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Comparative assessment of source-driven toxic metal bioaccumulation and human health risks in edible aquatic organisms from freshwater and estuarine ecosystems

Ruwan Tharanga Perera[1]*, Nalin Gunathilaka[2], Asith Umayanga Dias[3], Alecsha Sathnara Fernando[3] , Dilshani Sakunthala[2,4], Hiruni Gunathilaka[5], Janitha Liyanage[2,4]

[1] Department of Indigenous Medical Resources, Gampaha Wickramarachchi University of Indigenous Medicine, Sri Lanka
[2] Department of Chemistry, University of Kelaniya, Sri Lanka
[3] The Institute of Chemistry Ceylon, Sri Lanka
[4] CKDu Information and Research Centre, University of Kelaniya, Sri Lanka
[5] Department of Roga vignana, Gampaha Wickramarachchi University of Indigenous Medicine, Sri Lanka

* Corresponding author E.mail: wprtp@gwu.ac.lk

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Abstract
Heavy metal contamination in aquatic food sources poses potential risks to human health and ecosystems. This study evaluated the tissue-specific distribution, bioaccumulation patterns, and health risks of selected heavy metals and metalloids (Cr, Mn, Cu, Zn, As, Cd, and Pb) in *Etroplus suratensis* (freshwater and brackish water) and *Scylla serrata* (brackish water). Metal concentrations were analyzed in edible and non-edible tissues including muscle, gills, gut, and hepatopancreas. Results revealed significant tissue-specific accumulation influenced by ecological and physiological factors. In *Etroplus suratensis*, muscle tissues showed elevated chromium levels exceeding permissible limits, while gills, and gut accumulated higher levels of Zn, Mn, and Pb. In *Scylla serrata*, the hepatopancreas exhibited the highest metal accumulation, whereas body muscle showed extremely high Zn concentrations. Statistical analyses confirmed significant differences among tissues and ecosystems ($p < 0.05$), and correlation patterns suggested common anthropogenic pollution sources. Multivariate analysis (PCA) indicated that 85.44% of total variance was explained by metal associations linked to environmental inputs. Risk assessment showed no significant non-carcinogenic risk for *Etroplus suratensis* (HI < 1), while *Scylla serrata* indicated potential health risks (HI > 1) due to elevated Zn and As. These findings highlight the importance of monitoring heavy metal contamination in aquatic food systems, particularly in estuarine environments.
Keywords: *Aquatic food sources; Bioaccumulation; Health risk assessment; Heavy metals; Tissue-specific distribution.*

Introduction

Aquatic pollution has become a major environmental concern worldwide today due to the enhancement of anthropogenic activities (Beiras and Schönemann, 2020; Bashir *et al.*, 2020; Chaukura *et al.*, 2021). Industrialization poses major influence for elevate concentration of potential toxic elements (PTEs), especially Cd, Cr, As and Pb (Ali *et al.*, 2019; Li *et al.*, 2018). These substances are naturally occurring and non-biodegradable by biological processes (Tchounwou *et al.*, 2012). Heavy metal accumulation in food sources should be given priority because even a trace amount can be toxic to most of living organisms (Jaishankar *et al.*, 2014). Consuming contaminated food for a long-time lead to adverse human health effect including acute and chronic illness (Shetty *et al.*, 2025; Jaishankar *et al.*, 2014; Tchounwou *et al.*, 2012). Soil weathering and volcanic eruptions are natural incidences that release heavy metals in to aquatic ecosystem (Zhu, 2025). Atmospheric deposition from

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urban region, domestic sewage, ore mining, acid batteries manufacturing, fertilizer consumptions, transportations and industrial operations are anthropogenic sources which release of excessive quantity of heavy metals on a large scale resulting aquatic ecosystem imbalance (Aziz *et al.*, 2023; Saravanan *et al.*, 2024). These toxic metals are non-biodegradable and exist long period of time in biosphere which cause for long-term impact (Kayani and Mohammed, 2025). For instance, Cd availability promote the generation of reactive oxygen species (ROS) in aquatic organisms causing DNA damages (Shahjahan *et al.*, 2022; Kumar *et al.*, 2024). Cu disturb olfactory system in salmon like migratory fish (Vlaeminck *et al.*, 2020; Chang *et al.*, 2021). Pb, Ni and Zn negatively affect for other sensitive ecosystems by disturb soil functions (Saravanan *et al.*, 2024; Zhu, 2025). These consequences may occur ecosystem imbalances through alterations in aquatic insect community, increase acidity of natural water bodies and contaminated food sources (Clements and Newman 2002). Furthermore, owing to metal toxicity, reduce the population of certain mayflies and crustaceans named as a more sensitive indicator species in food webs leading to collapse food webs (Bonada *et al.*, 2006; Li *et al.*, 2010; Smalling *et al.*, 2022). In South Asian region, intensive agricultural system is utilized vast quantity of agrochemicals rich in Hg, Cd and As to enhance crop outcome which result in these metals leaching into nearby water bodies (Ali *et al.*, 2019; Li *et al.*, 2018). The solubility and bioavailability mechanisms of these PTEs alter the presence of physiochemical parameters such as pH, temperature and conductivity, leading to their deposition in bottom sediments and subsequently absorbed by aquatic organisms, effectively integrating toxic elements into the food web through direct ingestion and dermal absorption (Jeong *et al.*, 2023). Furthermore, the persistence of these PTEs allows them to move through various trophic levels with occurring biomagnification in higher-order predators. Consuming contaminated edible fish, mollusks and crustaceans are primitive pathways of human expose to PTEs (Jaishankar *et al.*, 2014; Yi *et al.*, 2011). Most PTEs are non-biodegradable and exist long period of time in biosphere which cause for long-term impact (Kayani and Mohammed, 2025). The accumulation of toxic metals promotes the generation of reactive oxygen species (ROS) in aquatic organisms, causing DNA damages (Shahjahan *et al.*, 2022; Kumar *et al.*, 2024). Cu disturb olfactory system in salmon like migratory fish (Vlaeminck *et al.*, 2020; Chang *et al.*, 2021).Certain mayflies and crustaceans named as a more sensitive indicator species in food webs (Bonada *et al.*, 2006; Li *et al.*, 2010). Owing to metal toxicity, reduce the population of these indicator species leading to collapse food webs and ultimately, loss of ecosystem imbalance (Smalling *et al.*, 2022). Consuming those contaminated food sources cause for many chronic illnesses on human. Comparing freshwater and. brackish environment is essential because there chemical and physical structures alter the metal solubility (Martinelli *et al.*, 2021; Zhang *et al.*, 2022). Heavy metal contaminant may remain water soluble or suspension. Regardless their form, its eventually settle as bottom sediments when the concentration higher (Forsius *et al.*, 2021). In estuaries, heavy metal solubility depends on various environmental factors such as salinity, dissolved organic carbon (DOC) and temperature. Relatively high salinity in water may increase the formation of chloride complexes with cadmium and lead (Turner and Millward, 2002; Du Laing *et al.*, 2009). Depending of the organisms, it may lead to increase or decrease the absorbing rate of metal-chloride complexes (Martinelli *et al.*, 2021; Mason *et al.*, 2022). Benthic organisms and filter-feeders directly interact with metal associated sediments. As a result, heavy metals are introduced into aquatic food chains and food webs (Wang and Fisher, 1999). This irreversible mechanism led to bioaccumulation of heavy metals which can cause adverse effect on both human an aquatic ecosystem. Heavy metals become hazardous when they are not involved for biological process and potential contribution to accumulate in soft tissues (Giglio *et al.*, 2022; Zhang *et al.*, 2023; Shetty *et al.*, 2025). In Sri Lankan dry zone, heavy metal-rich phosphate fertilizers and pesticides are commonly used in agricultural landscapes (Chowdhury *et al.*, 2016). Leaching these metals into inland water bodies contaminate staple food fish like *Oreochromis niloticus*, contributing to the prevalence of chronic kidney disease of unknown etiology (CKDu) in these regions (Chowdhury *et al.*, 2018). Contemporary, exceeding threshold level of Cd was indicated in Bolgoda lake where a semi-urban area with a highly industrial influenced (Kodikara *et al.*, 2023). These pollutants eventually leach to the estuaries and lagoons such as Negombo and Kalmatiyawa lagoons which are considered critical hotspots for the bioaccumulation of toxic metal because they frequently interact with tidal mixing and sediment (Kodikara *et al.*, 2023). The accumulation of toxic metals in both fresh water and estuary ecosystems is a cascade of detrimental effect on both flora and founa (Tchounwou *et al.*, 2012; Jaishan-

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kar *et al.*, 2014). Meanwhile, few studies in Sri Lanka and other south Asian region have focused on individual environments such as freshwater or estuary (Bandara and Pathiratne, 2023; Batapola *et al.*, 2023). Consequently, there is limited research comparing the toxicological impacts of metals in both freshwater and brackish water ecosystems. Moreover, only a few studies have integrated these assessments with public health risk evaluation using statistical approaches. Therefore, this study has design to compare most common edible aquatic organism in freshwater and brackish water: inland and estuaries. The main objecttives of this study were to evaluate the concentrations and tissue-specific distribution of selected heavy metals and metalloids in edible aquatic organisms collected from freshwater and brackish water ecosystems in Sri Lanka, and to assess the potential human health risks associated with their consumption.

Materials and Methods

Study area

The study area was selected based on the two types of aquatic ecosystems where highly consuming aquatic edible food sources. Sampling locations were selected from two selected sites; freshwater habitat from inland lake (*Minipe lake*) with highly presence of agricultural activities, while edible samples from estuaries (*Negombo lagoon*) adjacent to industrial zones. Geographical coordinates were appeared in Figure 1.

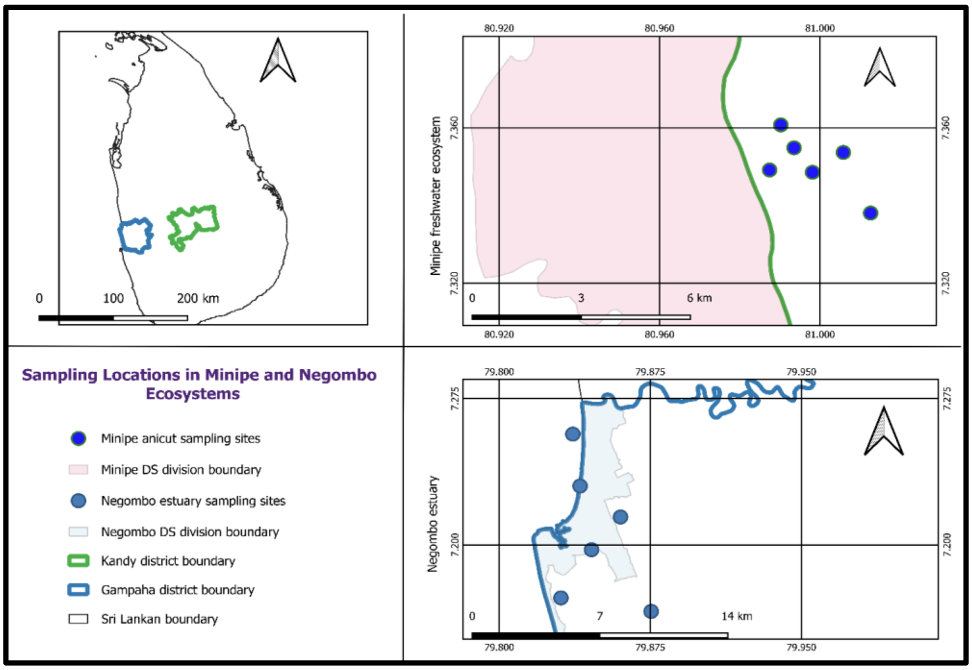

Figure 1
Spatial distribution of sampling locations in two aquatic ecosystems of Sri Lanka

Sample selection

Freshwater fish samples (*Etroplus suratensis*) were collected from Minipe reservoir located in mahiyangnaya, Sri Lanka. *Etroplus suratensis* and *Scylla serrata* were collected from Negambo estuary. 20 samples from each species were taken from both estuary and inland reservoir to avoid statistically robust and specialized external factors. This sample size (n = 20) was used to reduce potential biases associated with sample inadequacy and to ensure the robustness of conducting principal component analysis (PCA) and Spearman correlation analysis. All polyethylene containers were sterilized using 10% nitric acid for 24 h and rinsed thoroughly with deionized water prior to use to minimize contamination. Containers were placed in ice -packed coolers and transported to the laboratory. After, samples were washed with deionized water to removed surface debris and stored at -20 ^{0}C.

Sample preparation and acid digestion

Liver, gills, and muscle tissues in *Etroplus suratensis* were isolated and oven-dried at 60 ^{0}C. Each samples (0.20 g) were transferred to Teflon vessels for microwave digestion using US EPA (United States Environmental Protection Agency) method 3051A as describe below (closed-vessel microwave digestion) (EHOS EASY, Italy). Conc. HNO_3 (10.00ml of 98%) and deionized water (2.00ml) were added for each sample placed in vessels. Then all the prepared samples were placed in the microwave digester approximately for one hour.

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Final digested solutions were allowed for cooling until room temperature. Prepared samples were diluted using DI water (25.00 mL) at the room temperature inside a fume hood and filtered through 0.45 μm nylon filters ready to use ICP-MS.

Toxic element analysis

Quantitative determination of selected heavy metals; Cr, Mn, Cu, Zn, Cd, Pb and metalloids; As in digested samples was performed using an Inductively Coupled Plasma-Mass Spectrometer (ICP-MS; Agilent 7900 Series, Agilent Technologies, USA). The ICP-MS was operated under standard conditions with an RF power of 1550 W, plasma gas flow rate of 15 L min^{-1}, auxiliary gas flow rate of 0.9 L min^{-1}, and carrier gas flow rate of 1.05 L min^{-1}. Measurements were conducted in helium collision mode to minimize polyatomic interferences. Calibration was carried out using a certified multielement standard solution (Agilent Multi-element Calibration Standard-2A in a 5% HNO_3 matrix). The calibration ranges utilized were 0.1 ppb –10 ppb and 10 ppb - 1000 ppb, with all target analytes exhibiting excellent linearity (R^2 > 0.99). To ensure analytical accuracy and precision, internal standardization was employed using an internal standard mix designed for heavy metal analysis (Agilent Cannabis Heavy Metals Mix). Additionally, HNO_3 blank solutions were processed alongside each sample batch. The limits of detection (LOD) and limits of quantification (LOQ) were calculated and 10 times the standard deviation of the blank measurement divided by the calibration slope, respectively. Method validation and quality control procedures were adhered to ISO/IEC 17025 guidelines.

Statistical Analysis

All statistical analysis were perform using lme4 (mixed-effects models), ggplot2 (data visualization) and SPSS 22.

Human health risk assessment

The Estimated Daily Intake (EDI) [Eq 1], Hazard Index (HI) [Eq 2], Target Hazard Quotient (THQ) [Eq 3], and Carcinogenic Risk (CR) [Eq 4] were calculated using following equations:

$$EDI = \frac{C \times IR}{BW} \quad [1]$$

where C means specified metal concentration in edible tissue (mg/kg), IR define as ingestion rate (kg/day), BW refers average body weight (kg) (EFSA 2012).

$$HI = \Sigma\, THQi = THQCr+THQAs+THQCd+THQPb \quad [2]$$

$$THQ = \frac{EDI}{RfD} \quad [3]$$

where RfD refers the reference oral dose (USEPA 2000)

$$CR = EDI \times CSF \quad [4]$$

where CSF is the cancer slope factor (USEPA 2011).

Results and Discussion

This study revealed the tissue-specific bioaccumulation patterns in both *Etroplus suratensis* and *Scylla serrata* based on the specific ecological niches. The PTEs concentrations of the collected samples in aquatic edible food sources are summarized in table 1 The Cr and Pb concentrations of *Etroplus suratensis* muscle tissues were elevated WHO/FAO safe limits revealing potential health risk on long-term consumption. Internal organs showed highly accumulated Zn, Mn and Pb. However, these tissues are not commonly consumed as food sources. Similar results were found in Koggala lagoons in Sri Lanka that Cr (39.633 mg/kg) was the second most abundant metal found in *Etroplus suratensis* and all the detected element, including Cr, were below WHO/FAO safe limits (Abeysooriya *et al.*, 2023). Nikawewa and Mahakanadarawa reservoirs also reported relatively low levels of metal concentration (Nikawewa - Cr=1.76±0.09 mg/kg, Mahakanadarawa – Cr = 0.22±0.03 mg/kg) (Perera *et al.*, 2024). However, these regions were observed relatively low levels of Cr comparing to minipe lake. The higher agricultural intensity in Minipe lake, relative to Koggala Lagoon, Nikawewa Reservoir, and Mahakanadarawa Reservoir, may significantly contribute to the increased availability of PTEs (Silva *et al.*, 2024; Shuraik *et al.*, 2023; Herath *et al.*, 2022). This condition further exacerbated by the application of contaminated fertilizers, high evaporation rate and geological weathering processes that encourage releasing metals into the aquatic system (Wan *et al.*, 2024; Ali *et al.*, 2013; Kumar *et al.*, 2024). Moreover, *Etroplus suratensis* have highly metabolically active organs such as liver. It was resulted for accumulating many toxic regents abundant (Kumar *et al.*, 2024). The Body muscles of *Scylla serrata* collected from Negombo lagoon showed extremely high concentration of Zn and other heavy metals such as Cr, Mn, As, Cd and Pb also exceeded WHO/FAO safe limits. Hepatopancreas were the highest PTEs accumulation part in *Scylla serrata*. Excepting Cu, all the elements were surpassed the WHO/FAO safe limits. Tolkou *et al.*, (2023) revealed that the accumulation of

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Table 1. *Tissue-specific distribution of PTEs in selected edible organisms collected from Minipe lake and Negombo estuary*

Species	Tissue type	Element	Mean concentration (mg/kg)	SD
Etroplus suratensis (Minipe Lake)	Gut	Cr	2.53	0.63
		Mn	8.47	12.95
		Cu	0.86	0.16
		Zn	177.00	126.65
		As	1.03	0.68
		Cd	0.02	0.01
		Pb	0.95	0.83
	Gills	Cr	2.12	0.14
		Mn	3.11	2.50
		Cu	0.64	0.09
		Zn	23.05	9.67
		As	0.22	0.03
		Cd	0.01	0.01
		Pb	0.41	0.25
	Muscles	Cr	2.29	0.22
		Mn	0.54	0.06
		Cu	0.95	0.73
		Zn	4.58	2.08
		As	0.20	0.06
		Cd	0.01	0.01
		Pb	0.25	0.09
Scylla serrata (Negombo estuary)	Claw muscle	Cr	1.75	0.43
		Mn	1.30	0.34
		Cu	6.54	0.95
		Zn	123.59	67.89
		As	0.81	0.25
		Cd	0.03	0.01
		Pb	0.63	0.22
	Body muscle	Cr	1.85	0.19
		Mn	1.62	0.20
		Cu	5.68	1.37
		Zn	1872.64	1682.23
		As	0.71	0.14
		Cd	0.08	0.03
		Pb	1.75	0.95
	Hepato pancrea s	Cr	1.73	0.04
		Mn	9.67	6.57
		Cu	8.21	0.26
		Zn	685.11	120.53
		As	1.13	0.23
		Cd	1.35	0.54
		Pb	2.00	0.55

Cd and Pb in *Scylla serrata* reflects a strong influence from industrial discharge into the estuarine ecosystem. Consequently, hepatopancreas, function as a liver that digestion, detoxification, and metal storage, exhibits relatively high level of PTEs accumulation compared to edible tissues (Jamil *et al.*, 2023). This finding was also aligned with our HCA, mentioned in Figure 3, results that gill, gut, claw muscle, and edible muscle tissues clustered closely together, indicating similar exposure routes and accumulation tendencies through direct contact with contaminated water and food sources. Hepatopancreatic tissue showed moderate separation from the main tissue cluster because of its physiological role. In contrast, body muscles showed the highest linkage distance due to different accumulation dynamics. In South Asian coastal ecosystem, variety of crustaceans frequently consume Pb and Cd contaminated water due to high influence of industrial exposure and it accumulate in hepatopancreas because of the benthic feeding behavior (Cano *et al.*, 2016; Murray *et al.*, 2020; Zhang *et al.*, 2025).

Table 2. *Correlation matrix of toxic elements in Etroplus suratensis muscles..* **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

	Cr	Mn	Cu	Zn	As	Cd	Pb
Cr	1.000	0.259	.511*	-0.011	0.304	0.000	0.255
Mn	0.259	1.000	0.243	.858**	.659**	0.337	.664**
Cu	.511*	0.243	1.000	0.174	0.263	0.067	0.236
Zn	-0.011	.858**	0.174	1.000	.637**	0.303	.684**
As	0.304	.659**	0.263	.637**	1.000	0.305	.506*
Cd	0.000	0.337	0.067	0.303	0.305	1.000	0.076
Pb	0.255	.664**	0.236	.684**	.506*	0.076	1.000

Table 3. *Correlation matrix of toxic elements in Scylla serrata Body muscle.* **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

	Cr	Mn	Cu	Zn	As	Cd	Pb
Cr	1.000	0.192	-0.118	-0.200	-0.366	-0.043	-0.124
Mn	0.192	1.000	.571*	.498*	0.342	.829**	.531*
Cu	-0.118	.571*	1.000	0.463	.672**	.771**	0.406
Zn	-0.200	.498*	0.463	1.000	0.273	.797**	.707**
As	-0.366	0.342	.672**	0.273	1.000	.540*	0.294
Cd	-0.043	.829**	.771**	.797**	.540*	1.000	.661**
Pb	-0.124	.531*	0.406	.707**	0.294	.661**	1.000

The combine interpretation of Kruskal–Walli's test (Table 4), Spearman correlation analysis (Table 2), principal component analysis (PCA)(Fig 2) and HCA (Fig 3) indicated the occurrence of tissue-specific accumulation patterns within the freshwater ecosystem, providing insight into the relationship between metal uptake mechanisms, metabolic activities, and metal exposure frequencies and mechanisms in *Etroplus suratensis*. These analyses were carries out using Ward's linkage method pose to reveal specific contaminated sources and distribution patterns. The Kaiser–Meyer–Olkin (KMO) value (0.631) reveals the samples ade-

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quately and Bartlett's test of sphericity (x^2 = 104.76, p < 0.001) confirmed acceptable for PCA application. The PCA results which presented in table 4 are strongly supported to identify the major factors for distributing heavy metal and indicating grouping patterns sources of heavy metal contamination. 85.44% of the total variance was showed. The Kruskal–Walli's test was used to identify significant differences of toxic metal contamination among body tissues mentioned in table 5. Mn (p = 0.003), Zn (p = 0.002), As (p = 0.003) and Pb (p = 0.039) have significant differences among tested three body parts of *Etroplus suratensis*, confirming a similar bio-accumulation pathways. The correlation matrix (table 3) also confirmed this finding by showing significant positive correlations of Mn–Zn (r = 0.858, p < 0.01), Mn–Pb (r = 0.664, p < 0.01), Zn–Pb (r = 0.684, p < 0.01), and Mn–As (r = 0.659, p < 0.01), suggesting similar contamination sources. PCA and HCA were strongly supported to the spearman correlation matrix and the Kruskal–Walli's test results with PC1- mainly associated with Mn, Zn, Pb, and As- accounting for 69.18% of the total variance. The HCA dendrogram further associated with similar results by clustering these elements (Mn-As, Cu-Cd and Zn-Pb) with closely related groups at lower distances. This associations suggest that these elements shared common contamination pathways, similar transport mechanisms and bioaccumulation behavior within the *Etroplus suratensis*. In contrast, Cr showed a different statistical relationship throughout all statistical analysis, showing no significant correlation with other metals and no significant differences in the Kruskal–Wallis test. According to the PCA and HCA analysis, Cr was primarily loaded in PC2 accounted as 16.26% of the total variance with isolated from the other PTEs with highest distance (Fig 2). These collective observations suggest that Cr contamination primarily originated from localized geogenic weathering processes or intensive agricultural output rather than mixed anthropogenic inputs. A similar result was recorded in Meghna River estuary in Bangaladesh, which indicated significant differences in inter-tissue variability and bioaccumulation patterns for As, Pb, Cu, and Cr due to anthropogenic contaminated sources (Ahmed *et al.*, 2019). The supported phenomenon was introduced by Ahmed *et al.*, 2019 and Rahman *et al.*, 2012 that nearby industries discharge inadequately treated wastewater into river systems, significantly elevating the levels of As, Cd and Pb in aquatic ecosystems, including fish tissues, in Bangaladesh. Moreover, feeding behavior and niches significantly influence for altering metal accumulation in different body tissues in benthic and omnivorous organisms according to their type of ecosystem (Hamidian *et al.*, 2023).

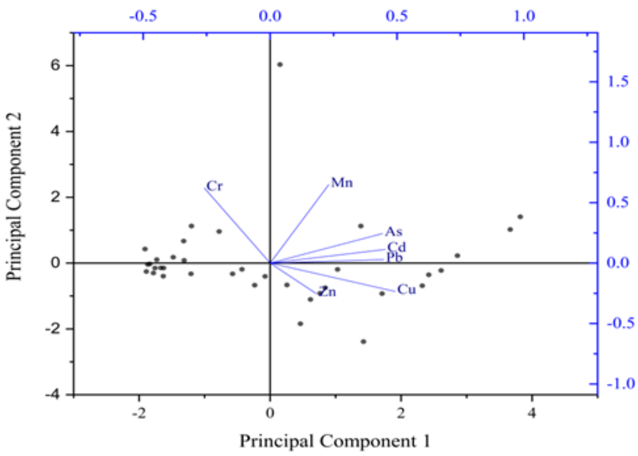

Figure 2. *PCA biplot of potentially toxic element (PTE) loadings and sample scores in aquatic organisms from freshwater and estuarine ecosystems.*

The concentrations of Mn, Cu, Zn, As, Cd and Pb showed high significant variation (Kruskal–Wallis Test, p < 0.05) across the tissue of *Scylla serrata* than in *Etroplus suratensis*. This heterogeneous distribution patterns were occurred due to physiological and environmental factors, along with occasional input from specific contaminated sources (Ahmed *et al.,* 2019). Sigamani *et al.*, (2024) revealed that the strong tissue-specific bio-accumulation in *Scylla serrata* was observed because estuarine and coastal regions are highly contaminated with Pb, Cd, and As than freshwater ecosystem due to elevate industrial influence. This phenomenon was confirmed the Mann–Whitney U Test (table 5) comparing *Etroplus suratensis* and *Scylla serrata* in pairwise comparisons of analogous tissues, specifically muscle versus body muscle and gut versus hepatopancreas. According to the Mann–Whitney U Test results, all metal accumulations revealed significant differences (P < 0.05) between *Etroplus suratensis* and *Scylla serrata*. These variations were occurred due to geological, hydrological and anthropogenic influences differ from both freshwater and brackish water ecosystems (Han e*t al.,* 2020). Freshwater ecosystems frequently expose to the geochemical weathering and agricultural runoff, where metals like Cr and Mn are more prevalent due to soil erosion and irrigation drainage (Alloway *et al.*, 2013). In contrast, estuaries have complex hydrology influenced by tidal mixing. As a result, high salinity can be observed due to formation of chloride complexes, which alters solubility and avai-

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lability of PTEs for uptaking benthic organisms such as *Scylla serrata* (Turner and Millward., 2002; Zhang and Davison 2000). The spearman correlation matrix, PCA and HCA results also supported mentioned phenomenon. The correlation matrix of *Scylla serrata* indicated that Mn–Cd ($r = 0.829$, $p < 0.01$), Zn–Cd ($r = 0.797$, $p < 0.01$), Cu–Cd ($r = 0.771$, $p < 0.01$), Zn–Pb ($r = 0.707$, $p < 0.01$), and Cu–As ($r = 0.672$, $p < 0.01$) have strongsignificant positive correlations. Indicated strong co-accumulation and shared uptake pathways under brackish water environment. These correlation patterns strongly align with PCA and HCA results, where Mn, Cu, Cd, As, Zn, and Pb were strongly loaded in PC1 (69.18% of the total variance) and Cu–Cd and Zn–Pb appeared as closely related clusters due to high anthropogenic influence. However, Cr displayed an isolated in both PCA and HCA, suggesting a specific contaminated source influence for elevate amount of Cr to the brackish water ecosystem.

Table 4
Statistical evaluation of heavy metal variations using Kruskal–Wallis Test in Etroplus suratensis and Scylla serrata

	Etroplus suratensis		Scylla serrata	
Metal	Kruskal-Wallis H	Asymp. Sig.	Kruskal-Wallis H	Asymp. Sig.
Cr	3.404	0.182	0.179	0.915
Mn	11.942	0.003	13.053	0.001
Cu	3.193	0.203	11.661	0.003
Zn	12.316	0.002	11.661	0.003
As	11.966	0.003	6.351	0.042
Cd	2.837	0.242	14.966	0.001
Pb	6.503	0.039	8.924	0.012

Table 5. *Pairwise comparison of heavy metal and metalloids accumulation between muscle tissues and internal organs using Mann–Whitney U test*

	Muscles Vs Body muscles			Gut vs Hepatopancreas		
Element	Mann-Whitney U	Z	Asymp. Sig. (2-tailed)	Mann-Whitney U	Z	Asymp. Sig. (2-tailed)
Cr	1.000	-2.722	0.006	0.000	-2.882	0.004
Mn	0.000	-2.882	0.004	10.000	-1.281	0.200
Cu	0.000	-2.882	0.004	0.000	-2.882	0.004
Zn	0.000	-2.882	0.004	6.000	-1.922	0.055
As	0.000	-2.892	0.004	14.000	-0.641	0.522
Cd	0.000	-2.903	0.004	0.000	-2.892	0.004
Pb	0.000	-2.882	0.004	4.000	-2.242	0.025

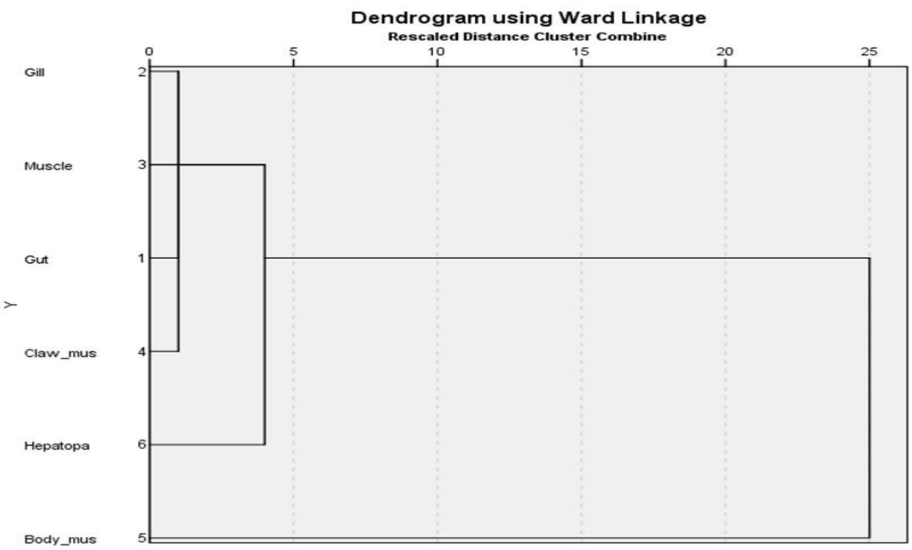

Figure 3
Hierarchical cluster analysis (HCA) dendrogram showing tissue-specific clustering patterns using Ward's linkage method.

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The potential health risk indices based on THQ and EDI indicated in figure 5. All the EDI values of both organisms (*Etroplus suratensis* and *Scylla serrata*) were lower than tolerable daily intake values (TDI). The cumulative hazard index (HI) of *Etroplus suratensis* accounted as 0.488 indicating no evidence for chronic non-carcinogenic health risk for public. In contrast, elevated hazard index was obtained in *Scylla serrata* (HI = 3.15) because of the high detected THQ values of zinc (Zn) and arsenic (As) reflecting potential health risk associated with daily consuming *Scylla serrata* body muscles. Zn and As availability in estuary ecosystem may influence on redox fluctuations. As solubility increases under low dissolved oxygen (DO) conditions (Madadi *et al.*, 2021). Redox reactions and pH variations manipulate the Zn solubility. Acidic conditions increase Zn mobility by enhancing metal dissolution (Wang *et al.*, 2022; Madadi *et al.*, 2023). In contrast, alkaline conditions reduce solubility through adsorption and precipitation processes (Özşeker and Terzi, 2025). This process may increase high exposure of PTEs to bottom-feeding organisms through enhanced metal mobility and bioavailability in sediments and surrounding water (Simpson *at el.,* 2004). All the carcinogenic risk (CR) values of *Etroplus suratensis*, mentioned in table 6, were within the acceptable range (10^{-6} to 10^{-4}), indicating relatively lower carcinogenic risk through consumption. However, CR values of As and Cd in *Scylla serrata* were exceeded the acceptable threshold (10^{-4}) revealing potential influence for cancer risk. This elevated carcinogenic risk in *Scylla serrata* may be associated with its benthic feeding behavior and close interaction with contaminated sediments (de Prado-Bert *et al.*, 2021; Mistri *et al.*, 2022). Recent findings revealed brackish water environment high possibility to contaminate with heavy metals because of the industrial activity (Alam *et al.*, 2022; Rangel-Buitrago *et al.*, 2023; Real *et al.*, 2024). However, Salinity-induced metal desorption is also taken place a possible factor to high heavy metal availability in brackish water environment. This process is a natural scenario aid to escalate metal availability through ion exchange reaction (Luo *et al.*, 2021; Yuan *et al.*, 2022).

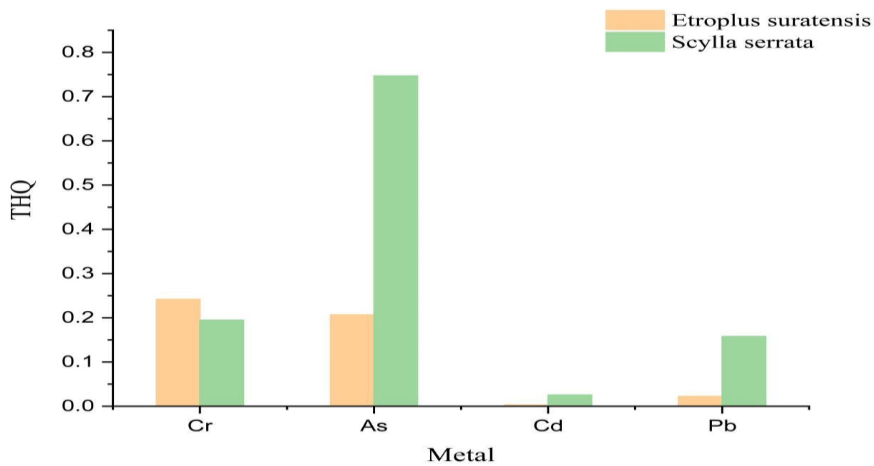

Figure 5
Comparison of total hazard quotient (THQ) values for Cr, As, Cd, and Pb in Etroplus suratensis and Scylla serrata, indicating species-specific variation in metal-associated health risk.

Table 6. *Estimated daily intake (EDI), target hazard quotient (THQ), and carcinogenic risk (CR) values of potentially toxic elements (PTEs) through consumption of Etroplus suratensis and Scylla serrata*

Metal	Etroplus suratensis			Scylla serrata		
	EDI (mg/kg/day	THQ	CR (10^{-5})	EDI (mg/kg/day	THQ	CR (10^{-4})
Cr	0.000726	0.242	-	0.000586	0.195	-
Mn	0.000170	0.0012	-	0.000513	0.0037	-
Cu	0.000301	0.0075	-	0.001797	0.0449	-
Zn	0.001451	0.0048	-	0.5937	1.98	-
As	0.000062	0.207	9.3×10^{-5}	0.000224	0.747	3.36
Cd	0.00000317	0.0032	2.0×10^{-5}	0.0000257	0.0257	1.62
Pb	0.000079	0.0226	6.7×10^{-7}	0.000555	0.158	4.72

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Conclusions

This study indicates the distribution of PTEs in edible aquatic organisms from both freshwater and brackish water ecosystem in Sri Lanka. Findings reveal that internal organ which highly metabolically active tend to accumulate heavy metals *Etroplus suratensis*. It detected elevated level of Cr because of the highly influence for agricultural runoff and estuary. *Scylla serrata* were highly accumulated certain toxic metals such as Zn, As, Cd and Pb revealing strong industrial and urban influences. Multivariate and none parametric statistical evaluations validated these variances. The Mann-Whitney U test confirmed highly significant metal accumulation profile differences ($P<0.05$) between *Etroplus suratensis* and *Scylla serrata*. PCA and HCA results revealed that Mn, Zn, Pb, As and Cd share common pathways including anthropogenic, urban, and industrial discharges. In contrast, Cr contamination originated from distinct, localized sources—specifically geogenic weathering or intensive agricultural runoff—rather than the mixed industrial inputs affecting other metals. Consuming freshwater fish poses minimal non-carcinogenic health risk. In contrast, brackish water ecosystem more susceptible to heavy metal contamination associate with As and Cd. Continuous monitoring and effective management strategies need to minimize the ecological hazardous impact.

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Authors' contributions

Conceptualization and supervised by Ruwan T. Perera; Sampling and analysis performed by M.A.U. Dias, W. A. S. Fernando , Dilshani Sakunthala; Original draft was written, performed the analysis by Nalin Gunathilaka, Performed analysis and final proof reading by Hiruni Gunathilaka; Research supervision by Janitha A. Liyanage

All authors have carefully read and accepted submitting the manuscript.

Declaration of Interest Statement

The authors declare no conflict of interest.

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