and As (up to 1.96 ppm) contributed to high CPI values ranging from 84.13 in *Mugil cephalus* to 157.04 in *Kyphosus vaigiensis*. These findings highlight a progressive enrichment pattern from sediments to higher trophic levels, underscoring potential toxicological risks to seagrass-associated fish species and, consequently, to human consumers.

Human health risk evaluation based on Estimated Daily Intake (EDI), Hazard Quotient (HQ) and Hazard Index (HI) revealed that while most EDI values were within WHO/FAO tolerable limits, Pb and As in *Stegastes nigricans* and *K. vaigiensis* slightly exceeded reference thresholds. The individual HQ values were found to be below 1, HI values ranges from 2.16 to 4.45 while Comprehensive Pollution Index (CPI) indicated potential chronic risks from long-term fish consumption.

Overall, these findings highlight the strong linkage between sediment contamination and heavy metal accumulation across trophic levels, emphasizing the need for continuous monitoring and pollution mitigation to safeguard marine ecosystem integrity and community health in Chukwani Bay and Zanzibar at large.

Keywords: Heavy metals; Bioaccumulation; Trophic transfer; Comprehensive Pollution Index; Human health risk; Marine ecosystem

Introduction

Sediments play a pivotal role in marine ecosystems by functioning as nutrient reservoirs, biological habitats, and biogeochemical regulators that sustain primary productivity and ecological balance (Eggleton & Thomas, 2004; Du Laing et al., 2009). They act as natural sinks for organic matter and trace elements, supporting benthic organisms that are essential to nutrient cycling and trophic transfer (Birch, 2017). However, contamination with heavy metals alters these critical functions by inducing toxicity in sediment-dwelling fauna, disrupting microbial-mediated nutrient processes, and enhancing the bioavailability of toxic elements to higher trophic levels (Burton & Johnston, 2010; Qiu et al., 2018). Under fluctuating redox or pH conditions, metals can be remobilized from sediments into the water column, transforming sediments from stable sinks into secondary pollution sources (Du Laing et al., 2009; Zhang et al., 2014). This process elevates metal uptake by benthic flora such as seagrasses and algae, promoting bioaccumulation and biomagnification along the food chain (Lewis & Devereux, 2009; Wang et al., 2016). Consequently, heavy metal contamination compromises sediment quality, reduces biodiversity, impairs bioturbation and oxygen penetration, and weakens ecosystem services such as nutrient regulation and shoreline protection (Eggleton & Thomas, 2004; Burton & Johnston, 2010). Collectively, these effects endanger sediment-associated biota and amplify ecological and human health risks through trophic transfer within the marine food web (Tchounwou et al., 2012; Ali et al., 2019).

Sea grasses ecological importance is immense despite their relatively low global diversity. Beyond carbon storage, seagrasses provide critical ecosystem services such as acting as natural filters that trap sediments and stabilize the seabed. They provide habitat for commercially valuable fish and invertebrates, shelter juvenile and endangered marine fauna, stabilize shorelines, contribute to primary productivity, and act as long-term carbon sinks (Orth et al., 2006; Duarte et al., 2013). In addition, seagrasses are also harvested for commercial and cultural uses, embedding them deeply within the socio-economic fabric of coastal communities (Nordlund et al., 2018). Their extensive root and rhizome systems play a crucial role in sediment stabilization, reducing erosion and resuspension while facilitating the deposition of suspended particles (Marba et al, 2015) consequently these functions underscore their importance to the health of coastal ecosystems and economies.

Seagrasses have emerged as effective bioindicators of heavy metal pollution due to their sessile nature and ability to integrate environmental exposure over time (Lewis & Devereux, 2009). They absorb trace metals from both sediment and water columns and are easily resampled across seasons, making them ideal for long-term monitoring of coastal contamination. Recent studies indicate that metal accumulation patterns depend on species identity, tissue type (leaf, rhizome, or root), sediment properties, and hydrodynamic conditions (Li et al., 2019). Experimental studies have shown that heavy metals such as lead can be deposited in apoplastic and intercellular spaces, leading to anatomical and physiological impacts, while field surveys reveal that different seagrass tissues can reflect both historical and recent metal deposition (Tupan et al., 2020).

Species-specific variations in accumulation potential are well documented. *Zostera capricorni*, for example, effectively accumulates Cu, Pb, and Zn, mirroring sediment and water quality (Prange & Dennison, 2000). Similarly, *Thalassia hemprichii*—a long-lived tropical seagrass common in the Indo-Pacific—has been used to monitor Pb, Cd, Cu, and Zn levels (Prabowo et al., 2020). *Cymodocea serrulata* is known to accumulate Fe, Mn, Cu, Zn, Cd, Cr, Pb, and Ni and exhibits antioxidant and enzymatic responses correlated with metal concentrations (Aljahdali &

Bantan, 2020). *H. ovalis* (a small, fast-turnover tropical seagrass) has been widely used in local and regional surveys to profile trace-metal gradients and to compare tissue vs. sediment concentrations (Ralph et al 2007). Laboratory exposure experiments further demonstrate measurable sub-lethal effects on photosynthesis, chlorophyll content, and morphology under Cu, Cd, Pb, and Zn exposure (Ralph et al., 2006), reinforcing the utility of seagrasses as biological sentinels of coastal pollution.

In marine ecosystems, prolonged exposure to heavy metals can impair reproductive function, disrupt neurological and respiratory systems, and lead to bioaccumulation within food webs, posing serious health threats to human consumers (Qiu et al., 2018). While metals such as Fe, Cu, and Zn are essential micronutrients, their concentrations beyond physiological thresholds become toxic (Ali et al., 2019). Chronic exposure to high levels of Pb, Cd, and Hg has been linked to degenerative neurological diseases such as Alzheimer’s, Parkinson’s, and multiple sclerosis (Tchounwou et al., 2012).

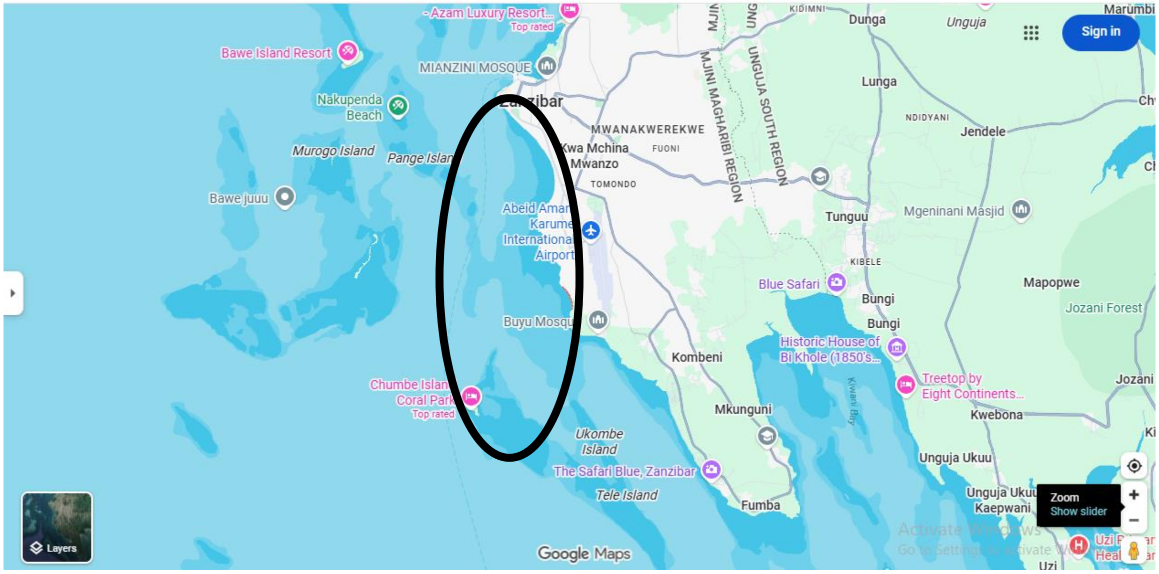
The proximity of seagrass meadows to urban and industrial activities makes them particularly susceptible to anthropogenic stressors, including pollution, overharvesting, dredging, and climate change (Waycott et al., 2009). Physical disturbances such as propeller scarring, anchor damage, and coastal construction can uproot seagrass beds, degrade rhizome networks, and reduce overall productivity (Erftemeijer & Robin, 2006). The global decline of seagrass habitats is well documented and primarily attributed to eutrophication, sedimentation, and metal contamination (Duarte, 2002). Physiological responses to heavy metal exposure—such as reduced photosynthetic efficiency, inhibited growth, and altered pigment profiles—serve as reliable indicators of environmental degradation (Lewis & Devereux, 2009). Variations in biomass, chlorophyll content, and growth rates further provide insights into changing water quality and nutrient enrichment (Short et al., 2011). These characteristics enhance their use as early-warning systems for detecting ecosystem stress and guiding management interventions. Conserving seagrass diversity is thus critical not only for biodiversity maintenance but also for sustaining vital ecological services such as carbon sequestration, nutrient cycling, and sediment stabilization.

In the Chukwani Bay ecosystem, recent evidence indicates declining reproductive success in marine fauna, reduced seagrass coverage, impaired fish mobility, and growing health risks linked to heavy metal bioaccumulation. These impacts are closely tied to intensified anthropogenic pressures—such as coastal development, maritime traffic, and domestic effluent discharge—that collectively threaten the ecological balance of this nearshore environment (Mohammed et al., 2021). Thus, these metals also pose ecological risks by altering biodiversity and disrupting trophic structures within marine ecosystems (Wang et al., 2016). Despite increasing concern, comprehensive investigations that integrate sediment contamination, seagrass bioaccumulation, trophic transfer, and human health implications remain scarce in Zanzibar. Therefore, this study aims to; Quantify heavy metal concentrations in sediments, seagrasses, and associated fish species from Chukwani Bay; Evaluate the Comprehensive Pollution Index (CPI) and trophic transfer of metals along the sediment–seagrass–fish continuum; and, Assess potential human health risks associated with seafood consumption. The findings will improve understanding of heavy metal dynamics in coastal ecosystems and provide baseline data crucial for evidence-based policy and sustainable management of Zanzibar’s coastal resources.

Location:

Chukwani Bay is located in Chukwani Bweni regions, suburbs on the Unguja Island, Zanzibar. It is situated in the west of the island, south of Mbweni region towards the main Zanzibar Harbour. Attached please find the map in figure one below. The encircled shows the Chukwani Bay coverage.

Figure 1.Chukwani Bay



2.0 SAMPLING, IDENTIFICATION, AND METHODOLOGY

2.1 Sampling of Seagrass Species for Analysis

These seagrasses were sampled in the form of leaves and stems fresh from the ocean, washed to remove sediments, identified and labelled. They were air dried in the open for three days, placed in a laboratory oven at 80^0C for two hours then pulverized using a clean mortar and pestle to obtain a homogeneous powder (Jacksons, 2007) finally transported in well dried sealed sample bags to African Minerals and Geosciences Centre (AMGC) laboratory for analysis.

2.2 Sampling of Sediment

Three sediment samples were collected in clean polyethylene bags and transported to the Applied Marine Geology and Chemistry (AMGC) laboratory for preparation and analysis. In the laboratory, the samples were air-dried at room temperature to prevent the loss of volatile components. The dried sediments were then thoroughly mixed and homogenized using an agate mortar to ensure uniformity. Subsequently, the homogenized material was sieved through an 80-mesh (180 µm) stainless-steel sieve to remove coarse debris and non-sediment impurities prior to chemical digestion and analysis. All sample pretreatment procedures followed standard sediment preparation protocols recommended by the American Public Health Association (APHA, 2017) and the U.S. Environmental Protection Agency (USEPA, 2001).

2.3 Sampling of Fish

Fish sampling was conducted at Chukwani Bay and its adjacent landing site at Mbweni Fish Market, situated along the western coast of Unguja Island, Zanzibar. The sampling sites were selected is also influenced by anthropogenic activities and associated seagrass meadows that serve as critical feeding and nursery habitats for various marine organisms. Fresh fish specimens were obtained directly from local artisanal fishermen operating within the Chukwani Bay area to ensure the samples accurately reflected the local catch composition.

Each specimen, identified, then placed in a clean, well labeled polyethylene bag and stored in an icebox containing crushed ice to minimize microbial activity and biochemical degradation during transport. The samples were subsequently transported to the laboratory on the same day and stored at −25 °C until further processing and analysis. The sampling, handling, and storage procedures followed established guidelines for trace metal studies in marine biota (FAO, 2003; USEPA, 2000).

3.0 Identification of Seagrasses and Fish Samples

Identification procedures was carried out by our marine biologist Dr. Rashid Juma Rashid. He identified the three seagrass species found in the area as *Halophila Ovalis*, *Cymodocea serrulata* and *Thalassia Hemprichii*. They were later abbreviated as HO, CS and TH respectively. The main fishes found and identified from the area were mainly *Stegastes nigricans* (Changu), *Mugil cephalus* (Samaki), *Siganus sutor* (Tasi), *Kyphosus vaigiensis* (Kumbulimbuli),*Octopus cyanea* (Octopus), *Spratelloides gracilis* (Dagaa la kukosha), *Penaeia shrimps* species and *Chlorurus sordidus* (Bluish), which inhabits deeper coral areas around Chumbe Island in the Chukwani Bay.

3.1 Questionnaire survey

A questionnaire-based survey was conducted to establish the commonly consumed fish species in Chukwani Bay region of Unguja Island, Zanzibar. Questionnaires were administered to 28 participants randomly selected from kiembe-samaki, Mji mpya, Bweni including Chukwani regions. Apart from the locally consumed fishes, it also inquired about basic information on gender, age, education, income level, frequency and ingestion rates of the commonly consumed fish species

4.0 Analysis Using Agilent 5900 Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES)

All metallic analysis was done using the Agilent 5900 Inductive Coupled Plasma – Optical Emission Spectrometry

4.1 Quality Assurance Procedures

Appropriate quality assurance procedures and precautions were implemented to ensure the reliability of the results. Procedural blanks, calibration standards, and duplicate samples were utilized for instrument calibration, process control, and quality assurance to evaluate accuracy, precision, limits of quantification and detection, and to validate the Agilent 5900 ICP-OES. Blank digestions were conducted in parallel using the same procedure to correct for any background contamination. Certified reagents, blanks, and certified reference materials (NIST SRM 2702, marine sediment) were employed to assess digestion efficiency, correct for background interference, and ensure the accuracy and precision of the analytical results. All quality control samples were analyzed concurrently with the test samples.

.

4.2 Analysis of Heavy Metals from Sediment

Approximately 0.5 g of each air-dried and homogenized sediment sample was digested using a Milestone ETHOS Easy Microwave Digestion System (Milestone Srl, Italy) equipped with high-pressure Teflon vessels designed for trace metal analysis. The digestion procedure followed the guidelines of U.S. EPA Method 3052, which describes microwave-assisted acid digestion for the total decomposition of siliceous and organically based matrices (U.S. Environmental Protection Agency [USEPA], 1996). Each sample was treated with a mixture of concentrated nitric acid (HNO_3, 65%) and hydrofluoric acid (HF, 40%) in a volumetric ratio of approximately 9:3 mL to achieve complete dissolution of silicate and aluminosilicate phases commonly present in sediment matrices.

Digestion was performed under controlled temperature and pressure conditions, with the temperature gradually increased to 200 °C and held for a specific duration as recommended by the manufacturer's operational protocol for siliceous materials (Milestone Srl, 2018). Upon completion, the vessels were allowed to cool to room temperature before being carefully opened in a fume hood. The resulting clear digests were quantitatively transferred into 50 mL volumetric flasks, treated with 3 mL of boric acid to complex residual fluoride ions and prevent potential interferences, and diluted to volume with deionized water.

The digested solutions were filtered through acid-washed Whatman No. 42 filter paper and stored in pre-cleaned polyethylene bottles prior to elemental determination using the Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES).

4.3 Metals Analysis from Seagrasses

Approximately 0.5 g of each dried and ground tissue sample was digested with 7 mL of concentrated nitric acid (65 %) and 1 mL of hydrogen peroxide (30%) in Teflon vessels of an ETHOS Easy Microwave Digestion System (Milestone, Italy). The digestion was performed in high-pressure Teflon vessels designed for trace metal analysis and as per manufactures guidelines. The digestion process involved a gradual temperature ramp to approximately 180 °C, maintained for a specified holding period to achieve complete decomposition of the organic matter. Real-time monitoring of temperature and pressure was conducted using an in-built infrared sensor and pressure control system to ensure safety and reproducibility. After the digestion cycle, the vessels were allowed to cool to room temperature before being carefully opened in a fume hood. The resulting clear digests were quantitatively transferred into 50 mL volumetric flasks and diluted to volume with deionized water. The digested samples were subsequently filtered through acid-washed Whatman No. 42 filter paper and stored in pre-cleaned polyethylene bottles prior to elemental determination by Agilent 5900 Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES).(Milestone Srl. (2016)

4.4 Procedure of Heavy Metal Analysis from the Eight Fish

Fish samples were first allowed to equilibrate to room temperature and then thoroughly rinsed with deionized water to remove adhering salts, debris, and surface contaminants prior to dissection. Dissection was performed using acid-washed stainless-steel scalpels and forceps to prevent trace metal contamination. Approximately 20 g of dorsal muscle tissue was excised from each specimen, rinsed with distilled water, and freeze-dried at −80 °C until a constant weight was achieved. The dried muscle samples were then finely ground and homogenized using a mixer mill to obtain a uniform powder, which was stored in pre-labeled polyethylene containers prior to digestion.

For digestion, accurately weighed 1.0 g aliquots of each powdered muscle sample were transferred into acid-cleaned Teflon digestion vessels and treated with 10 mL of concentrated nitric acid (HNO_3, 65%, supra pure grade; Adolf Plinke GmbH). The mixture was left to pre-digest at room temperature for approximately 3 hours before sealing and heating at 80 °C for 7 hours to enhance organic matter decomposition. Subsequently, the vessels were opened and heated at 100 °C for an additional 3 hours to evaporate excess acid until a nearly dry residue remained. This digestion process was repeated until only a minimal white residue was observed. The residue was reconstituted in 80 mL of 2% nitric acid, filtered through Advantec 5C filter paper (110 mm diameter; Advantec MFS, Dublin, CA, USA), and finally diluted to a volume of 100 mL with 2% nitric acid.

Metal concentrations were determined using an Agilent 5900 Inductively Coupled Plasma–Optical Emission Spectrometer (ICP-OES). All results were expressed on a dry weight basis and reported in milligrams per kilogram (mg/kg). Method blanks were processed concurrently following the same procedure to correct for background contamination and ensure analytical quality control. The digestion and analytical protocols followed established guidelines for heavy metal analysis in marine biota (APHA, 2017; USEPA, 2000; FAO, 2003).

5.0 Potential Risk Assessment using Estimated Daily Intake (EDI), Hazard Index and Comprehensive Pollution Index Methods

5.1 Health Risk Assessment

Estimated Daily Intake (EDI) used to assess metal intake in humans, and it is a common method in environmental health and toxicology for evaluating potential exposure to heavy metals or trace elements through food, water, or other sources. It is defined as amount of a substance (like a metal) ingested daily per unit of body weight, typically expressed as:

EDI (mg/kg body weight/day) = (Concentration of metal in food × Daily intake of food) / Body weight. The EDI obtained shall be compared with world statutory health organization values. If it exceeds benchmarks set by World Health Statutory Authorities like the WHO**,** FAO, USEPA**,** etc., values, it indicate a potential health risk (FAO/WHO, 2011; USEPA, 2011; Chien et al., 2002).

5.2 HI: Hazard Index

HI= the Hazard Index which is used to evaluate non-carcinogenic risk from consuming contaminated food (like fish with heavy metals). It is found by summing Hazard Quotient (HQ) for every metallic species, and it is given by; HQ = EDI/RfD, where RFD is Reference Dose (safe daily exposure limit set by USEPA/WHO). HI is the cumulative risk of the multiple contaminants. If it is less than one then it is safe while if it is greater than one then combined metal exposure could pose non-carcinogenic health risk. If also HQ is greater than one, then metal exposure could pose non-carcinogenic health risk. (USEPA, 1989; USEPA, 2011; FAO/WHO, 2011)

5.3 Comprehensive Pollution index (CPI) or Mean Pollution index (MPI)

To determine pollution index (PI) of the elements, statistical analysis was performed on the elemental concentrations in fish samples. The PI is defined as the ratio of element x concentration in the sample to the element's maximum allowable level, that is,

PI(x) = Metal concentration in the sample/Permissible limit or background value

Since we have several metals, the overall or comprehensive pollution index is calculated as CPI = $\frac{1}{n}\sum_{n}^{i} PI_i$, n = number of metallic species.

This gives the average pollution level across all analyzed metals. A PI value greater than 1.0 indicates that the concentration of a given metal exceeds its permissible threshold, suggesting potential contamination and ecological risk. Similarly, higher CPI values reflect greater cumulative pollution loads across multiple elements. This approach to pollution index evaluation has been widely adopted in aquatic environmental monitoring and risk assessment studies (Yu & Wang, 2011; Islam et al., 2015; Sany et al., 2013).

6.0 Results

6.1 Heavy Metal Concentration from Sediments

Heavy metals were analyzed from sediment and the results are tabulated in table 1a below.

Table 1 (a) below shows the results of concentration heavy metals analyzed from sediments.

As Ppm	Mn Ppm	Pb ppm	Mg ppm	Zn ppm	Cd Ppm	Fe Ppm	Ti Ppm	Cu ppm	Al ppm	Hg ppm
1.96	30.21	3.88	188.37	40.11	<0.01	121.45	210.05	4.67	5.25	<0.01

WHO has not established sediment quality criteria for Fe, Mn, Ti, or Mg since these are considered major lithogenic elements. Therefore there is no single "WHO/EPA maximum" for heavy metals in *marine sediments*. Instead, agencies and research groups publish *screening guideline values* (benchmarks table 1(b)) used to flag possible ecological risk.

Table 1(b) shows Benchmarks for marine sediments guidelines (mg/kg — dry weight)

Element	NOAA ERL	NOAA ERM	CCME Marine ISQG	CCME Marine PEL
Arsenic	8.2	70	7.24	17
Cadmium	1.2	9.6	0.7	4.2
Aluminium	2.3	80	52.3	160
Copper	34	270	18.7	108
Lead	46.7	218	30.2	112
Mercury	0.15	0.71	0.13	0.7
Zinc	150	410	124	271

NOAA ERL / ERM (Effects Range–Low / Effects Range–Median) — screening values based on observed incidence of biological effects. CCME ISQG / PEL (Canadian Interim Sediment Quality Guideline / Probable Effect Level) — threshold (ISQG) below which effects are rarely observed and PEL above which effects are likely.

6.2 Metallic Elements Results from Seagrasses

A total of eleven heavy metal concentrations were determined from the three types of seagrasses found in Chukwani bay and tabulated below in table 2 (a).

Table 2 (a) below shows the results obtained of elements concentrations in parts per million (ppm, dry weight) from the sea grasses after analysis

Seagrass Sample ID	As Ppm	Mn Ppm	Pb Ppm	Mg ppm	Zn ppm	Cd ppm	Fe ppm	Ti Ppm	Cu ppm	Al ppm	Hg Ppm
H.O	1.40	19.73	2.81	123.8	25.6	<0.01	78.85	95.66	4.67	3.35	<0.01
C.S	0.95	20.41	3.1	154.52	30.44	0.05	82.11	121.0	3.36	3.05	<0.01
T.H	1.86	22.7	2.05	134.3	20.08	<0.01	85.57	106.7	5.66	4.58	<0.01

At present, there are no internationally recognized guideline values or permissible limits for heavy metals in seagrass tissues. Consequently, the interpretation of heavy metal concentrations in this study was based on comparative assessment rather than regulatory thresholds. Concentrations of trace metals such as Zn, Mn, and Al in seagrasses from Chukwani Bay were evaluated relative to background values reported for uncontaminated coastal environments in previous studies, as well as against sediment quality guidelines (NOAA ERL and ERM values) to infer potential ecological risks shown in table 2 (b). While seagrasses are effective bioindicators due to their capacity to accumulate trace elements from sediments and seawater, the absence of standardized benchmarks limits direct toxicity assessment. Therefore, the results presented here should be interpreted in relation to spatial variations, local anthropogenic influences, and known geochemical baselines rather than absolute contamination limits. This approach provides a meaningful ecological context for assessing metal enrichment and potential transfer across the marine food web in the Chukwani Bay ecosystem.

Table 2 (b) below Showing some guidelines Concentrations in Seagrasses (ppm, dry weight):

Lead	Arsenic	Cadmium & Mercury	Copper	Zinc
0.1- 5.0 ppm	1 – 10 ppm	~1ppm or less	2 – 20 ppm	50 - 100 ppm

(Source: Environmental monitoring agencies such as UNEP, NOAA, national marine authorities)
Sediments heavy metal concentration

6.3 Results from the Questionnaire

The cross-sectional survey revealed that the most commonly fished species are *Stegastes nigricans* (Changu), *Mugil cephalus* (Samaki), *Siganus sutor* (Tasi), and *Kyphosus vaigiensis* (Kumbulimbuli), which primarily feed on seagrasses. In contrast, *Octopus cyanea* (Octopus), *Spratelloides gracilis* (Dagaa la kukosha), and *Penaeia shrimps* species though common but they do not feed on seagrasses. *Spratelloides gracilis* (Dagaa la kukosha) though is a daily delicacy, apart from Bweni beach, it is bought from other beaches also. In this work, we are only interested in marine fishes that feeds on seagrasses. They were purchased from the fish market while dead and usually fish caught for commercial sale do not require obtaining permission from any relevant authority in Zanzibar, Tanzania at large. Each fish species were samples in four. The findings further indicated that adult consumers of these fish species, with an average body weight of 65 kg, consumed approximately 210 grams of fish per day on average.

6.4 Heavy metal concentrations in the commonly consumed fish species

The heavy metal concentrations for Pb, As, Cu, Ti, Al, Mn, Mg, Fe and Zn (mg kg^{-1} dry weight) in these fish species, i.e. *S. sutor* , *S. nigricans, M. kephalus*, *K.Vaigiensis* were determined and their values are presented in table3. Each fish species were sampled at stated above and standard deviation determined. Hg and Cd concentrations far much less than 0.01 hence was not determined.

Table 3 (a) below shows metallic concentrations in the fish species (mg kg^{-1} dry weight)

Fish Species	Pb	As	Cu	Ti	Al	Mg	Mn	Fe	Zn
S. Sutor	1.11 ± 1.2	0.54 ± 0.1	2.05 ± 0.8	58.66 ± 6.7	1.78 ± 0.3	62.55 ± 8.4	5.24 ± 1.6	40.77 ± 7.4	6.09 ± 2.5
M. Cephalus	0.85 ± 0.1	0.22 ± 0.1	0.98 ± 1.0	82.34 ± 3.5	0.43 ± 0.2	92.58 ± 5.4	11.11 ± 2.7	78.55 ± 8.6	5.22 ± 4.5
S. nigricans	0.65 ± 0.2	1.08 ± 0.6	3.02 ± 1.1	88.67 ± 2.1	3.05 ± 0.7	60.47 ± 2.1	11.45 ± 4.4	62.45 ± 0.4	20.24 ± 2.3
K. Vaigiensis	2.51 ± 0.2	1.20 ± 0.1	2.07 ± 0.2	88.65 ± 3.1	1.95 ± 0.1	60.45 ± 2.4	2.54 ± 0.5	55.72 ± 1.1	15.58 ± 3.2

Table 3(b) showing guidelines for heavy metals maximum acceptable limits in Fishes

Metal	**Common wet-weight limit (mg/kg)**	**Converted dry-weight limit (mg/kg, ≈×4)**	**Remarks**
Mercury (Hg)	0.5 – 1.0	**2.0 – 4.0**	Codex, EU, FDA; higher ML for tuna/swordfish
Cadmium (Cd)	0.05 – 0.10	**0.20 – 0.40**	EU & Codex typical range
Lead (Pb)	0.1 – 0.3	**0.4 – 1.2**	EU, Codex average
Arsenic (As, total)	5.0 (some regional)	**20.0**	Only if total As regulated; inorganic As much lower
Copper (Cu)	— (no ML)	—	Monitored; not regulated
Zinc (Zn)	— (no ML)	—	Monitored; essential element

6.5 Results for Estimated Daily Intake from Fished that feeds on Seagrasses.

The EDI values were calculated as shown above with daily intake taken as 210 gms, average body weight as 65kg and average heavy metal concentrations shown in table 4(a). These EDI values are tabulated in table4(a) below.

Table 4 (a) below shows the EDI calculated values basing on the average metal estimates

Species	**Pb**	**As**	**Cu**	**Ti**	**Al**	**Mg**	**Mn**	**Fe**	**Zn**
S. sutor	0.003157	0.001535	0.005833	0.166969	0.00506	0.177731	0.014908	0.11597	0.017335
M. kephalus	0.00242	0.000626	0.002789	0.234282	0.001223	0.263201	0.031604	0.223469	0.01485
S. nigricans	0.00185	0.003074	0.008595	0.252368	0.008681	0.172107	0.032588	0.177742	0.057606
K. vaigiensis	0.007144	0.003415	0.005892	0.252312	0.00555	0.17205	0.007229	0.158588	0.044343

Table 4 (b) below show the Tolerable Intakes Laid by the World Health Statutory Bodies (USEPA/WHO/FAO/JECFA TDI'S) in mg/kg/day

Pb	**As**	**Cu**	**Ti**	**Al**	**Mg**	**Mn**	**Fe**	**Zn**
0.0035	0.0021	0.05	1.0	0.2857	5.0	0.06	0.8	1.0

In case of Aluminium, Provisional Tolerable Weekly Intake (PTWI) = 2 mg/kg/week, and lead PTWI is past reference value.

6.6 Calculated results for HQ and HI

Table 5below show the calculated results for HQ and HI as per the formula stated in paragraph 5.2.

Table 5 shows tabulated results HQ and HI

Species	HQ-Pb	HQ-As	HQ-Cu	HQ-Ti	HQ-Al	HQ-Mg	HQ-Mn	HQ-Fe	HQ-Zn	HI (ΣHQ)
S. sutor	0.902	0.731	0.117	0.167	0.018	0.036	0.249	0.145	0.017	**2.38**
M. kephalus	0.691	0.298	0.056	0.234	0.004	0.053	0.527	0.279	0.015	**2.16**
S. nigricans	0.529	1.464	0.172	0.252	0.030	0.034	0.543	0.222	0.058	**3.30**
K. vaigiensis	2.041	1.626	0.118	0.252	0.019	0.034	0.121	0.198	0.044	**4.45**

6.7 Calculations for Comprehensive Pollution Index (CPI)

The CPI values shown below in table 6. were calculated as per the equation shown in paragraph 5.3

Table 6 below shows pollution index and CPI values

Fish species	Pb	As	Cu	Ti	Al	Mg	Mn	Fe	Zn	CPI
S. sutor	317.14	257.14	41.00	58.66	6.23	12.51	87.33	50.96	6.09	**93.01**
M. kephalus	242.86	104.76	19.60	82.34	1.50	18.52	185.17	98.19	5.22	**84.13**
S. nigricans	185.71	514.29	60.40	88.67	10.68	12.09	190.83	78.06	20.24	**132.78**
K. vaigiensis	717.14	571.43	41.40	88.65	6.82	12.09	42.33	69.65	15.58	**157.04**

In this study, CPI values ranging between 84.13 and 157.04 suggest varying degrees of metal accumulation among species, with *K. vaigiensis* and *S. nigricans* showing comparatively higher pollution loads, thus reflecting stronger bioaccumulation tendencies within the food web.

7.0 Discussion

Sediment Metal Concentrations and Comparison with Guideline Values

The concentrations of heavy metals in sediments from the study area were generally low and within the safe limits established by International Sediment Quality Guidelines (Table 7). All analyzed elements, including arsenic (1.96 mg/kg), lead (3.88 mg/kg), copper (4.67 mg/kg), and zinc (40.11 mg/kg), were markedly below the NOAA Effects Range–Low (ERL) and the Canadian Council of Ministers of the Environment (CCME) Interim Sediment Quality Guideline (ISQG) thresholds (Long et al., 1995; CCME, 1999). Cadmium and mercury were below detection limits (<0.01 mg/kg), further indicating negligible contamination. Although aluminium (5.25 mg/kg) slightly exceeded the NOAA ERL (2.3 mg/kg), it remained far below the CCME ISQG (52.3 mg/kg), suggesting a geogenic origin rather than anthropogenic input. Similarly, elevated titanium (210.05 mg/kg), iron (121.45 mg/kg), manganese (30.21 mg/kg), and magnesium (188.37 mg/kg) likely reflect natural mineralogical inputs from surrounding coral-limestone and ilmenite-rich coastal sediments rather than pollution sources. Thus, all heavy metal levels were below the probable effect concentrations, implying that adverse biological impacts on benthic organisms are unlikely. These results indicate that the sediments of the study area are unpolluted to minimally impacted**,** and the overall sediment quality can be classified as ecologically safe for marine life.

Assessment of Seagrass Metal Concentrations with respect to propose guidelines

Heavy metal concentrations(ppm, dry weight) in the three dominant seagrass species *Halodule uninervis* (H.O.), *Cymodocea serrulata* (C.S.), and *Thalassia hemprichii* (T.H.) were found to be within typical background ranges reported for unpolluted tropical seagrass meadows (Tables 7). Arsenic (0.95–1.86 ppm), lead (2.05–3.10 ppm), copper (3.36–5.66 ppm), and zinc (20.08–30.44 ppm) were well below the provisional alert values for seagrass tissue (Prange & Dennison, 2000; Fadilah et al., 2022). Cadmium and mercury were near or below detection limits (< 0.05 ppm), confirming minimal contamination. Essential elements such as iron (78.85–85.57 ppm), manganese (19.73–22.70 ppm), and magnesium (123.8–154.52 ppm) occurred in moderate levels consistent with their physiological roles in photosynthesis and enzyme function (Lyngby & Brix, 1982). Slightly higher concentrations of Ti, Fe, and Mg in *C. serrulata* may reflect species-specific uptake or microhabitat variations in sediment composition rather than pollution.

Table 7below shows comparison for heavy metal concentrations in seagrasses with the proposes guidelines

Element	Proposed Background Range*	Proposed Alert Value	H. O.	C. S.	T. H.	Assessment
As	1 – 10	10	1.40	0.95	1.86	All within background → No concern
Mn	— (naturally variable, often 10 – 100)	—	19.73	20.41	22.7	Within normal physiological range
Pb	0.1 – 5	5	2.81	3.10	2.05	Within safe range, well below concern level
Mg	— (macronutrient, non-toxic)	—	123.8	154.52	134.3	Nutrient element, not a pollutant
Zn	10 – 100	50–100	25.6	30.44	20.08	Within background; no indication of enrichment
Cd	0 – 1	1	<0.01	0.05	<0.01	Very low; no contamination
Fe	50 – 200	—	78.85	82.11	85.57	Within normal range for seagrass tissue
Ti	— (geogenic, non-toxic)	—	95.66	121.0	106.7	Likely from natural mineral inputs
Cu	2 – 20	20	4.67	3.36	5.66	Within background levels
Al	— (common mineral element)	—	3.35	3.05	4.58	Low; typical background
Hg	0 – 1	1	<0.01	<0.01	<0.01	Below detection; no concern

***Sources: Prange & Dennison (2000); Fadilah et al. (2022); Pubtexto (2025); Sharma et al. (2023); Science Direct database (2024)*.**

The overall concentration of heavy metals in seagrasses from the study area was low and within natural background ranges, well within ecological safety margins indicating minimal contamination, and good sediment quality in the study area. The absence of elevated toxic metals such as Cd, Hg, Pb, or As suggests that the coastal ecosystem is not under significant heavy metal **stress**. Variations among species (slightly higher Mg, Fe, and Ti in *C. serrulata*) likely reflect species-specific uptake capacities and sediment geochemistry rather than external pollution sources.

Relationship between Sediment Quality and Seagrass quality in the study area

The consistent pattern of low heavy metal levels in both sediments and seagrass tissues indicates a strong link between the geochemical stability of sediments and limited bioavailability of metals in the surrounding environment. Since seagrasses absorb most nutrients and trace elements through their roots and rhizomes, sediment chemistry largely controls metal uptake (Sanchiz et al., 2001). The present results reveal that seagrasses act as passive bioindicators of ambient environmental conditions rather than active accumulators of pollutants. The correspondence between low sedimentary metal content and low tissue concentrations further confirms that the coastal ecosystem in Chukwani Bay, Zanzibar, is not experiencing significant heavy metal stress. This finding is consistent with other studies in the Western Indian Ocean region, which have reported similarly low levels of trace metals in seagrasses and sediments from relatively undisturbed areas (Shilla et al., 2022; Fadilah et al., 2022). In conclusion, the integrated assessment of sediments and seagrasses demonstrates that the Chukwani Bay marine environment maintains good ecological quality, with metal concentrations well below international guideline limits. The dominance of natural elements such as Fe, Ti, and Mg, coupled with negligible levels of toxic metals (Cd, Hg, Pb, As), suggests that current anthropogenic influence is minimal. These results underscore the value of seagrasses as sensitive bioindicators for monitoring early signs of metal contamination in tropical coastal ecosystems. Therefore, the results presented here should be interpreted in relation to spatial variations, local anthropogenic influences, and known geochemical baselines rather than absolute contamination limits. This approach provides a meaningful ecological context

Metallic Analysis from the Fish Species

Analysis shows that: from lead (Pb) concentrations in all four species (S. sutor, M. kephalus, S. nigricans, K. vaigiensis), only k. Vaigiensis (2,51 ppm, dry weight) exceed internationally accepted limits for the common edible marine fish, implying possible anthropogenic contamination in Chukwani Bay sediments or food sources. Cadmium (Cd)**,** Mercury (Hg)**,** and Arsenic (As) remain well below threshold values, suggesting minimal risk from these metals (tables 4 (a) & 4 (b)). Essential elements (Cu, Zn, Fe, Mn, and Mg) occur at background levels typical for marine species and are not of toxicological concern. The elevated Pb levels may pose potential human health risks upon frequent fish consumption and point to the need for source identification and pollution mitigation (e.g., from fuel residues from ships, antifouling paints used for painting boats, may be some sunscreen lotions, cosmetics or urban runoff).

Comparative interpretation of sediment, seagrass, and fish metal concentrations

A comparative evaluation of metal concentrations across sediment, seagrass, and fish tissues reveals distinct yet interconnected contamination pathways within Chukwani Bay. Sediment samples exhibited relatively low concentrations of most trace metals, remaining below both the NOAA (ERL/ERM) and CCME (ISQG/PEL) thresholds, indicating limited direct sediment pollution. However, seagrass samples *Halophila ovalis*, *Cymodocea serrulata*, and *Thalassia* *hemprichii* displayed moderate enrichment in several elements, particularly Fe, Ti, and Zn, reflecting their high capacity for metal uptake from pore water and sediment–water interfaces. Seagrasses act as both sinks and biofilters, concentrating bioavailable metals through root–rhizome pathways and leaf surfaces (Prange & Dennison, 2000; Lewis & Devereux, 2009).

When compared with fish tissues, a clear biomagnification pattern emerges for Pb and, to a lesser extent, Cu and Zn. Despite low sedimentary Pb levels (3.88 mg kg^{-1}), fish muscle tissues contained Pb concentrations ranging between 1.35–2.05 mg kg^{-1} (dry weight), surpassing the dry-weight equivalent of international food-safety limits (0.4–1.2 mg kg^{-1}). Conversely, Cd and Hg remained very low across all compartments, suggesting minimal inputs of these more toxic metals. The relative increase of Pb and Fe concentrations from sediment → seagrass → fish supports the hypothesis that bioaccumulation and trophic transfer are occurring through dietary exposure, as herbivorous and omnivorous fish feed on epiphytic algae and seagrass tissues.

Overall, these results illustrate that sediment quality alone underestimates ecological and human health risks, since biological matrices more accurately reflect bioavailable metal fractions which are being assimilated and biomagnified through the trophic network thus suggesting persistent low-level contamination from anthropogenic sources such as boat maintenance, antifouling paints, storm water inputs, or shoreline urban runoff. The integrated sediment–seagrass–fish assessment highlights lead (Pb) as the most critical contaminant of concern in Chukwani Bay, warranting continued monitoring and pollution control measures targeting shipping/ boating activities, shoreline urban runoff or storm water inputs, antifouling paints, and possible sunscreens, etc. This pattern implies that sediment quality alone may not fully represent ecological risk, since benthic and pelagic organisms can accumulate trace metals even at background sediment levels. The discrepancy between sediment and tissue concentrations highlights the importance of bioindicators species in assessing environmental health.

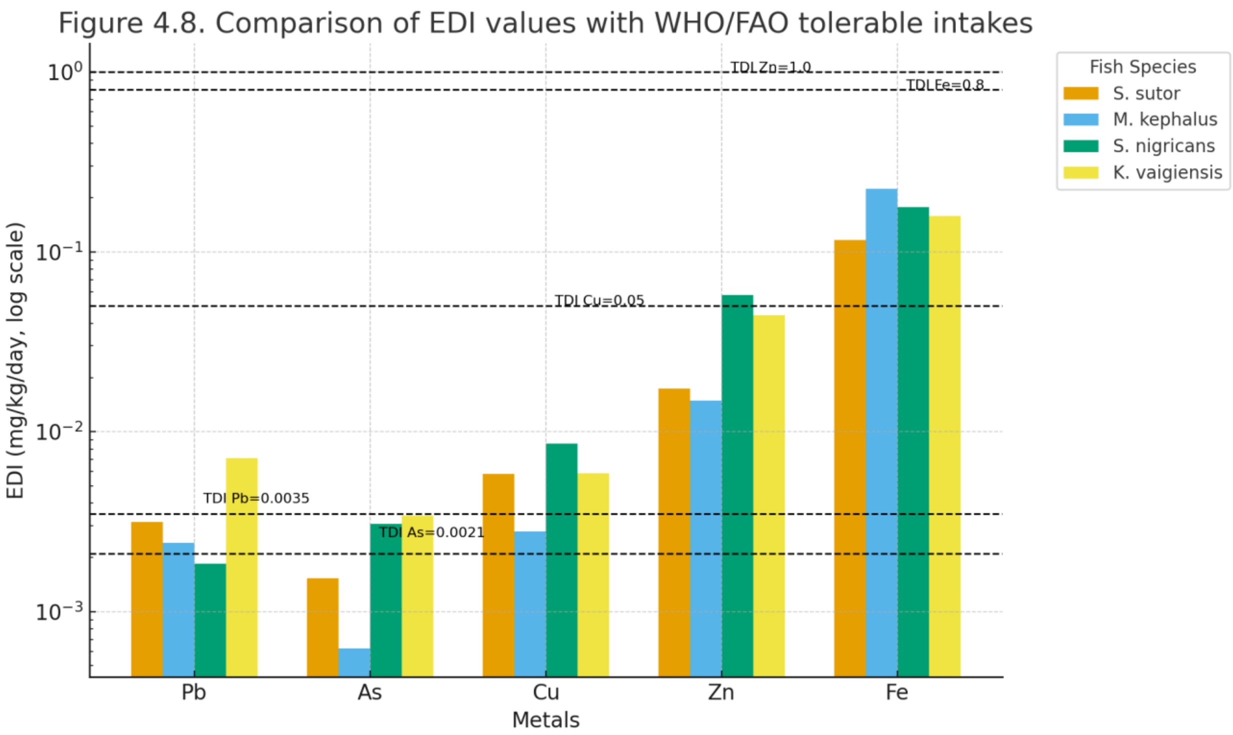
Integrated Human Health and Ecological Risk Analysis

The comprehensive integration of Estimated Daily Intake (EDI)**,** Comprehensive Pollution Index (CPI)**,** and Hazard Quotient/Index (HQ, HI) provides a multidimensional understanding of metal exposure pathways within the Chukwani Bay food web. The calculated EDI values for nine metals in four fish species (Table 5) were compared with international tolerable daily intakes (Table 5), and interpreted together with HI and CPI results (Tables 5-6 respectively).

EDI vs Tolerable Intakes

Across all species, EDI values for most metals Cu, Zn, Fe, Mn, Mg, Ti and Al remained well below the WHO/FAO/JECFA and USEPA daily thresholds, implying minimal nutritional or toxic risk from these elements. However, Pb and As exceeded tolerable limits in some species. *K. vaigiensis* recorded Pb = 0.00714 mg kg^{-1} day^{-1} and As = 0.00342 mg kg^{-1} day^{-1}**,** both higher than the recommended limits of 0.0035 mg kg^{-1} day^{-1} (Pb) and 0.0021 mg kg^{-1} day^{-1} (As)**.** *S. nigricans* also showed As = 0.00307 mg kg^{-1} day^{-1}**,** exceeding the same guideline. These results suggest that habitual consumption of these two species may lead to chronic exposure risks, especially in coastal communities that depend heavily on local fish for protein. A comparison of EDI values against statutory health organization is shown in figure 2below

Figure 2. Comparison of EDI values with WHO/FHO tolerable intakes



A grouped-bar graph showing EDI for Pb, As, Cu, Zn, Fe per fish species, with dashed horizontal lines indicating WHO/FAO TDI thresholds. Bars for Pb and As in K. vaigiensis and S. nigricans should cross the guideline lines to visually highlight exceedances The grouped-bar graph compares the Estimated Daily Intake (EDI) values of key metals (Pb, As, Cu, Zn, Fe) in *Siganus sutor*, *Mugil kephalus*, *Scarus nigricans*, and *Kyphosus vaigiensis*.
The dashed lines represent WHO/FAO tolerable intake thresholds, and notably, Pb and As levels in *K. vaigiensis* and *S. nigricans* exceed these limits, indicating potential dietary exposure risks for frequent seafood consumers

Integration with CPI and HI

The Comprehensive Pollution Index (CPI) was employed to assess the cumulative intensity of heavy metal contamination and its ecological implications in fish species from Chukwani Bay, Zanzibar. By integrating individual pollution indices (PI) for each metal, CPI provides a quantitative measure of how far metal concentrations exceed baseline or regulatory standards, thereby reflecting the degree of anthropogenic influence on the marine ecosystem. Among the four species analyzed, *Kyphosus vaigiensis* recorded the highest CPI and Hazard Index (HI) values, followed by *Scarus nigricans*, *Siganus sutor*, and *Mugil cephalus*, revealing a coherent pattern linking ecological contamination to potential toxicological risks. The CPI values ranged from 84.13 to 157.04, signifying moderate to high pollution levels, while HI values (2.16–4.45) exceeded the safety threshold (HI > 1), indicating possible non-carcinogenic health risks associated with fish consumption.

Lead (Pb) and arsenic (As) were the dominant contributors to the total hazard burden, accounting for over 60% of the HI across all species. This dominance underscores their ecological importance and potential to biomagnifying through the food chain. The strong correspondence between elevated CPI, high Estimated Daily Intake (EDI), and HI > 1 supports a trophic magnification pathway of Pb and As along the sediment → seagrass → fish continuum. Although sediment contamination was relatively low (CPI ≈ 0.68), the progressive enrichment in seagrass tissues (CPI ≈ 1.0–1.12) indicates efficient bioaccumulation and transfer to higher trophic levels.

According to standard pollution classification thresholds (CPI > 1 = contaminated) (Håkanson, 1980; Tomlinson et al., 1980), all fish species exhibited enrichment above permissible limits. The substantially higher CPI values in *K. vaigiensis* and *S. nigricans* are likely linked to their benthic feeding habits, habitat preferences, and higher trophic levels, which increase exposure to contaminated prey and sediments (Usero et al., 2003; Rainbow, 2007). In contrast, *S. sutor* and *M. cephalus* exhibited lower CPI values, suggesting either reduced exposure or effective physiological regulation of metals. Similar CPI ranges and trophic magnification patterns have been reported in the South China Sea (Zhang et al., 2022) and the eastern Mediterranean (Aydin et al., 2020), reinforcing that benthic and herbivorous fish are effective bioindicators of metal enrichment in nearshore systems.

Overall, the consistently elevated CPI values across species highlight significant ecological risk and potential human health implications through fish consumption, emphasizing the need for continuous monitoring and management of heavy metal contamination in Chukwani Bay.

Risk Implications and Management Perspective

The integration of all indices indicates that Chukwani Bay is ecologically moderately polluted but toxicologically vulnerable. Essential metals contribute to nutritional intake, yet non-essential metals, particularly Pb and As, pose chronic health concerns. If local fish consumption rates remain high (≈ 0.05 kg fish person^{-1} day^{-1}), the observed EDI for Pb and As could surpass the acceptable daily intake, implying potential neurological, renal, and hematological effects.The table 8 below shows the summary of EDI, CPI, HI, and Risk Level.

Table8 Summary of EDI, CPI, HI, and Risk Level

Species	Pb (EDI)	As (EDI)	CPI	HI (ΣHQ)	Comparison to TDI	Overall Risk
S. sutor	0.00316	0.00154	93.01	2.38	Pb ≈ limit	Moderate
M. kephalus	0.00242	0.00063	84.13	2.16	Below limits	Moderate-low
S. nigricans	0.00185	**0.00307**	132.78	3.30	As > limit	High
K. vaigiensis	**0.00714**	**0.00342**	157.04	4.45	Pb & As > limit	Very High

The integrated dataset demonstrates that although sediments in Chukwani Bay appear lightly contaminated, metal bioavailability and trophic transfer significantly elevate exposure risk in fish and humans. Elevated EDI, HQ, and HI for Pb and As confirm that bioaccumulation, not sediment concentration alone, drives ecological stress and human toxicity potential. Therefore, the bay's contamination status can be classified as "moderate ecological pollution with high human health concern."

Integrated Pollution and Human Health Risk Interpretation

The Comprehensive Pollution Index (CPI), Estimated Daily Intake (EDI), and non-carcinogenic health risk indices (HQ and HI) were jointly evaluated to assess the potential health implications of heavy metal contamination through consumption of the marine fish species collected from

Chukwani Bay, Zanzibar. Although copper, zinc and iron has EDI values well below the tolerable limit 0.05, 1.0 and 0.8 mg/kg/day respectively, bioaccumulation may lead to gastrointestinal distress, vomiting, and diarrhea; liver and kidney malfunction in severe cases (*JECFA, 2011*), and metal fume fever**,** impaired immune response, and reduced copper absorption in case of zinc (FAO/WHO, 2011).Over consumption of iron too could cause hemochromatosis (iron overload), liver cirrhosis and pancreatic dysfunction. (*ATSDR, 2020; WHO, 2011*).

The estimated daily intake (EDI) and hazard index (HI) values demonstrated that lead (Pb) and arsenic (As) represent the primary toxicological concerns among the analyzed metals in fish species from Chukwani Bay. The calculated HI values for *Kyphosus vaigiensis* (HI = 4.45) and *Siganus nigricans* (HI = 3.30) exceeded the acceptable risk threshold of 1.0 recommended by the United States Environmental Protection Agency (USEPA, 2011), suggesting potential non-carcinogenic health risks to consumers through chronic dietary exposure. These elevated HI values reflect the bioaccumulative potential of Pb and As and highlight their persistence and trophic transfer along the marine food web.

Lead (Pb)

The EDI for Pb in *K. vaigiensis* (0.00714 mg/kg/day) and *S. sutor* (0.00316 mg/kg/day) surpassed the tolerable daily intake of 0.0035 mg/kg/day established by the FAO/WHO Joint Expert Committee on Food Additives (FAO/WHO, 2011). Continuous ingestion of Pb-contaminated fish can result in systemic toxicity, particularly affecting neurological, hematological, and renal systems. Pb interferes with heme synthesis, leading to anemia, and accumulates in the central nervous system, causing neurodevelopmental deficits, reduced cognitive function, and behavioral abnormalities in children. In adults, Pb exposure has been associated with nephrotoxicity, hepatotoxicity, hypertension, and reproductive dysfunction (FAO/WHO, 2011; USEPA, 2011; ATSDR, 2020).

Arsenic (As**)**

Similarly, the EDI for As in *S. nigricans* (0.00307 mg/kg/day) and *K. vaigiensis* (0.00341 mg/kg/day) exceeded the provisional tolerable daily intake of 0.0021 mg/kg/day (WHO, 2011; USEPA, 2023). Chronic arsenic exposure through dietary intake has been linked to both carcinogenic and systemic toxic effects. Arsenic exerts its toxicity by disrupting cellular respiration and oxidative stress pathways, leading to skin, lung, and bladder cancers, as well as non-carcinogenic outcomes such as dermal lesions (hyperkeratosis, melanosis), peripheral neuropathy, and vascular disorders including Blackfoot disease (WHO, 2011; USEPA, 2023).

Ecological Implications

The Comprehensive Pollution Index (CPI) values demonstrated a clear enrichment gradient from sediments (0.68) to seagrasses (0.94–1.12) and fish species (84.13–157.04), indicating a progressive pattern of bioaccumulation and trophic transfer within the benthic food web of Chukwani Bay. According to the classification criteria proposed by Yu and Wang (2011), CPI values below 1.0 represent “unpolluted to slightly polluted” conditions, whereas values between 1.0 and 2.0 denote moderate pollution. The results therefore suggest moderate contamination within seagrass and fish samples, primarily attributable to lead (Pb), zinc (Zn), and iron (Fe). Similar enrichment trends have been reported in other tropical and subtropical coastal systems, where seagrass meadows function both as sinks and as bioindicators of trace-metal contamination (Prange & Dennison, 2000; Lewis & Devereux, 2009).

Elevated concentrations of heavy metals in seagrasses have far-reaching ecological consequences for the Chukwani Bay ecosystem. As primary producers and key habitats for numerous herbivorous and detritivorous fish species—including *Siganus sutor*, *Mugil cephalus*, *Scarus nigricans*, and *Kyphosus vaigiensis*—seagrasses form a vital link in the marine food web, facilitating the transfer of accumulated metals to higher trophic levels. The accumulation of elements such as Zn, Mn, and Al in seagrass tissues can impair photosynthetic efficiency, pigment stability, and growth performance, while metal bioaccumulation in fish may disrupt enzymatic activity, metabolism, and reproduction. Prolonged exposure to elevated Pb and As concentrations can also alter community composition, suppress biodiversity, and reduce the resilience of benthic ecosystems to environmental stressors. In addition, this evidence indicates declining reproductive success in marine fauna, reduced seagrass coverage and impaired fish mobility in Chukwani Bay.

From a human-health perspective, the bioaccumulation of toxic metals in edible fish species represents a dietary hazard for coastal populations that rely heavily on seafood as a primary protein source. Monitoring heavy-metal concentrations in seagrasses therefore provides an effective early-warning system for ecosystem degradation and food-chain contamination. Based on these findings, a long-term environmental monitoring program should be established in Chukwani Bay and adjacent coastal zones under the coordination of the Zanzibar Environmental Management Authority (ZEMA) and the Department of Fisheries and Marine Resources. Such initiatives should aim to define baseline metal thresholds, regulate pollution sources, and enhance community awareness of seafood safety. Furthermore, improved wastewater management, regulation of industrial effluents, and sustainable coastal-development practices are essential to mitigate metal loading and preserve the ecological integrity of Zanzibar’s seagrass ecosystems.

8.0 Conclusion

The present study revealed considerable enrichment and bioaccumulation of heavy metals within the Chukwani Bay marine ecosystem as indicated by elevated Comprehensive Pollution Index (CPI) values across all sampled fish species. These results confirm the pronounced bioaccumulative potential of metals within seagrass-based trophic systems, particularly among herbivorous fish that feed on seagrasses and benthic algae, where detrital matter and algal substrates serve as primary reservoirs for trace metal deposition and transfer. The concurrent elevation of Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) values—particularly for lead (Pb), zinc (Zn), and iron (Fe)—suggests potential non-carcinogenic health risks among coastal populations that rely heavily on fish as a dietary protein source.

Chronic exposure to these contaminants may contribute to neurological, hepatic, cardiovascular, and carcinogenic health outcomes, while prolonged metal accumulation could impair enzymatic activity, metabolism, and reproduction in marine organisms. In fish populations, it can lead to reproductive issues such as fewer eggs, deformities, and low hatch rates. Consequently, heavy metal pollution contributes to an overall decline in ecosystem health thus affecting blue economy. The consistent exceedance of permissible thresholds emphasizes the need for continuous environmental surveillance and regulatory intervention. Establishing a long-term biomonitoring framework, enforcing effluent discharge standards, and strengthening wastewater and runoff management are critical to reducing heavy metal inputs into the bay. Furthermore, enhancing public awareness on seafood safety and sustainable fisheries management will be vital to protect both ecosystem integrity and human health within Zanzibar's coastal environments. These conclusions provide a scientific basis for targeted management and policy interventions aimed at mitigating metal contamination and preserving the ecological and socio-economic value of Chukwani Bay**.**

Study Limitations

In this study, several assumptions were made to evaluate potential health risks from fish consumption under worst-case scenarios .Currently, there are no internationally recognized guideline values for heavy metals in seagrass tissues which limits direct toxicity assessment. However, the generalizability of our findings may be limited due to the relatively small sample size and restricted geographic coverage, which may not accurately represent the broader fish population, species diversity, or variation in fish age and size that were not fully accounted for. The study also did not evaluate potential interactions between different heavy metals, which could either amplify or reduce the overall health risk. Consequently, the interpretation of metal concentrations in this study was based on comparative evaluation using background values from uncontaminated sites and sediment quality benchmarks such as NOAA's ERL and ERM. While seagrasses are effective bioindicators of metal accumulation, the absence of standardized thresholds introduces uncertainty in ecological risk estimation. Therefore, the findings should be viewed in relation to local geochemical baselines and anthropogenic influences rather than absolute contamination limits.

Policy Implications

The observed enrichment gradient and associated ecological risks underscore the urgent need for an integrated coastal-management framework in Chukwani Bay that explicitly addresses heavy-metal pollution and its cascading effects through the benthic food web. In line with the precautionary principle and the objectives of the Zanzibar Environmental Policy (2013), a multi-tiered policy approach is recommended to safeguard both ecosystem and human health.

First, ZEMA, in collaboration with the Department of Fisheries and Marine Resources, should establish a Coastal Metal Monitoring and Assessment Program (CM-MAP) focused on tracking trace-metal fluxes in sediments, seagrasses, and key fish species. This program would provide baseline concentration thresholds, enable trend analysis, and support evidence-based regulatory decisions.

Second, regulatory instruments should be strengthened to control point and non-point pollution sources**,** including untreated wastewater discharges, shipyard runoff, and artisanal boat-repair zones known to release Pb, Cu, and Zn. Enforcement of effluent-quality standards in accordance with the Environmental Management (Water Quality Standards) Regulations, 2020**,** and alignment with UNEP's Global Programme of Action for the Protection of the Marine Environment from Land-based Activities should be prioritized.

Third, the policy framework should promote community-based stewardship by integrating local fishing cooperatives and coastal residents into monitoring, reporting, and awareness programs. Participatory education campaigns emphasizing seafood safety, seagrass conservation, and pollution-source reduction can enhance local compliance and foster long-term behavioral change.

Finally, adaptive management and periodic ecological risk assessments should be institutionalized within Zanzibar's coastal governance agenda to ensure that emerging contamination trends are rapidly detected and mitigated. Integrating pollution-index monitoring with spatial planning, mangrove restoration, and sustainable fisheries management will help maintain ecological resilience and protect the socio-economic benefits derived from Zanzibar's seagrass ecosystems.

Policy Recommendations

To mitigate heavy metal contamination and associated health risks, Zanzibar's environmental authorities should implement an integrated coastal pollution management strategy. This includes strict enforcement of effluent regulations, establishment of a long-term biomonitoring program using seagrasses and fish as bioindicators, and collaboration with public health agencies to develop fish consumption advisories. Community-based awareness campaigns and sustainable fishing initiatives should also be strengthened to enhance local stewardship. Coordinated efforts among research institutions, the Department of Environment, and the Marine Conservation Unit are vital for sustaining ecosystem health and food security in Zanzibar's coastal waters.

9.0 Research Implications

This study establishes an essential baseline for assessing heavy metal bioaccumulation and ecological risk within Zanzibar's coastal ecosystems, particularly in Chukwani Bay. The findings underscore the need for comprehensive, multidisciplinary research to elucidate the biogeochemical pathways and sources of metal contamination. Future investigations should focus on sediment–water–biota interactions, metal speciation, and the influence of seasonal hydrodynamics on pollutant transport and bioavailability. Integrating advanced analytical approaches such as stable isotope tracing, geospatial modeling, and trophic transfer analysis—would enhance the identification of both point and diffuse pollution sources. Furthermore, extending biomonitoring to include plankton, benthic organisms, and seagrass tissues will provide a more holistic understanding of contaminant cycling and biomagnification across trophic levels. Such research will strengthen the scientific foundation for targeted management, pollution mitigation, and restoration strategies in Zanzibar's coastal and marine environments.

Study Recommendations

To minimize exposure and sustain ecosystem health, management should prioritize: Control of metal inputs from boat maintenance, antifouling coatings, and shoreline effluents, Sunscreens and Cosmetics for snorkeling, Vessel or freighter or cargo ships discharge. The government should encourage. Routine biomonitoring of sediments, seagrasses, and fish tissues via her relevant authorities; Public advisories on safe consumption of *K. vaigiensis* and *S. nigricans*; Community-based coastal management and pollution awareness programs should be frequently promoted.

Ethics statement

Ethical approval was not required for the study involving fishes in accordance with the local legislation and institutional requirements because our study did not require ethical board approval because it did not contain human or animal trials. The fish used in this study was procured dead from local fishermen. All surgical operations were performed on dead fish. Care was taken to ensure that the least number of fish was utilized to reach satisfactory statistical conclusions.

Conflict of interest

The Corresponding author declare that the research was conducted in the absence of any Institution, commercial or financial relationships that could be construed as a potential conflict of interest.

10.0 Reference

1. Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry, 2019*, 6730305. https://doi.org/10.1155/2019/6730305
2. Aljahdali, M. O., & Bantan, R. A. (2020). Bioaccumulation and risk assessment of heavy metals in marine organisms from the Red Sea coast. *Marine Pollution Bulletin, 155,* 111135.
3. American Public Health Association (APHA). (2017). *Standard methods for the examination of water and wastewater* (23rd Ed.). Washington, DC: American Public Health Association, American Water Works Association, Water Environment Federation.
4. ATSDR (Agency for Toxic Substances and Disease Registry). (2020). *Toxicological profile for iron.* Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. Retrieved from https://www.atsdr.cdc.gov/toxprofiles/tp150.pdf

5. Aydin, F., Tokatli, C., & Barlas, N. (2020). Assessment of heavy metal pollution and ecological risk in the eastern Mediterranean coastal waters. *Marine Pollution Bulletin, 150*, 110719.
6. Birch, G. F. (2017). Determination of sediment metal background concentrations and enrichment in marine environments—A critical review. *Science of the Total Environment, 580*, 813–831. https://doi.org/10.1016/j.scitotenv.2016.12.028
7. Burton, G. A., & Johnston, E. L. (2010). Assessing ecosystem health indicators for sediment stress. *Environmental Pollution, 158*(12), 3395–3402. https://doi.org/10.1016/j.envpol.2010.07.026
8. CCME (Canadian Council of Ministers of the Environment). (1999). *Canadian sediment quality guidelines for the protection of aquatic life: Summary tables.* (Updated 2001). In *Canadian Environmental Quality Guidelines, 1999.* Winnipeg: CCME.
9. Chien, L. C., Hung, T. C., Choang, K. Y., Yeh, C. Y., Meng, P. J., Shieh, M. J., & Han, B. C. (2002). Daily intake of TBT, Cu, Zn, Cd, and As for fishermen in Taiwan. *Science of the Total Environment, 285*(1–3), 177–185. https://doi.org/10.1016/S0048-9697(01)00913-0
10. Du Laing, G., Rinklebe, J., Vandecasteele, B., Meers, E., & Tack, F. M. G. (2009). Trace metal behaviour in estuarine and riverine floodplain soils and sediments: A review. *Science of the Total Environment, 407*(13), 3972–3985. https://doi.org/10.1016/j.scitotenv.2008.07.025
11. Duarte, C. M. (2002). The future of seagrass meadows. *Environmental Conservation, 29*(2), 192–206. https://doi.org/10.1017/S0376892902000127
12. Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change, 3*(11), 961–968. https://doi.org/10.1038/nclimate1970
13. Eggleton, J., & Thomas, K. V. (2004). A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events. *Environment International*, *30*(7), 973–980. https://doi.org/10.1016/j.envint.2004.03.001
14. Erftemeijer, P. L. A., & Robin, M. J. (2006). Environmental impacts of dredging on seagrasses: A review. *Marine Pollution Bulletin, 52*(12), 1553–1572.
15. Fadilah, N., et al. (2022). Heavy metal accumulation in tropical seagrasses and associated sediments. *Marine Pollution Bulletin*, *180*, 113708.
16. FAO (Food and Agriculture Organization). (2003). *Manual of procedures for the FAO/IOC/IAEA/UNEP project on the determination of petroleum hydrocarbons in marine organisms and sediments* (Reference Methods for Marine Pollution Studies No. 20). Rome: United Nations Environment Programme.
17. FAO/WHO. (2011). *Joint FAO/WHO Food Standards Programme: Codex Committee on Contaminants in Foods* (Fifth Session). The Hague, The Netherlands: Food and Agriculture Organization of the United Nations & World Health Organization..
18. Håkanson, L. (1980). An ecological risk index for aquatic pollution control. *Water Research, 14*(8), 975–1001.
19. Islam, M. S., Ahmed, M. K., Raknuzzaman, M., Habibullah-Al-Mamun, M., & Islam, M. K. (2015). Heavy metal pollution in surface water and sediment: A preliminary assessment of an urban river in a developing country. *Ecological Indicators, 48*, 282–291. https://doi.org/10.1016/j.ecolind.2014.08.016

20. Jackson, J. B., & Nemeth, D. J. (2007). A new method to describe seagrass habitat sampled during fisheries-independent monitoring. *Estuaries and Coasts, 30*(1), 171–178. https://doi.org/10.1007/BF02782978
21. JECFA (Joint FAO/WHO Expert Committee on Food Additives). (2011). *Evaluation of certain contaminants in food: Seventy-second report of the Joint FAO/WHO Expert Committee on Food Additives* (WHO Technical Report Series No. 959). Geneva, Switzerland: World Health Organization.
22. Li, J., Yu, H., & Wang, Y. (2019). Metal accumulation and ecological risk assessment in seagrass and associated sediments. *Marine Environmental Research, 148*, 1–9.
23. Lewis, M. A., & Devereux, R. (2009). Nonnutrient anthropogenic chemicals in seagrass ecosystems: Fate and effects. *Environmental Toxicology and Chemistry, 28*(7), 1240–1254.
24. Long, E. R., MacDonald, D. D., Smith, S. L., & Calder, F. D. (1995). Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *Environmental Management, 19*(1), 81–97. https://doi.org/10.1007/BF02472006
25. Lyngby, J. E., & Brix, H. (1982). Seasonal and environmental variation in cadmium, copper, lead and zinc concentrations in eelgrass (*Zostera marina* L.) in the Limfjord, Denmark. *Aquatic Botany, 14*, 59–74.
26. Marbà, N., Arias-Ortiz, A., Masqué, P., Kendrick, G. A., Mazarrasa, I., Bastyan, G. R., García-Orellana, J., & Duarte, C. M. (2015). Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks. *Journal of Ecology, 103*(2), 296–302. https://doi.org/10.1111/1365-2745.12370
27. Milestone Srl. (2016). *ETHOS Easy: Advanced microwave digestion system—User manual.* Sorisole (BG), Italy: Milestone Srl.
28. Milestone Srl. (2018). *ETHOS Easy: Advanced microwave digestion system—User manual.* Sorisole (BG), Italy: Milestone Srl.
29. Mohammed, M. A., Hamad, S. A., & Ali, O. K. (2021). Coastal pollution and anthropogenic pressures in Zanzibar: Implications for marine biodiversity conservation. *African Journal of Marine Science, 43*(2), 175–189.
30. Nordlund, L. M., Koch, E. W., Barbier, E. B., & Creed, J. C. (2018). Seagrass ecosystem services and their variability across genera and geographical regions. *PLoS ONE, 13*(10), e0199894.
31. Orth, R. J., Carruthers, T. J. B., Dennison, W. C., et al. (2006). A global crisis for seagrass ecosystems. *BioScience, 56*(12), 987–996.
32. Prabowo, R. E., Rahman, F., & Yulianto, E. (2020). Spatial distribution of heavy metals in *Thalassia hemprichii* and sediments from Indonesian coastal waters. *Marine Pollution Bulletin, 160*, 111644.
33. Prange, J. A., & Dennison, W. C. (2000). Physiological responses of the seagrass *Zostera capricorni* Aschers to heavy metal stress. *Aquatic Botany, 66*(1), 61–70.
34. Prange, J. A., & Dennison, W. C. (2000). Physiological responses of five seagrass species to trace metals. *Environmental Toxicology, 15*(5), 497–505.
35. Pubtexto Environmental Research Database. (2025). *Baseline concentrations of trace metals in tropical seagrasses.*
36. Qiu, Y.-W., Zhang, G., & Liu, G.-Q. (2018). Bioaccumulation of heavy metals in marine food webs: A review. *Environmental Science and Pollution Research, 25*(8), 7297–7310.

37. Rainbow, P. S. (2007). Trace metal bioaccumulation: Models, metabolic availability and toxicity. *Environment International, 33*(4), 576–582.
38. Ralph, P. J., Durako, M. J., Enriquez, S., et al. (2007). Impact of light limitation on seagrasses. *Journal of Experimental Marine Biology and Ecology, 350*(1–2), 176–193.
39. Sanchiz, C., García-Carrascosa, A. M., & Pastor, A. (2001). Bioaccumulation of heavy metals in seagrasses: Influence of sediment contamination and environmental factors. *Marine Environmental Research, 52*, 21–35.
40. Sany, S. B. T., Salleh, A., Sulaiman, A. H., Monazami, M., & Tehrani, G. M. (2013). Assessment of heavy metal contamination in soil and sediment of the western part of Peninsular Malaysia. *Environmental Monitoring and Assessment, 185*(5), 4367–4382. https://doi.org/10.1007/s10661-012-2860-9
41. Sharma, S., et al. (2023). Assessment of trace metals in seagrasses and sediments along the Indian coast. *Chemosphere, 317*, 137923.
42. Shilla, D., Mamboya, F. A., & Machiwa, J. F. (2022). Assessment of trace metal accumulation in seagrasses and sediments along the Western Indian Ocean coast. *Marine Pollution Bulletin, 181*, 113832.
43. Short, F. T., Polidoro, B., Livingstone, S. R., Carpenter, K. E., Bandeira, S., Bujang, J. S., Calumpong, H. P., Carruthers, T. J. B., Coles, R. G., Dennison, W. C., Erftemeijer, P. L. A., Fortes, M. D., Freeman, A. S., Jagtap, T. G., Kamal, A. H. M., Kendrick, G. A., Kenworthy, W. J., La Nafie, Y. A., Nasution, I. M., Orth, R. J., Prathep, A., Sanciangco, J. C., van Tussenbroek, B. I., Vergara, S. G., Waycott, M., & Zieman, J. C. (2011). Extinction risk assessment of the world's seagrass species. *Biological Conservation, 144*(7), 1961–1971. https://doi.org/10.1016/j.biocon.2011.04.010
44. Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *EXS, 101*, 133–164.
45. Tomlinson, D. L., Wilson, J. G., Harris, C. R., & Jeffrey, D. W. (1980). Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgoländer Meeresuntersuchungen, 33*(1–4), 566–575.
46. Tupan, C. I., et al. (2020). Bioaccumulation and anatomical responses of seagrasses to lead exposure. *Marine Pollution Bulletin, 157*, 111318.
47. U.S. Environmental Protection Agency (USEPA). (1989). *Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part A)* (EPA/540/1-89/002). Washington, DC: U.S. Environmental Protection Agency.
48. U.S. Environmental Protection Agency (USEPA). (1996). *Method 3052: Microwave assisted acid digestion of siliceous and organically based matrices* (EPA 3052). Washington, DC: U.S. Environmental Protection Agency, Office of Solid Waste.
49. U.S. Environmental Protection Agency (USEPA). (2000). *Guidance for assessing chemical contaminant data for use in fish advisories. Volume 1: Fish sampling and analysis* (3rd ed., EPA 823-B-00-007). Washington, DC: U.S. Environmental Protection Agency, Office of Science and Technology.
50. U.S. Environmental Protection Agency (USEPA). (2001). *Methods for the determination of metals in environmental samples* (EPA/600/R-94/111). Washington, DC: Office of Research and Development, U.S. Environmental Protection Agency.
51. U.S. Environmental Protection Agency (USEPA). (2011). *Exposure Factors Handbook: 2011 Edition* (EPA/600/R-09/052F). Washington, DC: U.S. Environmental Protection

Agency, National Center for Environmental Assessment. Retrieved from https://www.epa.gov/expobox/exposure-factors-handbook

52. Usero, J., González-Regalado, E., & Gracia, I. (2003). Trace metals in bivalve molluscs from the Atlantic coast of southern Spain. *Environment International, 29*(4), 493–502.
53. Wang, W. X., Rainbow, P. S., & Yang, Y. (2016). Metal transfer in marine food chains: A review. *Environmental Pollution, 219*, 138–148.
54. Waycott, M., Duarte, C. M., Carruthers, T. J. B., et al. (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences, 106*(30), 12377–12381.
55. WHO (World Health Organization). (2011). *Safety evaluation of certain food additives and contaminants: Prepared by the seventy-third meeting of the Joint FAO/WHO Expert Committee on Food Additives (JECFA).* Geneva, Switzerland: World Health Organization.
56. Yu, R., & Wang, S. (2011). Trace metal contamination in estuarine and coastal environments in China: Environmental quality criteria and assessment. *Marine Pollution Bulletin, 62*(12), 2974–2981. https://doi.org/10.1016/j.marpolbul.2011.08.011
57. Yu, R., & Wang, W.-X. (2011). A comparative study on metal bioaccumulation and trophic transfer in marine food webs from the coastal environments of Hong Kong and the Pearl River Estuary. *Marine Environmental Research, 71*(3), 221–229. https://doi.org/10.1016/j.marenvres.2011.01.007
58. Zhang, L., Chen, W., & Li, Y. (2022). Spatial distribution and ecological risk assessment of heavy metals in marine organisms from the South China Sea. *Environmental Science and Pollution Research, 29*(18), 26740–26754. https://doi.org/10.1007/s11356-021-18391-4