Heavy Metal Accumulation in Seafood: An Indication of Enhanced Effluent Influx in Aquatic Ecosystems

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ABSTRACT

Trace amounts of heavy metals such as iron, copper, zinc, and manganese are essential for physiological processes in living organisms, but excessive levels can pose serious health risks. This study investigated the accumulation of heavy metals—lead (Pb), chromium (Cr), copper (Cu), and cadmium (Cd)—in five crab species and edible portions of bivalves collected from Dakshina Kannada and Udupi districts. Crab samples (three individuals per site) were obtained from fishermen across ten locations, while bivalves were sourced from local fish markets. Heavy metal concentrations in tissues were quantified using Atomic Absorption Spectrophotometry (AAS). Results revealed that copper exhibited the highest concentration (4.54 ppm) in crabs, whereas cadmium showed the lowest (0.01 ppm) in clams. The overall order of accumulation was Cu > Cr > Pb > Cd. Notably, Cr levels in *Portunus sanguinolentus* from Malpe Beach (0.5336 ppm) exceeded permissible limits, while maximum copper concentrations occurred in *Charybdis lucifera* from Someshwara Beach. For bivalves, lead contamination was widespread, with the highest levels observed in Souparnika River (0.135 ppm). Alarmingly, cadmium levels in clams from the Nethravathi River, Mangalore (0.605 ppm), surpassed safety thresholds. These findings indicate significant bioaccumulation of toxic metals in edible marine species, raising concerns for seafood safety, public health, and the region's fishery economy. Crabs, while affected, show variable accumulation across species, whereas bivalves consistently reflect elevated pollution loads. Thus, bivalves can be considered reliable bioindicators of coastal heavy metal contamination, providing an effective tool for monitoring and managing marine environmental health.

Keywords Heavy metals, Crabs, Bivalves, Bioaccumulation, Bioindicators.

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INTRODUCTION

The term "heavy metals" is commonly used to refer to metals and metalloids linked to pollution and known for their potential toxic or ecotoxic effects (Duffus 2002).

Heavy metals are the subset of elements that exhibit metallic properties occurring in nature with a higher density, which is usually more than 5 g cm^{-3}. There are about 40 elements that fall into this category(Holleman and Wiberg 1985).

Living organisms that are naturally exposed to elevated metal concentrations follow various mechanisms to mitigate potential toxicity. To detoxify these metals, they may limit their uptake, increase excretion, or sequester the metals within their systems. Sequestration often involves metal-binding proteins like metallothioneins, as well as storage in cellular vesicles and granules. Additionally, certain heavy metal components act as stressors, triggering a range of defense responses—such as the production of heat shock proteins (HSPs), apoptosis, and autophagy depending on the concentration and duration of exposure(Chiarelli and Roccheri 2014).

High concentrations of heavy metals can pose serious risks to human health, especially through the consumption of contaminated bivalves. For instance, cadmium (Cd) is classified as a human carcinogen, lead (Pb) can impair blood circulation, and excessive zinc (Zn) intake may lead to electrolyte imbalances and fatigue(Hossen *et al.* 2015).

Bivalves are abundant components of the marine fauna, belong to Phylum Mollusca and include mussels, clams and oysters. Bivalves have a laterally compressed body with an external shell of two halves that is hinged dorsally and are united dorsally by elastic, a partially calcified or chitinous external or internal ligament and are held together by one or two adductor muscles. The Mussel Watch program is the longest-running biomonitoring initiative globally and has been successfully implemented in numerous countries. Bivalves, particularly mussels, are commonly used as pollution indicators due to their capacity to accumulate a wide range of environmental contaminants (Venkatesan and Mohamed 2015).

Heavy metals accumulate in the environment as they are persistent pollutants and contaminate the food chains. Potential health threat to their consumers including humans occurs due to accumulation of potentially toxic heavy metals in biota. Bioac-cumulation refers to the buildup of contaminants within an organism through absorption from both its surrounding environment and dietary sources (Ali *et al.* 2019). Benthic crustaceans like crabs are particularly vulnerable to metal pollution due to their habitat in bottom sediments, where many chemical pollutants tend to accumulate. Crabs possess several characteristics that make them effective bioindicators: they are relatively immobile, easy to identify, Abundant, long-lived, widely distributed, and available for sampling throughout the year. These features make crabs well-suited for monitoring heavy metal contamination in aquatic environments (Zhang *et al.* 2019). Jaishankar *et al.* (2020), emphasised that toxic metals—lead, cadmium, mercury, arsenic—have no beneficial role, disrupt essential metal homeostasis, accumulate through the food chain, and cause organ damage, developmental disorders.

Researchers (Khan *et al.* 2021), revealed the lead content in river fishes such as *L. rohita,* farm *L. rohita,* river *B. gonionotus,* and farm *B. gonionotus* were above the permissible limit. It may exhibit carcinogenic effects on the local consumers in Bagerhat, Bangladesh.

Metals and metalloids can be classified into three groups based on their toxicity. The first group, which includes mercury, cadmium, and lead, is highly toxic. The second group comprising bismuth, indium, arsenic, thallium, and antimony is considered less hazardous. The third group includes essential elements such as zinc, cobalt, copper, iron, and selenium, which become toxic only when present in excessive concentrations. Aquatic ecosystems play a crucial role in determining the safety and quality of aquaculture products, which form the base of the food web and are vital to human nutrition(Zaynab *et al.* 2022). There are various factors responsible for accumulation of heavy metals in sea food. The heavy metals analyzed in water, sediment and fish muscle samples of four finfish species such as *Mugil cephalus, Lates calcarifer, Etroplus suratensis,* and *Chanos chanos.* High metal concentrations in samples implies the influence of rainfall with heavy discharge along with pollutants from various industrial sources(Kumar *et al.* 2022). Singh *et al.* (2023) showed how metals like hexavalent chromium, lead, cadmium contaminate

aquatic environments through industrial/agricultural activities, the toxic effects on aquatic flora and fauna, and possible remediation routes. Liu *et al.* (2025) in their review discussed how fish accumulate heavy metal(loid)s via water and diet, leading to adverse effects on multiple body systems (neuronal, renal).

Kumar *et al.* (2025), clearly stated that heavy metals such as cadmium, lead, arsenic, and mercury—none of which are biologically beneficial—are persistent environmental pollutants, and describes their toxic effects on ecosystems and human organs, even at low concentrations.

In this project, we focus on the bioaccumulation of heavy metals by crab species and clams which were the native species in different habitats. There are marine, estuary and fresh water species. This study was carried out to provide baseline data on heavy metal concentrations in different edible crabs and mussels from Dakshina Kannada and Udupi districts.

MATERIALS AND METHODS

Sample collection of crabs

Samples are collected from the Fisher man at ten specified regions containing three fresh crab each in early morning. The crabs were washed with tap water twice to remove the soil particles, then kept in a refrigerator until dissection took place. Methodology is represented in Fig.1.

Sampling stations for crabs : Five different crab species were collected from three different habitat such as Marine, estuary and freshwater. In the above habitat number of available samples sites are six, two and two respectively, around Dakshina Kannada and Udupi districts. The abundantly available species in marine and estuary habitat were three spotted crab *(Portunussan guinolentus)* and mud crab *(Scylla serrata)* were available in freshwater. The blue swimmer crab (*P. pelagicus*) are more commercially important in crab fishery, also available in estuary habitat. In marine habitat less abundant available species are Crucifix crab (*Charybdis feriatus*) and yellowish-brown crab (*C. lucifera*) (Jose 2017).

Sample sites of clams : Byndoor: (Uppunda) –Sumanavathi River, Someshwara Beach , Kundapura (Arate) Souparnika River, Panchagangavali Hemmadi-Kundapura,Udupi–Papanashini River, Mangalore-Sasihithlu Estury,Ullal–Ullalendpoint, kuthar –Nethravathi River.

Collection and identification of sample: The bivalves species were collected from different fish markets. Samples were brought to laboratory in plastic container and stored in refrigerator until further processing. Samples were collected during the month of January and February.

Identification of the collected specimens were conducted in the laboratory. The collected species were identified based on their morphological characteristics with the use of published articles (Albert *et al.* 2022).
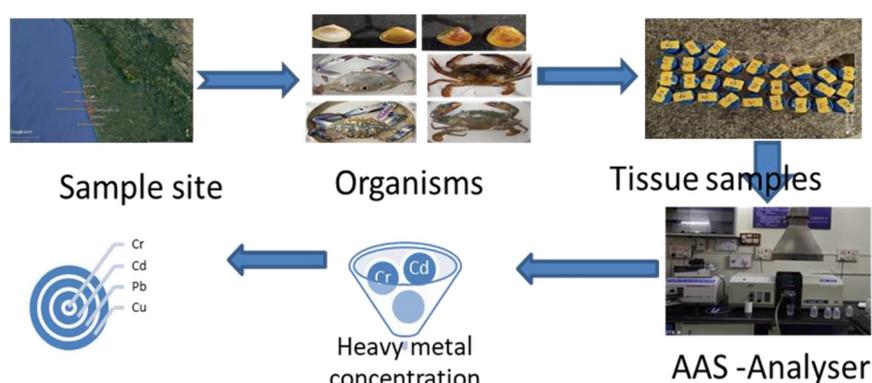

Fig. 1. Graphical representation of methodology.

Sample preparation

Clams of same size group were taken. Soft part of the animal in its shells was rinsed in distilled water. Tissues were placed in watch glass and wet weight taken and kept it in oven at 105˚c for about one hour. Each dry clam samples were weighed.

Chemical analysis of sample

Acid digestion: Acid digestion method used (Falusi and Olanipekun 2007). Heavy metal concentration was determined using an AAS (atomic absorption spectrophotometer).

Statistical analysis

Data analysis was done using R Studio 4.2.3, M S Excel and Jamovi 2.4.11.Results are presented in Tables an Figures.

RESULTS

The concentration of heavy metals such as chromium (Cr), lead (Pb), copper (Cu) and Cadmium (Cd) in the edible part of the crabs species such as Mud crabs, Blue swimmer crab, Three spotted crab, Crucifix crab, Yellowish brown crab and three species of bivalves i.e *Meretrix casta* clams, *Merecia recens* clams and *Perna perna* mussels is presented in Table 1and 2.

Metal concentrations in crabs studied

The heavy metal concentrations in crabs across various locations reveal notable disparities. At Malpe Beach, copper (Cu) demonstrates the highest concentration at 4.56 ppm, but lowest concentration at Uppunda River with 3.35 ppm.While cadmium (Cd) exhibits the lowest concentration at Ullal Beach, measuring 0.022 ppm, but highest at Someshwara Beach (0.12 ppm). Additionally, chromium (Cr) levels peak at Malpe Beach with 0.53 ppm, contrasting with the lowest concentration found at Someshwara Beach (0.212 ppm). Lead (Pb) concentration is highest at Someshwara Beach (0.27 ppm) and lowest at Ullal Beach (0.19 ppm).

Metal concentrations in clams studied

Based on the obtained data for clam metal concentrations at different locations, here's the interpretation:

The clam samples analyzed reveal varying concentrations of heavy metals across different locations. Copper (Cu) exhibits the highest concentration at organisms from Panchagangavali (3.88 ppm), while lowest concentration was observed at Papanashini (1.51ppm). Cadmium (Cd) shows the lowest concentration at Papanashini (0.00 ppm), highest at Nethravathi (0.01ppm). Chromium (Cr) levels range from 0.34 ppm at organisms from Papanashini to 0.60 ppm at Nethravathi River. Lead (Pb) ions vary widely, with the highest recorded from organisms at Souparnika (0.13 ppm), while both Someshwara Beach and Papanashini organisms register the lowest levels at 0.00 ppm. Permissible levels shown in Table 3.

Monthwise heavy metal concentration in crabs and Clams

Based on the Table 4, there is a significant decrease

Table 1. Crab species selected for study from different resources.

Sl. No.	District	Habitat	Sample site	Crab species
1	Dakshina Kannada	Marine	Someshwara Beach	*Charybdis lucifera*
2	Dakshina Kannada	Marine	Ullal Beach	*Protunus sanguinolentus*
3	Dakshina Kannada	Marine	Thannirbavi Beach	*Protunus sanguinolentus*
4	Dakshina Kannada	Marine	Thannirbavi Beach	*Charybdis feriatus*
5	Dakshina Kannada	Marine	Surathkal Beach	*Protunus sanguinolentus*
6	Udupi	Marine	Kaup Beach	*Protunus sanguinolentus*
7	Udupi	Marine	Malpe Beach	*Protunus sanguinolentus*
8	Dakshina Kannada	Estuary	Ullal end point	*Protunus sanguinolentus*
9	Dakshina Kannada	Estuary	Ullal end point	*Protunus pelagicus*
10	Dakshina Kannada	Estuary	Sasihithlu	*Protunus sanguinolentus*
11	Dakshina Kannada	Fresh Water	Nethravathi River	*Scylla serrata*
12	Udupi	Fresh Water	Uppunda River	*Scylla serrata*

Table 2. Bivalves selected from different reservoirs.

Sl. No.	District	Habitat	Sample site	Clams species
1	Udupi	Fresh water	Sumanavathi	*Meretrix casta*
2	Udupi	Marine	Someshwara Beach	*Perna perna*
3	Udupi	Fresh water	Souparnika	*Meretrix casta*
4	Udupi	Fresh water	Souparnika	*Mercia recens*
5	Udupi	Fresh water	Papanashini	*Marcia recens*
6	Udupi	Fresh water	Panchagangavali	*Meretrix casta*
7	Dakshina Kannada	Fresh water	Nethravathi River	*Meretrix casta*
8	Dakshina Kannada	Esturine	Ullal end point	*Merertix casta*
9	Dakshina Kannada	Fresh water	Nethravathi River	*Meretrix casta*
10	Dakshina Kannada	Esturine	Sasihithlu Estury	*Meretrix casta*

Table 3. Permissible level of Cr, Pb, Cu and Cd (ppm) in Crustaceans and bivalves (FAO 1990).

Heavy metals	Chromium (Cr)	Lead (Pb)	Copper (Cu)	Cadmium (Cd)
Crustaceans (ppm)	0.3	0.5	10	0.5
Bivalves (ppm)	2	1	10	1

in Chromium concentration from January to February in both crab and clams. Lead concentration increases notably in clams from January to February, while it remains relatively stable in crab. There is a substantial decrease in Copper concentration in both

crab and clams from January to February. Cadmium concentration shows minimal changes between January and February for both crab and clams and there are considerable variations in metal concentrations between the two months and among species. This study was done to find out month wise variations in heavy metal concentrations.

Crab's heavy metal concentrations: Comparing mean concentrations of heavy metals in crab samples between January and February using a bar chart reveals significant changes. Chromium levels experienced a substantial decrease from January (0.37 ppm) to February (0.005 ppm), indicating a significant reduction in contamination. Lead levels showed a slight increase from January (0.08 ppm) to February (0.10 ppm), suggesting a minor rise in contamination. Copper concentrations significantly decreased from January (4.17 ppm) to February (0.76 ppm), indicating a notable reduction in contamination. Cadmium levels remained relatively stable between January (0.04 ppm) and February (0.03 ppm) (Fig. 2).

Box plot (crab samples)

Analyzing the distribution of heavy metal concentrations in crab samples between January and February using box plots provides additional insights. In January, Chromium concentrations exhibited a wider spread and higher variability compared to February, where concentrations were more tightly clustered around the median. Lead concentrations showed a wider spread and higher variability in January,

Table 4. Concentration (ppm) of studied metals –monthwise data.

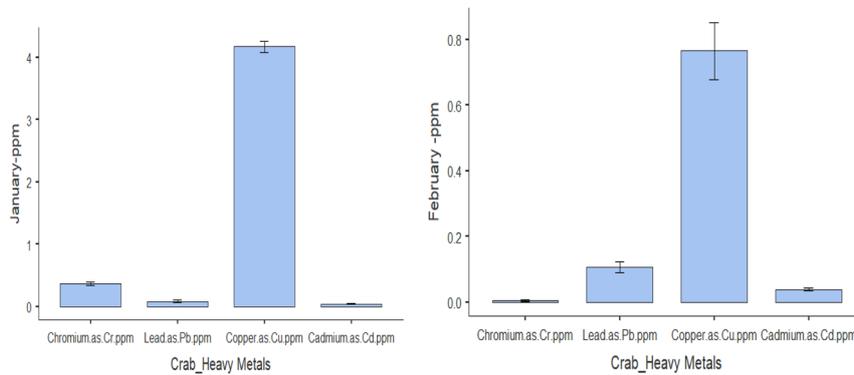|		January Crab	January Clams	February Crab	February Clams
Chromium as Cr	Mean	0.3819	0.7147	0.005	0.0803
	SD	0.1778	0.3112	0.0172	0.3540
Lead as Pb	Mean	0.0840	0.1033	0.1062	0.2720
	SD	0.1119	0.0909	0.1021	0.2611
Copper as Cu	Mean	4.1755	4.0959	0.7659	0.4206
	SD	0.5402	1.2943	0.5246	0.4682
Cadmium as Cd	Mean	0.0408	0.0249	0.0389	0.0323
	SD	0.0489	0.0163	0.0260	0.0115

Fig. 2. Concentrations of metals (ppm) in crab samples collected during January and February.

with more outliers compared to February. Copper concentrations had a wider interquartile range and more outliers in January, indicating greater variability compared to February. Cadmium concentrations exhibited consistent distribution patterns with narrow interquartile ranges and no outliers in both months (Fig. 3).

Clams: Heavy metal concentrations

Examining the mean concentrations of heavy metals in clam samples for January and February through a bar chart reveals notable differences. Chromium levels showed a substantial decrease from January (0.7147 ppm) to February (0.0803 ppm), indicating a significant reduction in contamination. Lead con-

centrations exhibited a considerable increase from January (0.1033 ppm) to February (0.2720 ppm), suggesting a notable rise in contamination. Copper levels experienced a drastic decrease from January (4.0959 ppm) to February (0.4206 ppm), indicating a significant reduction in contamination. Cadmium concentrations remained relatively stable between January (0.0249 ppm) and February (0.0323 ppm) (Fig. 4).

Box plot (clam samples)

Analyzing the distribution of heavy metal concentrations in clam samples between January and February using box plots offers further insights. In January, Chromium concentrations displayed a wider
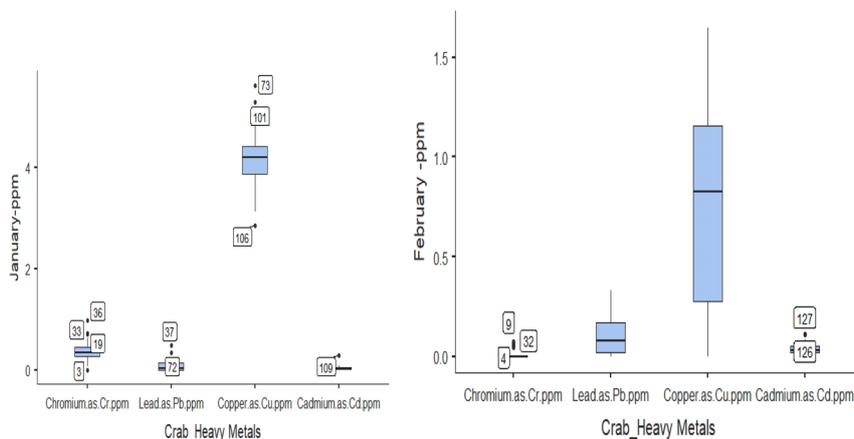

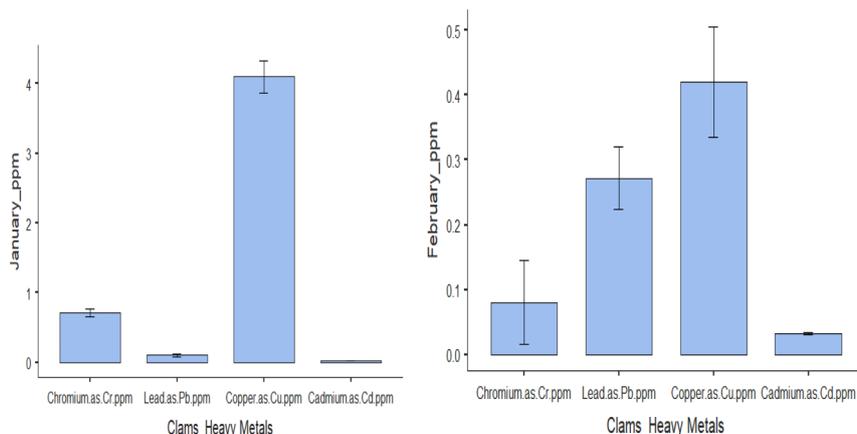**Fig. 3.** Variations in concentrations of metals in crabs over two months.

Fig. 4. Concentrations of metals (ppm) in clam samples collected during January and February.

interquartile range and higher variability compared to February, where concentrations were more tightly clustered around the median. Lead concentrations showed a wider spread and higher variability in January, with more outliers compared to February. Copper concentrations exhibited a wider interquartile range and more outliers in January, indicating greater variability compared to February. Cadmium concentrations displayed consistent distribution patterns with narrow interquartile ranges and no outliers in both months (Fig. 5).

Charybdis lucifera from Someshwara Beach shows relatively low chromium levels compared to other crab species, while *Protunus sanguinolentus* from Malpe Beach exhibits the highest chromium concentration. Lead concentrations peak in *Charybdis lucifera* from Someshwara Beach, whereas *Protunus sanguinolentus* from Kaup Beach displays the lowest levels. Copper levels reach their maximum in *Charybdis lucifera* from Someshwara Beach, closely followed by Sasihithlu, while *Scylla serrata* from Uppunda River demonstrates the lowest copper con-
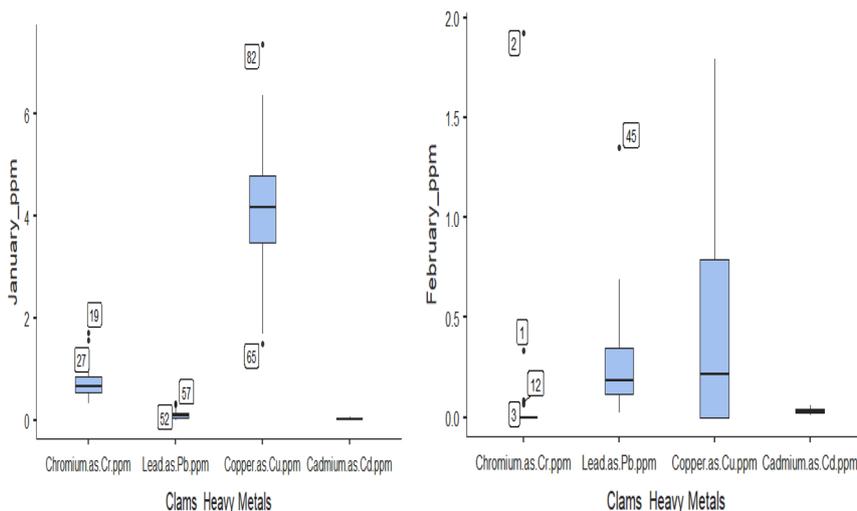

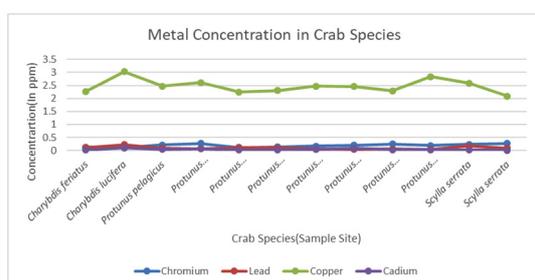**Fig. 5.** Variations in concentrations of metals in clams over two months.

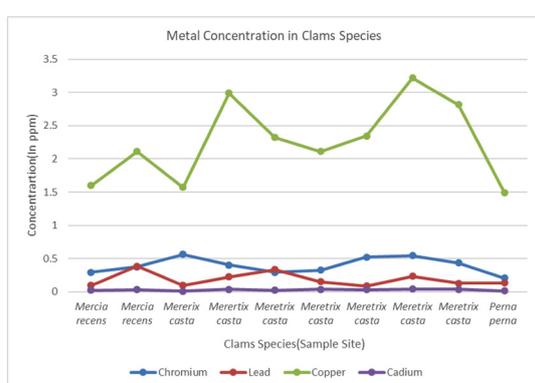**Fig. 6.** Concentrations in different crabs from various habitats.

Fig. 7. Concentrations in different bivalves from various habitats.

centration. Additionally, cadmium concentrations are highest in *Protunus sanguinolentus* from Kaup Beach, while *Scylla serrata* from Uppunda River shows the lowest levels (Fig. 6).

Meretrix casta from Sumanavathi and Nethravathi River exhibit elevated chromium levels, contrasting with *Perna perna* from Someshwara Beach, showing lower concentrations. Mercia recens from Papanashini and *Meretrix casta* from Souparnika display the highest lead concentrations, while *Meretrix casta* from Nethravathi River demonstrates the highest copper levels, followed by Ullal End Point, Souparnika, and Sasihithlu Estuary. *Meretrix casta* from Nethravathi River and Sasihithlu Estuary also exhibit the highest cadmium concentrations, with lower levels in Ullal End Point and Panchagangavali, and the lowest in *Perna perna* from Someshwara Beach (Fig. 7).

DISCUSSION

This study investigates the concentration of heavy

metals in the tissues of selected crabs and bivalves (clams and mussels) using atomic absorption spectrometry, with a focus on assessing environmental pollution and potential human health risks. Marine organisms such as crabs and bivalves are increasingly recognized as effective bioindicators due to their capacity to bioaccumulate contaminants and their sensitivity to changes in water quality. Moreover, these species form an integral part of the human diet in many coastal regions, including Karnataka, India, making the monitoring of heavy metal accumulation in their tissues critically important for both ecosystem health and food safety.

Numerous studies have demonstrated the bioindicator potential of shellfish. Scientists (Olusegun *et al.* 2021) reported that crabs from the Ojo River exhibited significantly higher mean concentrations of lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) than prawns, underscoring the crabs' superior capacity for bioaccumulating trace metals. In northern Vietnam, high arsenic (As) concentrations were detected in cultured oysters (*Saccostrea glomerata*) and clams (*Meretrix lyrata*), raising concerns over human health risks(Dang *et al.* 2022). Similarly, Researchers(Ngo-Massou *et al.* 2022) found that cadmium, zinc, and aluminum levels in *Cardisoma armatum* from the Gulf of Guinea exceeded safe thresholds.

In Bangladesh, Scientists(Ahmed *et al.* 2023) analyzed two shrimp species (*Macrobrachium rosenbergii, Metapenaeus monoceros*) and a crab species (*Scylla serrata*) for nine heavy metals, concluding that although crabs showed higher accumulation levels, concentrations remained below permissible limits. It was demonstrated metal bioaccumulation patterns in *Portunus sanguinolentus, Portunus armatus*, and *Scylla serrata* along the southeast coast of India, highlighting interspecific and organ-specific differences likely driven by biomagnification and environmental variables (Vardi and Venkatrayulu 2023).

In our present study, we observed varying levels of Pb, Cr, and Cd in *Meretrix casta* collected from multiple habitats. These variations reflect the influence of factors such as local pollution sources, seasonal conditions, and species-specific accumulation potential. Supporting this, it was reported that Pb,

Hg, and Cd levels in blood clams from Jambi East Coast, Indonesia, that exceeded safety thresholds, emphasizing the need for rigorous monitoring (Lisna *et al.* 2023).

Given the widespread consumption of crabs and bivalves in coastal Karnataka, the detection of heavy metals in these organisms is of particular concern. Chronic exposure through dietary intake could pose significant health risks to local communities. Thus, this study contributes valuable data for environmental monitoring and underscores the importance of integrating food safety considerations into conservation strategies. It highlights the urgent need for comprehensive management of aquatic ecosystems to safeguard both ecological integrity and public health.

CONCLUSION

The present study provides valuable insights into the accumulation of chromium (Cr), lead (Pb), copper (Cu), and cadmium (Cd) in crab and bivalve species collected from the Dakshina Kannada and Udupi districts of coastal Karnataka. The results indicate that while the concentrations of most heavy metals remained within permissible limits, chromium levels exceeded recommended safety thresholds in certain samples. Spatial variation in heavy metal concentrations among sampling sites is likely influenced by a combination of factors, including tidal dynamics, anthropogenic and natural pollutant inputs, environmental parameters such as pH and salinity, and species-specific physiological traits.

These findings underscore the role of crabs and bivalves as effective bioindicators for monitoring coastal pollution and highlight the potential risk of heavy metal exposure through seafood consumption. Continued surveillance of metal contamination in aquatic organisms is essential for ensuring food safety and for the sustainable management of marine ecosystems. The study calls for integrated conservation and pollution control measures to mitigate the long-term ecological and public health impacts of heavy metal accumulation in coastal environments.

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REFERENCES

Ahmed, S., Uddin, M. F., Hossain, M. S., Jubair, A., Islam, M. N., & Rahman, M. (2023). Heavy metals contamination in shrimp and crab from southwest regions in Bangladesh: Possible health risk assessment. *Toxicology Reports,* 8(10), 580–588.

Albert, D. D. A., Bujeng, V., & Chia, S. (2022). Identification of mollusc remains (bivalve and gastropod) from archaeological sites in Semporna, Sabah. *Tropical Life Sciences Research*, 33(2), 197–237.

Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry,* 2019, Article ID 6730305. https://doi.org/10.1155/2019/6730305

Chiarelli, R., & Roccheri, M. C. (2014). Marine invertebrates as bioindicators of heavy metal pollution. *Open Journal of Metal,* 4(4), 93–106.

Dang, T. T., Vo, T. A., Duong, M. T., Pham, T. M., Nguyen, Q. V., Nguyen, T. Q., Bui, M. Q., Syrbu, N. N., & Do, M. V. (2022). Heavy metals in cultured oysters (*Saccostrea glomerata*) and clams (*Meretrix lyrata*) from the northern coastal area of Vietnam. *Marine Pollution Bulletin,* 184, 114–140.

Duffus, J. H. (2002). 'Heavy metal' – A meaningless term? *Pure and Applied Chemistry*, 74(5), 793–807.

Falusi, B. A., & Olanipekun, E. O. (2007). Bioconcentration factors of heavy metals in tropical crab (*Carcinu*s sp) from River Aponwe, Ado-Ekiti, Nigeria. *Journal of Applied Sciences and Environmental Management*, 11(4), 51–54.

Food and Agriculture Organization (FAO). (1990). Field guide to the commercial marine resources of the Gulf of Guinea (FAO Species Identification Sheets for Fishery Purposes). FAO Regional Office for Africa.

Holleman, A. F., & Wiberg, E. (1985). *Lehrbuch der anorganischen Chemie.* Berlin: Walter de Gruyter.

Hossen, M. F., Hamdan, S., & Rahman, M. R. (2015). Review on the risk assessment of heavy metals in Malaysian clams. *The Scientific World Journal,* pp 1–7.

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2020). Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. *International Journal of Environmental Research and Public Health,* 17(7), 2204.

Jose, J. (2017). Classification, biodiversity and conservation of marine commercial crabs of India. In *Training Manual on Species Identification* Crustacean Fisheries Division, Central Marine Fisheries Research Institute, Kochi. pp160–171.

Khan, M. A. R., Islam, M. S., & Mamun, M. S. A. (2021). Proximate compositions and risk assessment of lead in two common fishes (*Labeo rohita* and *Barbonymus gonionotus*) collected from river and farms of Bagerhat, Bangladesh.

Journal of Food Quality and Hazards Control, 8, 96–103.

Kumar, P. S. B., Mohamed, K., Balasubramani, R., Murugesan, C., Rajakrishnan, R., Ahmed, A., Chang, S. W., Ramamoorthy, A., Mukherjee, A., & Arunachalam, K. D. (2022). Potential health risk caused by heavy metal associated with seafood consumption around coastal area. *Environmental Pollution,* 294, 118553.

Kumar, A., Singh, S., Yadav, R., & Kumar, V. (2025). Heavy metals: Toxicity and human health effects. *Archives of Toxicology,* 99(3), 901–919.

Lisna, L., Ramadan, F., & Arfiana, B. M. (2023). Assessment of heavy metals in blood clams (*Anadara granosa*) in the waters of the east coast of Jambi, East Tanjung Jabung Regency, Jambi, Indonesia. *International Journal of Progressive Sciences and Technologies,* 41(2), 537–543.

Liu, L., Zhao, Y., Zhang, J., Zhang, C., Yang, Y., Li, S., & Wang, Y. (2025). Heavy metal(loid)s bioaccumulation in fish and its implications for human health. *Journal of Environmental Sciences,* 147, 153–164.

Ngo-Massou, V. M., Kottè-Mapoko, E. F., & Din, N. (2022). Heavy metal accumulation in the edible crab *Cardisoma armatum* (Brachyura: Gecarcinidae) and implications for human health risks. *Scientific African,* 16, e01248.

Olusegun, S. T., Ezeokoli, C., Fadimu, A. O., Badmus, K. W., Olatunde, A. A., Osundiya, T. M., & Olubunmi, M. (2021). Bioaccumulation of heavy metals in crab and prawn tissue from Ojo River, Ojo-Lagos. *Advances in Analytical Chemistry,* 11(1), 9–12.

Singh, V., Sharma, B., & Chauhan, P. K. (2023). Heavy metal contamination in the aquatic ecosystem: Toxicity and its remediation using eco-friendly approaches. *Toxics,* 11(2), 147.

Vardi, V., & Venkatrayulu, C. (2023). Bioaccumulation of heavy metals in three different edible crab species at Nellore Coast of Andhra Pradesh in Southeast Coast of India. *Biological Forum – An International Journal*, 15(2), 1064–1069.

Venkatesan, V., & Mohamed, K. S. (2015). Bivalve classification and taxonomy. In Summer School on Recent Advances in Marine Biodiversity Conservation and Management. Molluscan Fisheries Division, CMFRI, Kochi.

Zaynab, M., Al-Yahyai, R., Ameen, A., Sharif, Y., Ali, L., Fatima, M., Khan, K. A., & Li, S. (2022). Health and environmental effects of heavy metals. *Journal of King Saud University Science,* 34, 101653.

Zhang, Z., Fang, Z., Li, J., Sui, T., Lin, L., & Xu, X. (2019). Copper, zinc, manganese, cadmium and chromium in crabs from the mangrove wetlands in Qi'ao Island, South China: Levels, bioaccumulation and dietary exposure. *Watershed Ecology and the Environment,* 1, 26–32.