Ecological Risk Assessment And Seasonal Variation Of Heavy Metals In Water, Sediment And Biota Collected From Shambhavi Estuary, Mulki, Karnataka

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Abstract
This study investigated the levels of heavy metal contamination in the Shambhavi Estuary's water, sediment, and crab tissues. The results indicated that Fe had the highest concentration in both water and sediment, followed by Pb, Zn, Cr, and Cd. Moreover, the levels of all heavy metals in the water, sediment, and crab tissues exceeded the acceptable limits set by various international organizations, indicating a significant contamination issue. The study revealed that the levels of heavy metal contamination in the estuary's aquatic environment increased during the pre-monsoon, monsoon, and post-monsoon seasons, with waste discharge from industries, municipalities, and agriculture being identified as the primary source of pollution. The high levels of heavy metals detected in the water and sediment raised concerns about potential bioaccumulation in the estuary's most prevalent crab species, *Astruca annulipes*, which could pose a considerable threat to the ecosystem's integrity. The study's findings highlight the urgent need for appropriate management measures to reduce heavy metal pollution and ensure the maintenance of ecosystem health and biodiversity. This study could provide a baseline for future investigations into the estuary's heavy metal contamination and its potential impact on the ecosystem's biota.

Keywords: Heavy metal contamination, Shambhavi Estuary, ecosystem integrity, ecological health.

INTRODUCTION
The elevated levels of heavy metals, including cadmium, chromium, copper, mercury, lead, zinc, arsenic, boron, etc., in aquatic environments, can pose a significant toxic impact on various elements of ecosystem due to bio accumulation through different levels of the food chain [1]. The Karnataka coast (Karwar and Mangalore) in India is renowned for its diverse fish population [2]. however, the anthropogenic activity impacted this costal water toward a greater extent [3]. Hydrographic analysis of aquifers (river, estuary, and coastal components) of these region's offers insights into sediment texture, macrobenthic adaptation, and pollution levels [4]. Anthropogenic activities, such as agriculture, and discharge of sewage and industrial effluent, put pressure on the tropical wet zone region, affecting its rivers that serve as source of irrigation, domestic water, and water for industry [5]. The Shambhavi and Nandhini Rivers in the Dakshina Kannada district face pollution due to untreated effluent and sewage. The Shambhavi Estuary is a vital transition zone between freshwater and marine ecosystems, impacted by both [6]. The Shambhavi Estuary is vital for sediment transportation, provides habitat for diverse species, and is a critical area to study water quality and community diversity. The coastline zone spans 22 km along the southwestern coast of India in Dakshina Kannada district, making it an ideal research area [7]. As a result, the Shambhavi Estuary is a key research area for community diversity, sediment traits, and water quality, particularly in the intertidal or coastal zone.

Sediment movement i.e., transport of particles of sand, silt, clay, and other materials by various agents such as water, wind, ice, and gravity is a critical process, result into its deposition in different habitats of hydrogeological systems, including rivers, estuaries, and the sea. The sediment's chemical composition and texture are strongly influenced by various environmental parameters, affecting the benthic community's structure and composition [8]. The type of sediment found in estuaries plays a crucial role in determining the benthic community's type and abundance [9]. The factors at the water-sediment interface, such as contamination and organic enrichment, impact the macrobenthos composition and abundance. Other hydrochemical parameters like temperature, salinity, suspended solids, nitrate, and dissolved oxygen in the hypolimnion also impact the composition of macrobenthos [10]. To understand how benthic communities are organized and behave, it is crucial to understand both the benthic community and sediment. The composition of macrobenthic communities is determined by sediment texture, organic matter, and food availability [11]. These communities affect heavy metal accumulation and serve as a food source in the food chain. Benthos influences sediment layers, nutrient balance, and oxygen levels at the sediment-water interface [12]. Benthic invertebrates are adaptable to different environments and used in biomonitoring [13]. Heavy metals, including Zn, Pb, Cd, Cr, Ni, and Cu, are common pollutants in urban catchments that can reduce diversity, structure, and abundance [14]. The study of heavy metals in surface sediments is important to understand the exposure of macrobenthic invertebrates to these contaminants.

Human activities such as mining, fisheries, pollution, resource exploitation, and tourism can have negative impacts on estuaries, which are crucial coastal ecosystems [15]. Industrialization and urbanization in tropical countries like India have worsened these issues [16]. The Shambhavi Estuary in the study area is affected by various environmental disturbances, including river runoff, ocean intrusion, sediment transfer, and tidal action, as well as human activities like sewage and waste discharge and industrial pollution, including non-point sources like agricultural and sediment runoff [17]. The study aims to investigate the impact of human actions on the estuarine environment along the coast of Mangalore. Specifically, the authors will examine how surface sediment composition and the presence of macrobenthic organisms vary with the seasons and what factors contribute to heavy metal pollution levels. By determining the source and effect of pollutants in rivers, the study hopes to identify measures to safeguard the health of the Karnataka coast. The findings will be used to monitor heavy metal levels in water, sediment, and biota from both natural and human sources, and detect seasonal changes in affected areas. Overall, the study aims to provide a comprehensive understanding of human activity's impact on the estuarine environment and to recommend measures to improve its health.

METHODS AND MATERIALS

Study area

The study site, Chithrapu village, is located in the Dakshina Kannada district in the southwestern state of Karnataka in India (fig.1). Specifically, the village is situated at 13°9'03"N, 74°46'56.6"E, which places it to the northeast of Mulki. Chithrapu is famous for its mangrove ecosystem, which is formed where the Nandini River converges with the Arabian Sea. This site is approximately 30 km from the city of Mangalore.

Sample collection

For the assessment of heavy metals, samples are collected twice a month during low tide, from August 2021 to July 2022 in 7 different location by random sampling method. Three types of samples are collected: water, sediment, and biota, specifically the crustacean *Astruca annulipes*. Water samples are collected using polypropylene bottles, while sediment samples are collected using coring devices. Biota samples, such as the *A. annulipes* crustaceans, are collected by hand pick. Collecting these samples twice a month over the course of a year provides a comprehensive view of the ecosystem, including seasonal changes. This information can be used to understand the overall health of the mangrove ecosystem in Chithrapu village, and to identify any issues that may require attention to maintain the ecosystem's ecological balance.

Data Analysis

The data collected was analysed using One Way Analysis Variance(ANNOVA) using SPSS software Version 27 followed by Duncan test compared a differences among different samples, The data obtained was expressed in Mean±SD.

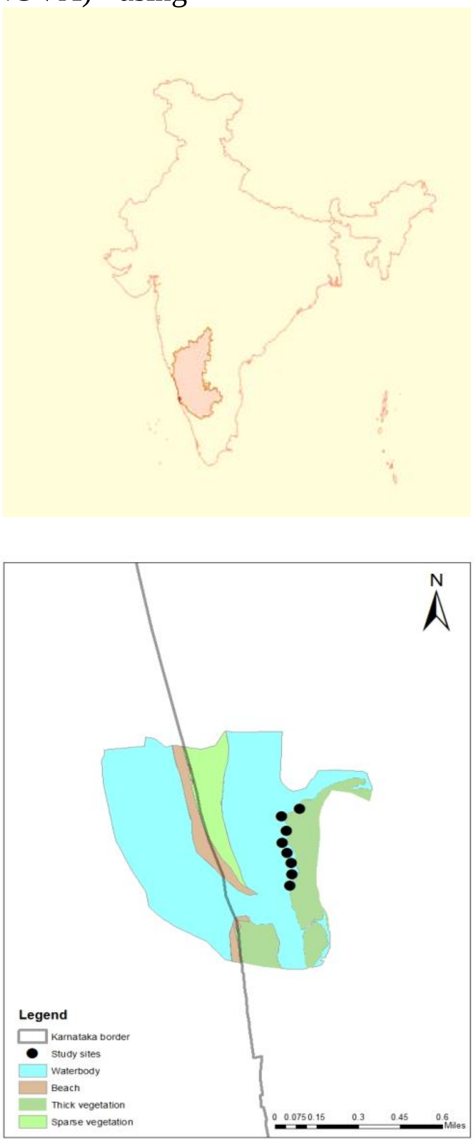

Fig. 1 Geographical location of the Shambhavi Estuary

Analysis of Heavy Metal Accumulation in Water, Sediment, and Biota

The sample was first dried for 24 hours in a hot air oven at 70±2 °C to remove any moisture content. After the sample were dried, it was ground into a fine powder to increase its surface area and make it easier to digest with wet acid digestion. In this process, 1 g of the powdered sample was digested using a mixture of 12 mL of nitric acid and 4 mL of hydrochloric acid in a fume hood, the mixture was heated on a hot plate set to 60 5 °C until the volume was reduced to 10 ml. This step was repeated until the solution became clear and the final volume is made up to 25 mL with deionised water using standard flask and the digest was filtered using Whatman No. 42 filter paper to remove any remaining solid particles in the solution that could interfere with the analysis. The heavy metals in the filtrate were analysed using an atomic absorption spectrophotometer (Shimadzu, AA-6880, Japan).

RESULT AND DISCUSSION

Table 1: Seasonal Variation of Cd, Cr, Fe, Pb and Zn (mg/L) in water samples collected from Shambhavi estuary, Mulki during the period of August 2021-July 2022.

	Pre Monsoon			Monsoon			Post Monsoon			
Metals	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	P Value
Cd	0.005446±0.000205a	0.005143	0.005595	0.018714±0.021654a	0.005587	0.050804	0.005882±0.00097a	0.005587	0.050804	0.284
Cr	0.053592±0.000878a	0.052558	0.054438	0.04796±0.032654a	0.002317	0.079929	0.062475±0.006838a	0.002317	0.079929	0.581
Fe	0.544368±0.045946a	0.505696	0.600496	0.670847±0.120813a	0.583046	0.842646	0.548873±0.032701a	0.583046	0.842646	0.076
Pb	0.238729±0.011827a	0.232379	0.256454	0.321627±0.118681a	0.204599	0.427996	0.264311±0.062691a	0.204599	0.427996	0.348
Zn	0.031783±0.007444a	0.02575	0.041237	0.093451±0.107559a	0.019627	0.249979	0.086152±0.116355a	0.019627	0.249979	0.6

Based on the data obtained, the concentrations of the various metals (Cd, Cr, Fe, Pb, and Zn) vary depending on the season monsoon, pre-monsoon, and post-monsoon (table 1). For Cd, the highest concentration was found during the monsoon season at 0.018714 mg/l, while the lowest concentration was found during the pre-monsoon season at 0.005446 mg/l. This variation in concentration could be due to several factors, such as changes in rainfall patterns and water flow which could affect the movement and distribution of pollutants [18]. Another factor that governess the heavy metal level of water body is the land that surrounds it. If the surrounding land is contaminated with cadmium, during monsoon the surface runoff which would carry Cd and it will get discharged into the surrounding bodies [19]. In general, high levels of cadmium in water can lead to various health problems such as kidney damage, hypertension, and cancer in humans [20]. Long-term exposure to cadmium can also weaken the immune system and increase the risk of developing osteoporosis [21]. Moreover, cadmium contamination can also have a significant impact on aquatic life [22]. Fish are highly sensitive to cadmium and can accumulate high levels in their tissues. This can lead to impaired growth and reproduction, as well as decreased survival rates [23]. The presence of cadmium in water can also disrupt the food chain and affect other species that depend on aquatic organisms for survival [24].

For Cr, the highest concentration was found during the post-monsoon season at 0.062475 mg/l, while the lowest concentration was found during the monsoon season at 0.04796mg/l. This variation in concentration could be due to differences in environmental conditions, such as temperature and humidity, which can impact the release of Cr into the water [25]. Hexavalent chromium is a highly toxic compound that can have significant negative impacts on both human health and aquatic environment [26]. Exposure to high levels of hexavalent chromium can lead to various health problems, including skin irritation, respiratory issues, and an increased risk of cancer. Prolonged exposure can also cause liver and kidney damage and increase the risk of developing gastrointestinal problems [27]. In the aquifers fishes and other aquatic organisms are particularly vulnerable to the toxic effects of hexavalent chromium, which can accumulate in their tissues and cause a range of health problems [28]. These include impaired growth and reproduction, decreased survival rates, and disruptions to the aquatic food chain that can affect other species that depend on aquatic organisms for survival [29].

For Fe, the highest concentration was found during the monsoon season at 0.670847 mg/l, while the lowest concentration was found during the pre-monsoon season at 0.544368 mg/l. This variation in concentration could be due to changes in water flow and sedimentation patterns, which can affect the amount of Fe in the water [30]. Iron distribution in marine water is influenced by a variety of factors, including ocean currents, atmospheric deposition, and sedimentation [31]. For example, iron-rich dust from deserts can be transported long distances by winds and deposited into the ocean, providing a source of iron for marine organisms [32]. Iron can also be released into seawater through the weathering of rocks and sediments on the ocean floor [33]. In addition to its role as a nutrient, iron can also have toxic effects on marine organisms when present in high concentrations. Excessive iron concentrations can lead to the formation of harmful algal blooms, which can produce toxins that can be harmful to fish, shellfish, and other marine organisms [34]. Iron contamination can also lead to the accumulation of heavy metals in marine organisms, which can pose a threat to human health when consumed [35]. Iron limitation can affect the growth of phytoplankton, the base of the marine food chain, which can have far-reaching effects on the entire ecosystem [36]. In some regions, iron fertilization experiments have been conducted to stimulate phytoplankton growth and enhance carbon sequestration. However, even small changes in iron concentration can have a significant impact on marine ecosystems [37].

For Pb, the highest concentration was found during the monsoon season at 0.321627 mg/l, while the lowest concentration was found during the pre-monsoon season at 0.238729 mg/l. This variation in concentration could be due to the movement and distribution of pollutants in the water, as well as changes in the environmental conditions, which can impact the release of Pb [38]. Lead is a toxic heavy metal that can have a range of negative effects on marine ecosystems when present in high concentrations [39]. Unlike iron, which is naturally occurring in marine waters, lead in the ocean is primarily derived from human activities such as industrial processes, mining, and leaded gasoline emissions [40]. Lead contamination can enter marine waters through a variety of sources, including runoff from urban areas, discharge from industrial facilities, and atmospheric deposition [41]. Once in the ocean, lead can accumulate in sediments and the food chain, with potential consequences for marine organisms and human health. Lead contamination can also affect human health when seafood and other marine products containing lead are consumed [42]. The bioaccumulation of lead in certain species of fish and shellfish can lead to health problems such as neurological damage, kidney damage, and reproductive issues [43].

For Zn, the highest concentration was found during the monsoon season at 0.093451 mg/l, while the lowest concentration was found during the pre-monsoon season at 0.031783 mg/l. This variation in concentration could be due to differences in the sources and pathways of Zn in the environment, as well as changes in water flow patterns and sedimentation, which can impact the amount of Zn present in the water [44]. Zinc is an essential trace element for marine organisms, playing a critical role in a range of physiological processes such as growth, reproduction, and immunity [45].

While zinc is present in marine waters in trace amounts, its distribution can vary depending on a variety of factors including ocean currents, sedimentation, and human activities [46]. Excessive zinc concentrations can cause toxicity to marine organisms, leading to impaired growth, reproduction, and survival. Zinc toxicity can also cause changes in behavior and metabolism and can interfere with the uptake of other essential elements [47]. As per the ANNOVA statistics none of the heavy metals showed any significant variation across the season. This may be due to the regular fluctuations of heavy metal concentration between the maximum and the minimum values. Overall, these results suggest that seasonal changes as potential impact the concentration of these metals in the water. It is essential to continue monitoring these pollutants levels to protect human health and the environment.

Table 2: Mean Concentrations of Cd, Cr, Fe, Pb and Zn (mg/kg) in sediment samples collected from Shambhavi estuary, Mulki during the period of August 2021-July 2022.

	Pre Monsoon			Monsoon			Post Monsoon			
Metals	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	P Value
Cd	0.0038±0.0002a	0.0036	0.0040	0.0061± 0.0035a	0.0024	0.0098	0.0033±0.0006a	0.0027	0.0039	0.179
Cr	0.0545±0.0030a	0.0515	0.0574	0.0502± 0.0299a	0.0255	0.0904	0.0532±0.0029a	0.0501	0.0569	0.939
Fe	5.7733±0.6516b	5.2243	6.5451	8.3214± 1.4428a	7.0683	9.6386	6.6004±0.4146b	6.1114	7.1256	0.012
Pb	0.5081±0.0185a	0.4858	0.5238	0.3491± 0.2845a	0.1064	0.6666	0.5529±0.0521a	0.5154	0.6298	0.247
Zn	0.2806±0.0384a	0.2470	0.3284	0.2983± 0.0650a	0.2352	0.3559	0.2787±0.0317a	0.2532	0.3217	0.816

The findings of this study on the concentration of heavy metals in the estuary sediment during different seasons provide essential insight into the temporal variation of metal pollution in the environment. The results indicate that seasonal changes have a significant impact on the concentration of heavy metals, including Cadmium (Cd), Chromium (Cr), Iron (Fe), Lead (Pb), and Zinc (Zn) in soil (table 2). The highest concentration of Cd was recorded during the monsoon season, with a value of 0.00609 mg/kg. This suggests that the monsoon season may increase the amount of Cd in the sediment due to increased rainfall, which can wash pollutants into the soil from other sources, such as industrial and agricultural runoff [48]. On the other hand, the lowest concentration of Cd was found during the post-monsoon season, with a value of 0.00331 mg/kg, which could be due to the leaching and dispersion of Cd into the surrounding environment [49]. Cadmium-contaminated sediment can release cadmium into the water, which can affect water quality. Elevated levels of cadmium in water can lead to decreased dissolved oxygen levels, increased turbidity, and changes in pH, which can have impacts on aquatic organisms and the overall health of aquatic ecosystems [50]. This can include changes in the physical structure of river channels, the availability of food and shelter for aquatic organisms, and the overall health of the ecosystem. This can have implications for the distribution of sediment-associated contaminants and the overall health of aquatic ecosystems [51].

The highest concentration of Cr was found during the pre-monsoon season, with value of 0.05447 mg/kg, while the lowest concentration was recorded during the monsoon season, with a value of 0.05019 mg/kg. This variation could be attributed to the impact of seasonal changes on the release of Cr from the sediment and its redistribution through wind erosion, water runoff, and soil sedimentation [52]. Chromium contamination in sediment can have a range of impacts on the environment. For example, it can alter sediment properties and reduce sediment stability, increase erosion and transport [53], ultimately leading to downstream impacts such as decreased water quality and changes in aquatic habitats. Chromium can also cause sediment particles to clump together, leading to compacted and dense sediment that is less porous and thus losing its ability to hold water [54]. The loss of water holding capacity of sediment has impact the aquatic life. [55-56].

The highest concentration of Fe was recorded during the monsoon season, with a value of 8.32138 mg/kg, while the lowest concentration was found during the pre-monsoon season, with a value of 5.77328 mg/kg. Fe is an essential element for plants and can be present in sediment due to the weathering of rocks and minerals [57]. The variation in concentration could be attributed to changes in water flow and sedimentation patterns that affect the amount of Fe in the soil. Iron-contaminated sediment can have several impacts on water quality [58]. The increased sedimentation caused by the transport of contaminated sediment can cause water turbidity, which can reduce the amount of light penetrating the water column, affecting photosynthesis in aquatic plants and algae. This can lead to a decrease in primary productivity, which can impact the food chain and aquatic organism populations [59]. Iron-contaminated sediment can also alter water chemistry by increasing the levels of dissolved iron and altering the pH of the water. This can affect the availability of certain nutrients [60].

The highest concentration of Pb was found during the post-monsoon season, with a value of 0.55291 mg/kg, while the lowest concentration was recorded during the monsoon season, with a value of 0.34906 mg/kg. Pb can be introduced into the environment through various sources, such as vehicle emissions, industrial processes, and consumer products [61]. The variation in concentration could be due to the movement and distribution of pollutants in the soil and environmental conditions that can impact the release of Pb [62]. Lead-contaminated sediment can affect the biogeochemical cycling of nutrients, which can lead to imbalances in the food web and ecological processes [63]. The accumulation of lead in the sediment can impact the availability and uptake of nutrients by plants and other organisms, which can in turn affect the entire food chain. Human health can also be impacted by lead-contaminated sediment, particularly through the consumption of contaminated seafood. Lead exposure can cause a range of health effects, including developmental and neurological disorders, cardiovascular disease, and cancer [64].

The highest concentration of Zn was recorded during the monsoon season, with a value of 0.29827 mg/kg, while the lowest concentration was found during the post-monsoon season, with a value of 0.27873 mg/kg. Zn is an essential element for plants and animals and can be present in soil due to natural processes such as weathering [65]. The variation in concentration could be attributed to differences in the sources and pathways of Zn in the environment, as well as changes in water flow patterns and sedimentation, which can impact the amount of Zn present in the sediment [66]. Zinc distribution in sediment can have a range of effects on the environment. Zinc is an essential element for many organisms but can become toxic at high concentrations. Zinc-contaminated sediment can also impact the biogeochemical cycling of nutrients [67]. Zinc can bind to organic matter in sediment, making it less available to organisms. This can affect the nutrient cycling and availability for plants and other organisms in the food web. Furthermore, zinc contamination can impact the microbial communities in sediment, which play important roles in nutrient cycling and other ecosystem processes [68]. High levels of zinc can negatively impact microbial diversity and activity, which can in turn affect nutrient cycling and other ecosystem functions. In addition to its ecological impacts, zinc contamination in sediment can also pose risks to human health [69]. High levels of zinc in seafood can cause health effects such as nausea, vomiting, and diarrhea [70]. As per the ANNOVA statistics heavy metals like Cd, Cr, Pb, and Zn did not show any significant variation across the season This may be due to the regular fluctuations of heavy metal concentration between the maximum and the minimum values. Significant variation could be seen in the case of Fe with respective to different season. In conclusion, the results of this study indicate that seasonal changes play a significant role in determining the concentration of heavy metals in soil. Further research is necessary to understand the sources of these heavy metals and their potential impacts on the environment and human health. Monitoring the levels of these pollutants in the soil is essential to protecting human health and the environment.

Table 3: Mean Concentrations of Cd, Cr, Fe, Pb and Zn (mg/kg) in hepatopancreas of *Astruca annulipes* collected from Shambhavi estuary, Mulki during the period of August 2021-July 2022.

	Pre Monsoon			Monsoon			Post Monsoon			
Metals	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**	**P Value**
Cd	0.009533±0.001864a	0.007633	0.011433	0.010778±0.00135a	0.009233	0.011733	0.01075±0.000959a	0.0095	0.0123	0.318
Cr	0.039617±0.002978b	0.0379	0.044067	0.044733±0.001184a	0.043367	0.045433	0.044767±0.002969a	0.0408	0.0498	0.023
Fe	3.731767±0.68292b	3.3324	4.75	5.490041±1.023758a	4.308	6.093923	5.310517±0.539539a	4.783533	0.228046	0.013
Pb	0.290108±0.033435a	0.241133	0.315367	0.295267±0.058047a	0.258733	0.3622	0.257042±0.046973a	0.210233	0.3363	0.378
Zn	0.360303±0.078791b	0.273747	0.465	0.506344±0.205845ab	0.347633	0.738933	0.257042±0.046974a	0.448233	0.7421	0.066

Based on the data presented, the concentrations of Cd, Cr, Fe, Pb, and Zn in the hepatopancreas vary based on the different seasons, particularly during the monsoon, pre-monsoon, and post-monsoon seasons. For Cd, the highest concentration was found during the monsoon season, and the lowest was found during the pre-monsoon season. Cadmium can inhibit the activity of enzymes that are essential for digestion in the hepatopancreas, leading to impaired digestive function [71]. The hepatopancreas is a major site of cadmium accumulation in crustaceans and molluscs. Excessive accumulation of cadmium can cause oxidative stress, damage to cellular components, and even cell death. Metallothionein's are proteins that bind to heavy metals, including cadmium, to help prevent their toxic effects [72]. Exposure to cadmium can cause alterations in the expression of metallothionein's in the hepatopancreas, leading to a reduced ability to detoxify the metal [73]. Long-term exposure to cadmium can cause histological changes in the hepatopancreas, such as the thickening of the connective tissue and the accumulation of lipid droplets. These changes can affect the structure and function of the organ [74].

For Cr, the highest concentration was found during the post-monsoon season, and the lowest was found during the pre-monsoon season. Chromium is a trace element that is important for the metabolism of carbohydrates and fats in the body. However, excessive exposure to chromium can have negative effects on the body, including on the hepatopancreas [75]. The hepatopancreas is a glandular organ found in some invertebrates and is responsible for both digestive and metabolic functions [76]. In crustaceans, such as shrimp and crabs, the hepatopancreas is a major site of chromium accumulation. Excessive exposure to chromium can lead to damage to the hepatopancreas, including oxidative stress, inflammation, and cell death [77]. This can result in a decrease in the function of the hepatopancreas, leading to impaired digestion and metabolism [78].

Similarly, for Fe, the highest concentration was found during the monsoon season, and the lowest concentration was found during the pre-monsoon season. In crustaceans, such as shrimp and crabs, the hepatopancreas is a major site of iron accumulation [79]. Excessive exposure to iron can have negative effects on the hepatopancreas through a variety of mechanisms. One of the primary mechanisms through which iron causes damage is by inducing oxidative stress [80]. Iron is a pro-oxidant that can promote the formation of reactive oxygen species (ROS), which can damage cell structures, including proteins, lipids, and DNA. This oxidative damage can lead to inflammation and cell death in the hepatopancreas [81]. Additionally, iron can promote the formation of advanced glycation end-products (AGEs), which are proteins or lipids that become glycated or oxidized. AGEs can accumulate in tissues over time and contribute to inflammation and oxidative stress [82]. The accumulation of AGEs in the hepatopancreas can lead to impaired function of the glandular organ, including digestion and metabolism. Iron can also interfere with mitochondrial function, leading to impaired energy production in the hepatopancreas [83]. This can further contribute to cellular stress and inflammation, leading to impaired function of the glandular organ [84].

For Pb, the highest concentration was found during the monsoon season, and the lowest was found during the post-monsoon season. Lead can have negative effects on the absorption and metabolism of essential minerals in the body, including calcium, zinc, and iron, which are important for the function of the hepatopancreas [85]. Lead can interfere with the normal transport mechanisms of these minerals and compete with them for binding sites on enzymes and proteins. For example, lead can replace calcium in calcium-dependent enzymes, such as ATPase, which are important for the proper function of the hepatopancreas. This can lead to impaired enzyme activity and reduced function of the hepatopancreas [86]. Similarly, lead can replace zinc in zinc-dependent enzymes and proteins, such as metallothionein's, which are important for regulating the metabolism of essential minerals in the hepatopancreas [87]. This can lead to impaired regulation of mineral metabolism and accumulation of toxic levels of metals in the hepatopancreas.

Lastly, for Zn, the highest concentration was found during the post-monsoon season, and the lowest concentration was found during the pre-monsoon season. In crustaceans, such as crabs, zinc is particularly important for the proper function of the hepatopancreas, which is responsible for both digestive and metabolic functions [88]. Excessive zinc intake can also have negative effects on the hepatopancreas. High levels of zinc can lead to oxidative stress and inflammation, which can damage the cellular structure and function of the hepatopancreas. This can lead to impaired energy production, reduced enzyme activity, and cellular damage [89]. Furthermore, excessive zinc intake can interfere with the absorption and metabolism of other essential minerals, such as copper and iron, which are important for the function of the hepatopancreas [90]. Zinc can compete with copper for binding sites on enzymes and proteins, leading to impaired function of copper-dependent enzymes and proteins, such as cytochrome c oxidase. Similarly, zinc can interfere with the absorption and utilization of iron, which can lead to iron deficiency and impaired function of iron-dependent enzymes, such as catalase and peroxidase [91]. As per the ANNOVA statistics heavy metals like Cd, and Zn did not show any significant variation across the season This may be due to the regular fluctuations of heavy metal concentration between the maximum and the minimum values. Significant variation could be seen in the case of Cr, Fe, and Zn with respective to different season. The variation in metal concentrations in the hepatopancreas during different seasons highlights the need for continuous monitoring and further research to understand better the sources and pathways of these metals in the ecosystem. Additionally, understanding the reasons behind the observed variations in metal concentrations in the hepatopancreas will provide important information for developing strategies to mitigate the negative impacts of these metals on the health of the organism and the ecosystem.

Mean Concentrations of Cd, Cr, Fe, Pb and Zn (mg/kg) in muscle of *Astruca annulipes* collected from Shambhavi estuary, Mulki during the period of August 2021-July 2022.

	Pre Monsoon			Monsoon			Post Monsoon			
Metals	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**	**Mean ± SD**	**Min**	**Max**	**P Value**
Cd	0.0093±0.0014a	0.0079	0.0113	0.0109±0.0016a	0.0090	0.0119	0.0105±0.0014a	0.0093	0.0117	0.265
Cr	0.0395±0.0083a	0.0322	0.0471	0.0372±0.0035a	0.0341	0.0410	0.0435±0.0031a	0.0409	0.0480	0.196
Fe	4.3877±1.0193a	3.6617	5.8773	5.0820±1.7060a	3.8741	7.0336	5.9409±0.7703a	5.2291	7.0361	0.188
Pb	0.2811±0.0329a	0.2546	0.3245	0.2765±0.0399a	0.2503	0.3224	0.2514±0.0576a	0.2061	0.3300	0.483
Zn	0.4977±0.1175a	0.4169	0.6723	0.5390±0.0942a	0.4481	0.6363	0.6445±0.1634a	0.4171	0.7723	0.367

Based on the data presented, the concentrations of Cd, Cr, Fe, Pb, and Zn in the crab muscle also vary based on the different seasons, particularly during the monsoon, pre-monsoon, and post-monsoon seasons. For Cd, the highest concentration was found during the monsoon season, and the lowest was found during the pre-monsoon season. The distribution of cadmium in crab muscles will depend on a variety of factors, including the concentration of cadmium in the surrounding environment, the duration of exposure, and the metabolic processes of the crab [92]. Cadmium tends to accumulate in the hepatopancreas (digestive gland) of crabs, which is responsible for filtering and detoxifying substances in the crab's body. However, cadmium can also accumulate in other tissues, including the muscle tissue of crabs [93]. The concentration of cadmium in crab muscles will depend on the degree of exposure, the length of exposure, and the individual characteristics of the crab It is important to note that high levels of cadmium in crab muscles can pose a health risk to humans who consume them, so it is important to monitor the levels of cadmium in the environment and in seafood products [94].

For Cr, the highest concentration was found during the post-monsoon season, and the lowest was during the monsoon season. Chromium is also known to interfere with the proper functioning of enzymes in the crab's body, which can lead to a variety of negative effects, including reduced growth and reproduction rates, as well as changes in behavior and physiology [95]. In addition, exposure to high levels of chromium can cause damage to the gills of crabs, which can impair their ability to breathe and ultimately lead to death [96].

Similarly, for Fe, the highest concentration was found during the post-monsoon season, and the lowest concentration was found during the pre-monsoon season. In crabs, iron is an important component of hemocyanin, which is responsible for oxygen transport in the blood [97]. In general, low to moderate levels of iron in crab muscles are not harmful and can even be beneficial for human consumption. However, high levels of iron in crab muscles can lead to oxidative stress and damage to cellular structures, which can cause decreased muscle quality and strength [98].

For Pb, the highest concentration was found during the pre-monsoon season, and the lowest was found during the post-monsoon season. Lead is a toxic heavy metal that can have harmful effects on both wildlife and human health [99]. Lead can enter the environment through a variety of sources, including industrial pollution, mining activities, and the use of lead-based products [100]. In crabs, lead can accumulate in the tissues, including muscle tissue, and can have a variety of negative effects. Lead exposure can lead to the accumulation of ROS in the crab's body. Lead can interfere with the normal functioning of antioxidant enzymes, such as superoxide dismutase and catalase, which are critical for neutralizing ROS. This disruption of antioxidant defenses can lead to an accumulation of ROS in the crab's tissues, resulting in oxidative stress [101]. Oxidative stress can have a variety of negative effects on the health of crabs, including on their muscle strength and quality. Muscle tissue is particularly susceptible to oxidative stress because it is a highly metabolically active tissue that generates large amounts of ROS during normal function [102].

Lastly, for Zn, the highest concentration was found during the post-monsoon season, and the lowest concentration was found during pre-monsoon season Zinc is an essential trace element that plays a critical role in a variety of physiological processes in crabs [103]. Zinc is required for the proper functioning of enzymes involved in protein synthesis, DNA synthesis and repair, and cell division. Zinc also plays a role in immune function, wound healing, and sensory perception. Zinc is distributed throughout the body of crabs, including their muscles [104]. Studies have shown that zinc levels in crab muscles can vary depending on factors such as the crab's diet, age, and environmental conditions. Zinc can have a variety of effects on crab muscles, including on muscle strength and quality [105]. Zinc plays a role in the formation of muscle tissue, as it is required for the synthesis of muscle proteins such as actin and myosin. Zinc is required for the proper functioning of immune cells, including neutrophils and macrophages, which play critical roles in defending the body against pathogens [106]. As per the ANNOVA statistics none of the heavy metals showed any significant variation across the season. This may be due to the regular fluctuations of heavy metal concentration between the maximum and the minimum values. Further research is needed to understand better the sources and pathways of these metals in the ecosystem and to develop strategies to mitigate the negative impacts of heavy metal exposure on the health of the organism and the ecosystem. In conclusion, the results of this study underscore the importance of understanding the complex interplay between different environmental factors and the bioaccumulation of heavy metals in organisms like crabs. This information can be used to develop effective and sustainable approaches to protect the health of the environment and the organisms that inhabit it.

CONCLUSION

The impact of environmental factors on heavy metal concentrations in the ecosystem was studied, with a focus on water, soil, and biota. The results showed that ongoing monitoring is crucial to understanding the causes of heavy metal pollution and developing effective strategies to reduce pollutants. The study highlighted the need for a multidisciplinary approach that included hydrological modelling, toxicological assessments, and environmental monitoring to comprehensively understand the sources and pathways of heavy metals in the ecosystem. The adverse effects of heavy metal pollution on public health, including kidney, bone, lung, and nervous, cardiovascular, and reproductive system damage, were also emphasized. The study's findings underscored the importance of regular monitoring and reduction measures to protect the environment and public health from the harmful effects of heavy metal pollution. Overall, the study's results provide essential insights into the seasonal variations of heavy metal concentrations in the ecosystem, which can help develop effective strategies to mitigate the adverse effects of heavy metal pollution on the environment and public health.

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