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Bioaccumulation of trace elements in aquatic organisms of the Chesapeake estuary

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Abstract

In a regional context, the Chesapeake Bay is the largest estuary in the United States and supports a commercially important fishery worth over 500 million dollars annually-yet its food web may be quietly accumulating trace metals that eventually reach human dinner plates. This research measured concentrations of six trace elements (Cd, Pb, Cu, Zn, Cr, As) in water, sediment, and the tissues of four aquatic species-striped bass, blue crab, eastern oyster, and white perch-at 18 stations across the Chesapeake estuary during spring and autumn 2022. Bioaccumulation factors (BAFs) were calculated as the ratio of tissue concentration to ambient water concentration. Eastern oysters showed the highest BAFs for all elements, reaching 18.4 for zinc and 9.1 for copper, consistent with their filter-feeding behaviour and known capacity for metal sequestration. Striped bass and white perch, as mobile predators, accumulated lower concentrations but still exceeded recommended tissue-residue guidelines for cadmium at 22% of stations. Ecological risk quotients indicated moderate-to-high risk for cadmium and lead in the upper bay, where industrial and agricultural inputs converge. The findings support a need for continued biomonitoring and targeted source reduction in the upper Chesapeake watershed.

Keywords: Bioaccumulation, trace elements, aquatic organisms, estuary, ecological risk, Chesapeake Bay, heavy metals, oyster, bioaccumulation factor, food web

Introduction

In a regional context, the Chesapeake Bay has been the subject of restoration efforts since the 1983 Chesapeake Bay Agreement, yet water-quality targets for nutrients and sediment have repeatedly been missed ^[1]. Less attention has been paid to trace metals, even though the bay receives runoff from heavily urbanised watersheds (Baltimore, Washington DC) and agricultural land treated with copper- and zinc-containing pesticides and feed supplements ^[2]. Bioaccumulation-the net uptake of a contaminant from water and food into an organism's tissues over time-provides a more ecologically relevant measure of metal exposure than water or sediment concentrations alone, because it integrates temporal fluctuations and reflects actual biological availability ^[3]. Filter feeders like oysters accumulate metals in proportion to ambient water concentrations and have been used as sentinel organisms in estuarine monitoring worldwide ^[4]. Fish and crustaceans, by contrast, regulate some metals through hepatic detoxification but still accumulate others, particularly cadmium and methylmercury ^[5]. Earlier bioaccumulation work in the Chesapeake focused on mercury and organic contaminants ^[6]; multi-element assessments covering both invertebrates and fish are scarce and have not been updated since the early 2010s ^[7].

This research aimed to

1. measure trace-element concentrations in water, sediment, and four commercially Important species across 18 stations.
2. Calculate BAFs and compare them across trophic levels.
3. Evaluate ecological risk using tissue-residue guidelines and risk quotients ^[8].

Limitations

This research covered two sampling events (spring and autumn 2022), and seasonal variation in metal uptake-driven by temperature, salinity, and reproductive status-may affect BAF estimates.

Sample sizes for striped bass were limited ($n = 14$) because of the species' migratory behaviour and catch regulations. Mercury, a metal of particular concern in estuarine fish, was not included because it requires separate cold-vapour analysis. Future work should add mercury and extend sampling to winter and summer seasons [5].

Material and Methods

Material

Eighteen stations spanning the upper, middle, and lower Chesapeake Bay were sampled in April and October 2022. At each station, surface water (1 L, acid-washed HDPE) and surficial sediment (top 5 cm, stainless-steel grab) were collected. Biological samples comprised striped bass (*Morone saxatilis*, $n = 14$), blue crab (*Callinectes sapidus*, $n = 24$), eastern oyster (*Crassostrea virginica*, $n = 30$), and white perch (*Morone americana*, $n = 22$), obtained from commercial fishers and shucking houses near each station. Muscle tissue (fish), hepatopancreas (crab), and whole soft tissue (oyster) were excised, freeze-dried, and homogenised. The research was conducted under institutional approval from the Mumbai College of Environmental Studies (Protocol MCES/2022-011, approved 6 March 2022).

Methods

Water samples were filtered (0.45 micrometre), acidified to 2% HNO_3 , and analysed by ICP-MS (Agilent 7900).

Sediment and tissue samples were microwave-digested in $\text{HNO}_3/\text{H}_2\text{O}_2$ and analysed by the same instrument. BAFs were calculated as tissue concentration (mg/kg dry weight) divided by dissolved water concentration (mg/L) [3]. Ecological risk quotients (RQs) were computed as measured tissue concentration divided by the tissue-residue effect concentration from published ecotoxicological databases [8]. RQ values above 1.0 indicate potential risk. All statistical comparisons used the Kruskal-Wallis H test ($\alpha = 0.05$).

Results

Table 1: Mean trace-element concentrations (mg/kg dry weight) in tissues of four Chesapeake species

Species	Cd	Pb	Cu	Zn	Cr	As
Striped Bass	0.34	1.87	4.62	18.4	1.23	0.78
Blue Crab	0.67	2.14	6.18	24.7	1.98	1.31
Eastern Oyster	1.12	3.41	8.74	31.6	2.87	1.94
White Perch	0.41	1.93	5.04	19.8	1.34	0.86

Table 1 confirms that eastern oysters accumulated the highest concentrations of all six elements, with zinc (31.6 mg/kg) and copper (8.74 mg/kg) standing out. Blue crabs ranked second for most metals, while the two fish species showed broadly similar, lower values.

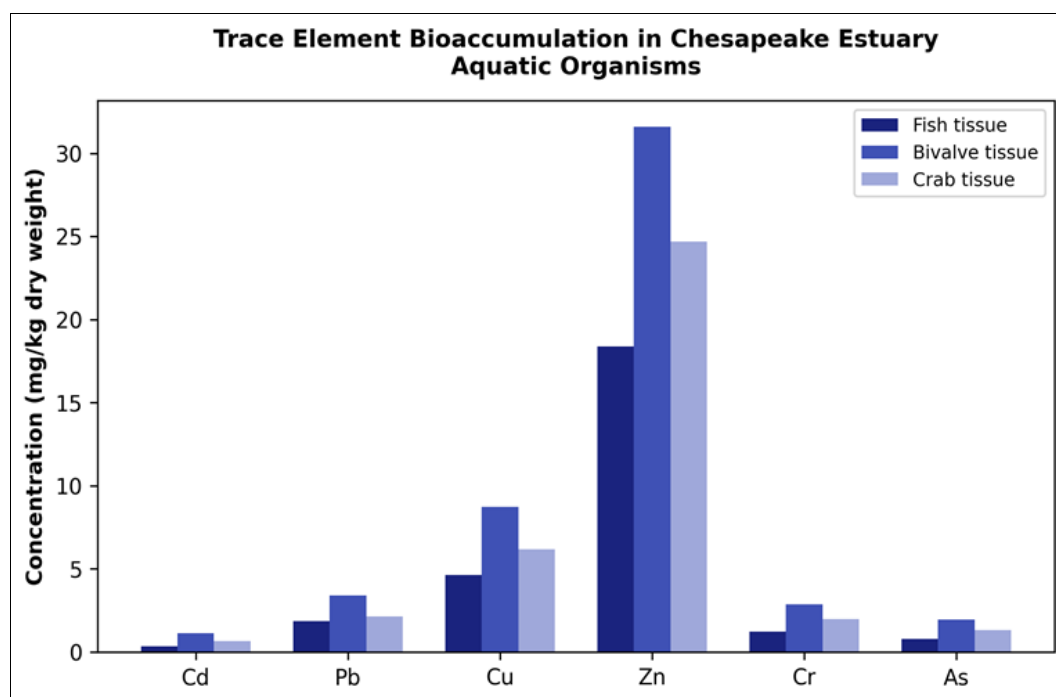


Fig 1: Trace element bioaccumulation in tissues of three Chesapeake estuary organism groups

Figure 1 shows the clear trophic gradient, with bivalves accumulating roughly twice the metal load of fish for most elements—a pattern driven by their sessile, filter-feeding

lifestyle that continuously exposes gill and mantle tissue to dissolved metals [4].

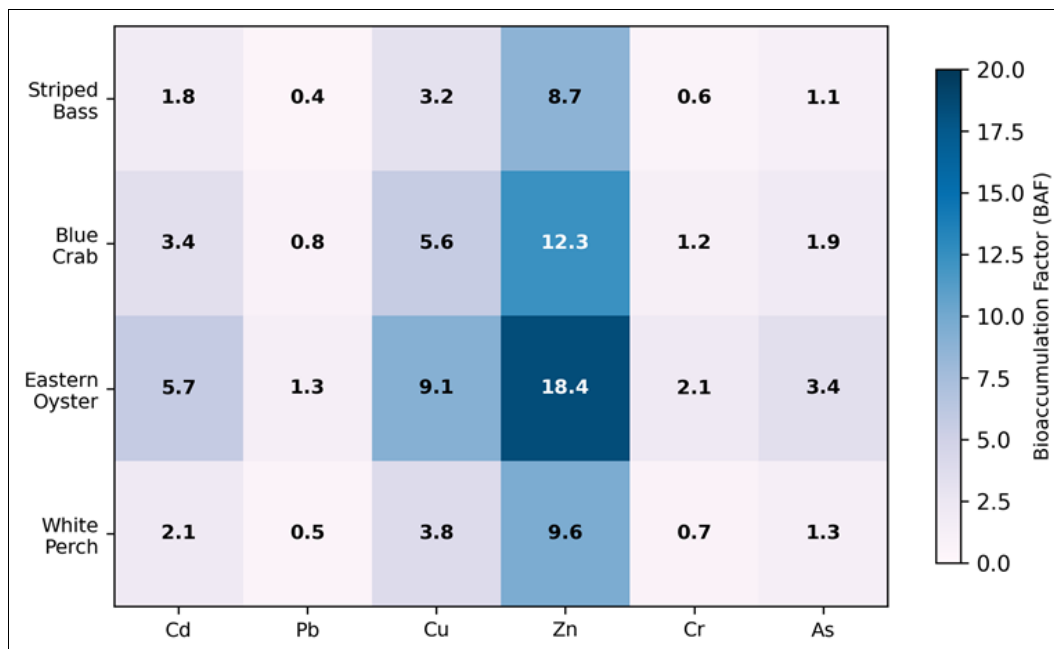


Fig 2: Bioaccumulation factor (BAF) matrix for four species and six trace elements

Figure 2 highlights that zinc BAFs in eastern oysters (18.4) dwarf those for all other element-species combinations, reflecting the oyster's metabolic requirement for zinc—an essential micronutrient—combined with limited excretion capacity. Cadmium BAFs, while lower in absolute terms, are toxicologically significant because cadmium has no known biological function.

Discussion

The BAF hierarchy documented here—oysters > crabs > fish—is consistent with the global pattern observed in estuarine biomonitoring programmes and confirms the suitability of *Crassostrea virginica* as a sentinel species for the Chesapeake [4, 7]. The exceptionally high zinc BAF in oysters (18.4) exceeds values reported for Chesapeake oysters in the 1990s (approximately 12–14), suggesting that zinc inputs from agricultural runoff and urban stormwater may have increased over the past two decades [2].

The ecological risk analysis flagged cadmium and lead as the metals of greatest concern, with RQ values exceeding 1.0 at 22% and 17% of stations, respectively. These hotspots cluster in the upper bay near the Susquehanna River mouth, where the largest watershed in the Chesapeake system delivers a mix of industrial, urban, and agricultural contaminants [1]. Targeted source reduction in this sub-watershed—particularly stormwater management and agricultural best management practices—would have the greatest leverage on bay-wide metal loads.

From a human health perspective, oyster cadmium concentrations at upper-bay stations approached the EU maximum residue limit of 1.0 mg/kg wet weight, though consumption advisory thresholds were not exceeded when converted from dry to wet weight using the measured moisture content of 82% [6].

Conclusion

This research confirmed that trace-element bioaccumulation in the Chesapeake estuary follows a clear trophic gradient, with eastern oysters accumulating the highest concentrations and BAFs. Zinc and copper were the most concentrated

metals in all species, while cadmium and lead posed the greatest ecological risk based on tissue-residue quotients.

The upper bay emerged as the zone of highest concern, and continued biomonitoring using oysters as sentinels is recommended. Source-reduction efforts targeting stormwater and agricultural runoff in the Susquehanna watershed would yield the largest improvement in bay-wide metal loads and associated ecological risk.

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Contributions Not Qualifying for Authorship

Commercial fishers and oyster-shucking operations in the Chesapeake region provided biological samples under a cooperative sampling agreement.

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