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REVIEW

Bioaccumulation of Selected Heavy Metals in Bivalve Molluscs from Northeastern Vietnam: Implications for Safe Seafood Utilization

Sinh Xuan Le [1*], ***Bach Van Nguyen*** [1], ***Hien Thi Minh Bui*** [1], ***Nam Van Le*** [1], ***Huy Van Dinh*** [2], ***Khuong Duy Le*** [3], ***Son Truong Cao*** [4], ***Kien Nguyen*** [5]

[1] *Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, Cau Giay District, Hanoi 100000, Vietnam*

[2] *Green Marine Environment Research Institute, Ngo Quyen District, Hai Phong 180000, Vietnam*

[3] *VNU School of Interdisciplinary Sciences and Arts, Vietnam National University, Hanoi 100000, Vietnam*

[4] *Faculty of Natural Resources and Environment, Vietnam National University of Agriculture, Gia Lam District, Hanoi 100000, Vietnam*

[5] *Viet Nam Environmental and Marine Sciences Institute, Ministry of Agriculture and Environment, Ha Dong District, Hanoi 100000, Vietnam*

ABSTRACT

Rapid industrial growth, urbanization, and agricultural activities have led to the discharge of large volumes of pollutants into coastal environments, raising levels of metals such as arsenic (As), cadmium (Cd), and mercury (Hg) in water and sediments. Bivalve molluscs, such as *Meretrix lyrata* and *Saccostrea glomerata* can accumulate high amounts of toxic heavy metals in their tissues that pose potential risks to human health. They are frequently used as bioindicators due to their filter-feeding behavior and high accumulation potential. This study evaluates heavy metal accumulation in bivalve molluscs from Northeastern Vietnam, including Quang Ninh Province and Hai Phong City. In this study, a systematic literature review was conducted, combined with a bibliometric analysis, to synthesize and evaluate data on heavy metal accumulation in bivalve molluscs from Northeastern Vietnam. The analysis results showed bio-concentration factors exceeding 1,000 for As, Cd, and Hg in certain species, particularly in samples from Quang Ninh Province. Meanwhile, sediment accumulation factors (BSAF) were lower, suggesting that waterborne pathways predominantly contribute to heavy metal uptake. These findings highlight significant food safety risks due to toxic metal accumulation in seafood resources, emphasizing the urgent need for continuous monitoring and the establishment of

*CORRESPONDING AUTHOR:
Sinh Xuan Le, Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, Cau Giay District, Hanoi 100000, Vietnam; Email: sinhlx@gmail.com

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local safety standards. The study provides important scientific evidence to support marine environmental management and public health protection.

Keywords: Heavy Metal Accumulation; Bivalve Molluscs; Coastal Pollution; Environmental Monitoring; Viet Nam

1. Introduction

In the current global context, rapid population growth combined with accelerated industrialization and urbanization has put immense pressure on natural resources, especially marine resources. Coastal areas, characterized by intensive industrial, transportation, and agricultural activities, continually receive large volumes of waste from various sources, leading to heavy metal accumulation in both water and sediments. Heavy metals (defined as metals and metalloids with densities above 5 g/cm^3) naturally occur in the lithosphere, and soil [1], and exist at varying concentrations within diverse ecosystems. However, anthropogenic activities, particularly stemming from urban, industrial, and agricultural sources, have significantly increased the concentration of both essential metals (such as Cu, Fe, Mn, Zn) and non-essential toxic metals (such as As, Cd, Hg, Pb) in the environment, causing serious concerns regarding environmental and public health impacts [2,3].

Due to increased heavy metal pollution, marine organisms, particularly bivalve molluscs such as oysters, clams, and mussels, face significant risks of toxin accumulation within their soft tissues. High bioaccumulation levels, often reaching concentrations 100 to 1000 times higher than those in surrounding waters, not only severely impact marine organism health but also pose a risk of toxin transfer through the food chain [4]. Therefore, bivalve molluscs are widely used as effective bioindicators of environmental pollution due to their ability to accumulate heavy metals in their tissues [5,6]. The concentrations of heavy metals in soft tissues serve as indicators of metal bioavailability and result from a complex interplay of geological, hydrological, physicochemical, and biological factors, including species-specific feeding behaviors and physiological characteristics [7]. Heavy metal concentrations in bivalves have been found to correlate strongly with those in water and sediments [8-10]. Given that bivalve molluscs constitute a major dietary component for coastal communities and represent an essential food resource globally, with annual production exceeding 15 million tons, their contamination not only threatens food safety but also directly affects food security and public health [11]. The close relationship between heavy metal pollution and seafood safety underscores the urgent need for environmental pollution monitoring and control. This is essential not only for protecting marine life from toxin accumulation but also for ensuring that seafood — a critical nutritional and economic resource for coastal communities —is maintained at safe and sustainable levels.

The accumulation of heavy metals in mollusc tissues can cause physiological disruptions such as inhibited growth, tissue damage, and metabolic disorders. Moreover, it can amplify toxicity through the food chain, thus threatening consumer health. Accumulation levels that exceed safety thresholds have been documented in numerous studies, highlighting the urgency of establishing food safety standards and implementing stringent environmental management measures [12]. Additionally, biological accumulation indicators such as the Bioconcentration Factor (BCF) and Biota-Sediment Accumulation Factor (BSAF) have been widely employed to elucidate heavy metal absorption mechanisms and their transport within mollusc species, providing essential scientific foundations for health risk assessments [13]. In particular, the elevated concentrations of heavy metals in molluscs have been linked to chronic health effects in humans, including neurotoxicity, kidney damage, and cancer. This highlights the need for continuous monitoring and more effective regulatory frameworks to limit pollutant exposure. Furthermore, applying bioindicator species, such as molluscs, in environmental monitoring programs offers valuable insights into the health of aquatic ecosystems, allowing for early detection of contamination levels and potential ecological risks. This comprehensive approach can inform policy-making and the development of effective mitigation strategies to safeguard both environmental and public health. A detailed summary of the major sources and documented health impacts of the selected heavy metals commonly studied in bivalve molluscs is provided in **Table 1**.

Table 1. Summary of sources and health impacts of selected heavy metals commonly studied in bivalve molluscs.

Metal	Major Sources	Health Effects
As	- **Natural sources**: Volcanic activity, mineral weathering. - **Anthropogenic sources**: Non-ferrous metal smelting, pesticide and herbicide manufacturing, ore mining, wood preservatives [14].	- Neurological impairment, blood cell abnormalities. - Chronic poisoning can cause skin diseases, lung diseases, hypertension, cardiovascular diseases, and diabetes [15].
Cd	- **Natural sources**: minerals such as greenockite (CdS). - **Anthropogenic sources**: Battery manufacturing, electroplating, fertilizers, and fossil fuel combustion.	- Kidney damage, anemia, bone marrow destruction, digestive dysfunction. - Acute poisoning can cause lung cancer and endocrine diseases [15].
Cu	- **Natural sources**: Dust intrusion, volcanic eruptions, forest fires, plant decomposition. - **Anthropogenic sources**: Metal production, iron casting, electricity generation, waste incineration, and electrical wires.	- Affects liver, kidneys, and brain, causing neurological disorders, stomach damage. - Copper deficiency also impedes growth and immune functions.
Hg	- **Natural sources**: Volcanoes, mineral decomposition, natural gas emissions. - **Anthropogenic sources**: Fossil fuel combustion, industrial production, medical - industrial equipment usage, and industrial discharge [16].	- Highly toxic methylmercury bioaccumulates through the food chain, damaging the nervous system, and especially dangerous for fetuses and children. - Mercury vapor and solution forms are easily inhaled, causing respiratory toxicity, affecting lungs, blood, and brain.
Pb	- **Natural sources**: Geological weathering, volcanic eruptions. - **Anthropogenic sources**: Mining, ore smelting, battery manufacturing, industrial waste treatment and transportation.	- Inhibits blood-synthesis enzymes, causing anemia and neurological issues. - Highly detrimental to children, causing neurological impairment, behavioral disorders, and physical growth retardation [17].
Zn	- **Natural sources**: Erosion, forest fires. - **Anthropogenic sources**: Mineral extraction, zinc production, zinc-containing fertilizers, and pesticides.	- Excess intake can cause vomiting, diarrhea, headaches, and digestive disorders. - Long-term poisoning leads to mineral imbalance, immune dysfunction, and anemia.

In Northeastern Vietnam, specifically in Quang Ninh Province and Hai Phong City, explosive industrial deve-lopment, maritime transport, and urbanization have exerted substantial environmental pressures. Toxic pollutants from terrestrial sources are discharged via river mouths such as Bach Dang, Van Uc, and Luc, significantly increasing heavy metal concentrations in coastal waters and sediments [18]. These pollutants, due to their persistence and high accumulation potential, severely degrade environmental quality and impact coastal ecosystems, notably affecting seafood species such as bivalve molluscs. In the study area, many of these bivalves, which are significant for both local ecology and aquaculture economies, are cultivated using diverse methods; for instance, species like clams (*Meretrix lyrata, Anadara granosa*) and rock oyster (*Saccostrea glomerata*) are often grown via bottom culture techniques directly on or in the sediment, whereas oysters (*Crassostrea spp.*) and mussels (*Perna viridis*) are frequently farmed using off-bottom systems (e.g., racks, longlines) suspended in the water column. Such distinct cultivation practices inherently modulate the organisms' primary exposure pathways to contaminants, influencing whether they predominantly interact with metals in the sediment or those dissolved or suspended in the surrounding water. Research has shown that, particularly in estuarine areas adjacent to industrial zones, heavy metal accumulation in marine organisms frequently exceeds safety limits, raising serious public health concerns and necessitating effective pollutant monitoring and control measures to protect food safety and the living environments of coastal communities [18].

Building on a synthesis of previously published research, this paper aims to comprehensively evaluate the bioaccumulation of selected heavy metals in bivalve molluscs from Northeastern Vietnam. Consequently, this study not only provides scientific evidence for establishing food safety standards but also proposes strategic solutions for safe seafood utilization to protect public health and sustain marine ecosystem integrity amid current economic integration and climate change conditions.

The issue of heavy metal accumulation in marine organisms has drawn extensive scientific attention due to its potential consequences for both the environment and human health. Many heavy metals such as Pb, Hg, and Cd are persistent, non-biodegradable, and capable of bioaccumulating through the food chain, negatively impacting biodiversity and reducing the quality of marine food resources. This accumulation process is influenced not only by natural sources of pollution such as mineral weathering, erosion, volcanic activity, and forest fires but also by anthropogenic sources including industrial discharge, urbanization, transportation, mineral extraction, and agriculture. The interactions between the physical and chemical properties of the environment and living organisms manifest through biological indicators such as community structure fluctuations, mortality rates, physiological and behavioral changes, and the progressive accumulation of toxic substances in organism tissues [19]. Indicator species, particularly bivalve molluscs, are selected based on criteria such as ease of identification, high bioaccumulation capacity without causing mortality, stable presence in study areas, and a direct correlation between the organism's contamination level and the level of environmental pollution.

The toxicity level of heavy metals to marine orga-nisms and humans depends on several critical factors [20]. Firstly, the chemical form of heavy metals in the environment — from mobile forms to those bound with organic compounds or present in precipitated forms — determines their bioavailability and uptake rates into organisms. Environmental factors such as temperature, pH, salinity, and dissolved oxygen further regulate metabolic processes and absorption capacity, thereby influencing metal toxicity. Moreover, the physiological characteristics of organisms, including age, gender, nutritional status, reproductive stage, and adaptive detoxification mechanisms, significantly contribute to bioaccumulation and determine toxicity levels. According to Ansari et al. (2004), the toxicity of heavy metals peaks when they exist in mobile forms that are easily absorbed and magnified across trophic levels within the food chain [20]. This highlights the necessity of thoroughly understanding the interactions between environmental factors and organism physiology to accurately evaluate the impacts of heavy metals on ecosystems and human health. Key factors influencing toxicity include the chemical form of metals, environmental conditions, and the physiological state of organisms. For example, metals in mobile forms, such as free ions, are more toxic than those bound in stable complexes, as they are more readily absorbed by organisms. Environmental conditions such as temperature, pH, salinity, and dissolved oxygen can also influence the uptake and toxicity of heavy metals. Additionally, the sensitivity of organisms varies based on factors like age, gender, and nutritional status. Many organisms have evolved mechanisms to cope with metal exposure, such as sequestering metals in specific cells or binding them to proteins like metallothioneins, which help mitigate their toxic effects. Overall, the toxicity of heavy metals peaks when they are in a mobile state, making it essential to consider these factors in risk assessments.

2. Materials and Methods

2.1. Data Collection

This study employed a systematic literature review to comprehensively evaluate heavy metal bioaccumulation in bivalve molluscs from Northeastern Vietnam and its implications for safe seafood utilization. Literature searches were conducted across major scientific databases, including Google Scholar (https://scholar.google.com), Scopus (https://www.scopus.com), PubMed (https://pubmed.ncbi.nlm.nih.gov), ResearchGate (https://www.researchgate.net/), and other relevant online sources.

Search queries combined terms related to "heavy metals", "trace elements", "bivalve" "molluscs", "bioaccumulation", "concentration", "Quang Ninh", "Hai Phong", "Northeastern Vietnam" and "seafood safety". Studies were included if they reported primary data on heavy metal concentrations or bioaccumulation in bivalve molluscs sampled from coastal areas within Northeastern Vietnam (i.e., Quang Ninh province and Hai Phong city). No language restrictions were applied during the retrieval process. Also, exclusion criteria were applied to review articles, theoretical papers, theses and studies conducted outside the defined geographical scope.

Key information extracted from selected studies comprised mollusc species, sampling location, heavy metal concentrations (i.e., As, Cd, Cu, Hg, Pb, Zn), sampling year, and reported health risk assessments or ecological implications. This data was then synthesized to identify bioaccumulation trends, assess associated risks, and formulate informed recommendations for safe seafood utilization.

2.2. Data Analysis

The retrieved data were exported and subsequently transformed into the necessary analytical format. The data retrieval and download date for this project occurred on December 10, 2024. To facilitate a thorough examination of the dataset, VOSviewer (version 1.6.20) was em-ployed [21]. The analysis centered on the construction of co-authorship networks and the investigation of term co-occurrence patterns. This approach allowed the identification of key collaborations and thematic relationships within the dataset, yielding insights into the research landscape surrounding bivalve mollusc bioac-cumulation and associated heavy metals, specifically in the coastal regions of Northeastern Vietnam, including Quang Ninh and Hai Phong.

3. Results and Discussion

3.1. Results of Bibliometric Analysis

The author cluster analysis performed using VOSviewer reveals distinct collaborative networks among researchers examining the bioaccumulation of heavy metals in bivalve molluscs from Northeastern Vietnam (**Figure 1A**). The largest cluster, depicted in yellow, demonstrates extensive collaboration and frequent co-authorship among numerous authors, reflecting a robust research network in this domain. Prominently, clusters focused around "sinh le xuan" (blue cluster) and "dung lq" (purple cluster) emphasize significant individual contributions and active research collaborations, albeit smaller in size. These findings highlight both collective endeavors and individual impacts within the field, implying that enhanced collaboration among these clusters could potentially foster research efforts in ensuring seafood safety in the study region.

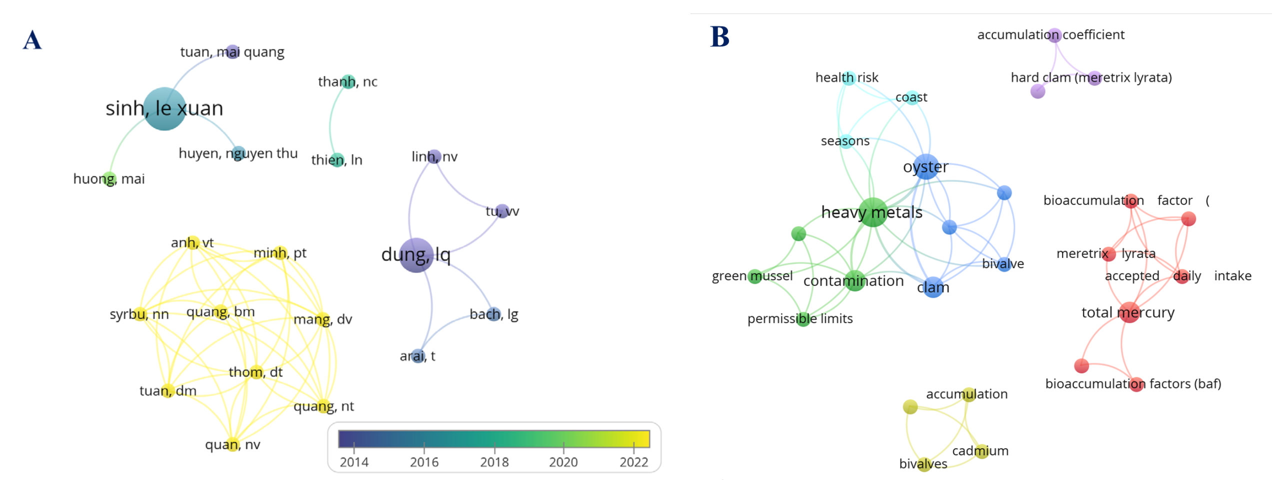

Figure 1. Bibliometric Analysis on Heavy Metal Concentrations in Bivalve Molluscs from Northeastern Vietnam. (**A**) Author cluster analysis. (**B**) Keyword cluster analysis.
Artwork generated with VOSviewer (Van Eck & Waltman, 2010).

The bibliometric analysis delineates six principal thematic clusters concerning heavy metal accumulation in bivalve molluscs from Northeastern Vietnam (**Figure 1B**). The green, blue, and light blue clusters are closely interconnected. The green cluster centers on pollution levels and permissible limits for heavy metals, particularly in key bioindicator species like green mussels. Meanwhile, the blue cluster emphasizes the ecological role of major bivalve species, such as oysters and clams, in monitoring coastal contamination. The light blue cluster addresses the impact of seasonal variations on heavy metal accumulation in bioindicator species in coastal areas, indicating varying health risks associated with these fluctuations. In contrast, the red, yellow, and purple clusters concentrate on distinct aspects of metal accumulation. The red cluster focuses on bioaccumulation coefficients and mercury content, clarifying health implications for the consumption of *Meretrix lyrata*, a common clam in the study area. Lastly, the yellow and purple clusters jointly investigate the technical aspects of metal accumulation, with particular attention to cadmium across various bivalve species, highlighting distinctive accumulation coefficients in hard clams. The six aforementioned clusters collectively offer a comprehensive overview of heavy metal pollution in marine bivalves, underscoring the critical need for targeted environmental monitoring and improved seafood safety practices in Northeastern Vietnam.

3.2. Concentrations of Selected Heavy Metals in Bivalve Molluscs

Table 2 summarizes the concentrations of selected heavy metals in common bivalve molluscs collected from Northeastern Vietnam between 2011 and 2022. These data illustrate the variability of metal accumulation levels across different regions and periods, providing essential insights into pollution risks concerning seafood resources and public health. For the purpose of standardizing units for comparison among studies, some data have been converted from mg/kg wet weight to mg/kg dry weight, assuming a moisture content of 80%, based on previous research [22,23].

Table 2. Concentrations of selected heavy metals in bivalve molluscs from coastal waters of Northeastern Vietnam during the period 2011–2022.

Sample Times	Location	Species	As	Cd	Cu	Hg	Pb	Zn	Reference
I. Northeastern Coastal Waters of Vietnam									
Apr. - Dec. 2021	Van Don, Quang Ninh	*Meretrix lyrata*	18.60	0.75	-	1.50	0.55	-	* [4]
2012-2017	Do Son, Hai Phong	*Meretrix lyrata*	-	-	-	0.078 – 0.085	-	-	[24]
2012	Kien Thuy, Hai Phong	*Meretrix lyrata*	11.54	1.15	10.57	-	1.08	58.18	[25]
2014	Cat Hai, Hai Phong	*Meretrix lyrata*	-	-	-	0.09	-	-	[26]
2012	Cat Ba, Hai Phong	*Meretrix lyrata*	10.65	0.78	13.14	-	1.31	60.14	[25]
Apr. - Dec. 2021	Cat Ba, Hai Phong	*Meretrix lyrata*	9.45	0.90	-	0.3	2.5	-	* [4]

Table 2. *Cont.*

Sample Times	Location	Species	As	Cd	Cu	Hg	Pb	Zn	Reference
Apr. - Dec. 2021	Van Don, Quang Ninh	*Saccostrea glomerata*	7.80	2.25	-	0.85	0.60	-	* [4]
2013	Ha Long, Quang Ninh		17.68	5.00	408.05	-	1.29	1,591.15	[27]
2012	Dinh Vu, Hai Phong		11.8	9.4	980	-	3.5	1,826	[28]
2013			11.63	10.71	1,065.3	-	4.22	2,365.4	[27]
2012	Do Son, Hai Phong		13.3	12.2	1,009	-	1.6	1,715	[28]
2012			11.98	5.85	654.9	-	1.36	902.1	[25]
2013			10.21	9.63	687.2	-	1.39	1,210.95	[27]
2012	Tien Lang, Hai Phong		11.0	5.8	507	-	1.9	1,004	[28]
2012	Cat Ba, Hai Phong		28.58	4.58	478.3	-	1.23	885.3	[25]
2013			10.41	6.07	636.05	-	1.80	1,158.75	[27]
Apr.-Dec. 2021			8.20	1.35	-	0.45	0.80	-	* [4]
2011	Quang Yen, Quang Ninh	*Austriella corrugata*	0.30	-	-	-	-	-	[28]
2014			-	-	-	0.43 ± 0.05	-	-	[26]
2011	Quang Yen, Quang Ninh	*Anadara granosa*	0.12	-	-	-	-	-	[29]
2014			-	-	-	0.11 ± 0.03	-	-	[26]
2011	Cat Ba, Hai Phong	*Lutraria rhynchaena*	0.05	-	-	-	-	-	[29]
2014			-	-	-	0.03	-	-	[26]
2012	Do Son, Hai Phong	*Perna viridis*	11.7	1.1	17.8	-	4.5	105	[28]
2012	Van Don, Quang Ninh	*Mimachlamys nobilis*	-	1.51	-	-	-	-	* [30]
		Paphia undulata	-	0.56	-	-	-	-	
		Anadara subcrenata	-	1.06	-	-	-	-	

Table 2. *Cont.*

Sample Times	Location	Species	As	Cd	Cu	Hg	Pb	Zn	Reference
2022	Quang Yen, Quang Ninh	*Crassostrea* spp.	4.15	2.55	46.2	-	2.00	108.05	* [31]
II. Other Areas in Vietnam and around the World									
Sep. 2003 - Nov. 2007	Nha Phu Bay, Khanh Hoa, Vietnam	*Meretrix meretrix*	13	0.7	7.2	<0.05	0.7	81.5	[32]
	Van Phong Bay, Khanh Hoa, Vietnam		19	0.3	20.4		1.3	239	
	Can Gio, Hochiminh City, Vietnam	*Meretrix lyrata*	8.4	0.9	7.7		0.3	81.3	
	Tan Thanh, Ba Ria Vung Tau, Vietnam		7.2	1.1	5.9		0.2	87.0	
	Can Duoc, Long An, Vietnam		6.2	0.4	5.5		0.2	59.3	
	Go Cong, Tien Giang, Vietnam		4.6	1.7	6.2		0.2	113	
	Binh Dai, Ben Tre, Vietnam		8.8	1.0	6.8		0.2	70.6	
	Duyen Hai, Tra Vinh, Vietnam		8.5	1.7	11.0		0.7	84.4	
	Vinh Chau, Soc Trang, Vietnam		8.4	1.2	6.9		0.4	60.3	
	Nha Mat, Bac Lieu, Vietnam		5.5	1.7	6.0		0.2	103	
	Ward 7 Market, Ca Mau, Vietnam		5.4	1.5	5.5		0.2	98.6	

Table 2. *Cont.*

Sample Times	Location	Species	As	Cd	Cu	Hg	Pb	Zn	Reference
Aug. 2012 – Mar. 2013	Thuan An, Thua Thien Hue, Vietnam	*Saccostrea sp.*	-	10.80	-	1.85	13.20	-	* [33]
	Han river, Da Nang, Vietnam		-	9.70	-	1.50	12.85	-	
	Cua Dai, Quang Nam, Vietnam		-	11.70	-	0.85	6.55	-	
	Sa Can, Quang Ngai, Vietnam		-	10.60	-	1.10	12.55	-	
	Con river, Binh Dinh, Vietnam		-	9.80	-	1.00	12.75	-	
	Thuan An, Thua Thien Hue, Vietnam	*Meretrix meretrix*	-	7.25	-	1.65	17.25	-	
	Han river, Da Nang, Vietnam		-	7.20	-	1.65	12.75	-	
	Con river, Binh Dinh, Vietnam		-	7.45	-	0.95	12.80	-	
	Thuan An, Thua Thien Hue, Vietnam	*Corbicula subsulcata*	-	8.35	-	1.90	15.50	-	
	Cua Dai, Quang Nam, Vietnam		-	9.80	-	1.10	13.40	-	
	Sa Can, Quang Ngai, Vietnam		-	11.25	-	1.00	14.55	-	
2015	Can Gio, Ho Chi Minh city, Vietnam	*Crassostrea belcheri*	7.00	2.40	65.50	0.50	3.45	524.00	* [34]
2015	Gianh river, Quang Binh, Vietnam	*Crassostrea rivularis*	-	-	-	-	-	872.5	* [35]
N/A	Likas estuary, Malaysia	*Meretrix meretrix*	-	3.27	6.62	-	1.72	106.7	[36]
	Kota Belud estuary, Malaysia		-	1.68	5.78	-	1.09	83.1	
	Likas estuary, Malaysia	*Anadara granosa*	-	0.63	6.89	-	4.74	96.0	
		Crassostrea iredalei	-	0.68	13.22	-	4.61	397.2	
2011	Laizhou Bay, China	*Scapharca subcrenata*	15.20	6.50	5.85	0.05	0.50	87.65	* [37]
		Mactra veneriformis	5.80	1.10	5.55	0.03	1.05	49.45	
		Ruditapes philippinarum	15.40	1.30	8.90	0.05	1.10	106.75	

Unit: mg/kg d.w.

Note: d.w: dry weight; "-": Not Available; "*": Converted from wet weight (mg/kg w.w) to dry weight (mg/kg d.w) based on an assumed moisture content of 80%.

3.2.1. In the Northeastern Vietnam

Table 2 provides comprehensive data on the con-cen-trations of various heavy metals in bivalve molluscs from Northeastern Vietnam, collected between 2011 and 2022. The results demonstrate differences in metal accu-mulation levels in different bivalve molluscs sampled from diff-erent locations during different periods. However, no consistent temporal trend in annual metal concentra-tions within the same bivalve species at a single sampling lo-cation was discernible. Derived from data in **Table 2**, **Figure 2** provides a detailed analysis of heavy metal con-centrations in bivalve molluscs from Northeastern Viet-nam, highlighting significant variability across species and regions. Copper (Cu) and zinc (Zn) have the highest con-centrations, far exceeding those of other metals. This pat-tern indicates substantial spatial variability, likely due to industrial pollution or localized point sources, and reflects the naturally higher seawater concentrations of Cu and Zn compared to trace metals like arsenic (As), cadmium (Cd), and lead (Pb). The wide interquartile range for As and Cd suggests diverse contamination sources within the study area. Conversely, mercury (Hg) and Pb exhibit consistent-ly low levels, implying a uniform distribution in the study area. The presence of outliers, particularly for As and Pb, suggests sporadic contamination or species-specific accu-mulation patterns. These insights underscore the impor-tance of targeted environmental monitoring to identify pollution sources and ensure the protection of marine eco-systems and seafood quality.

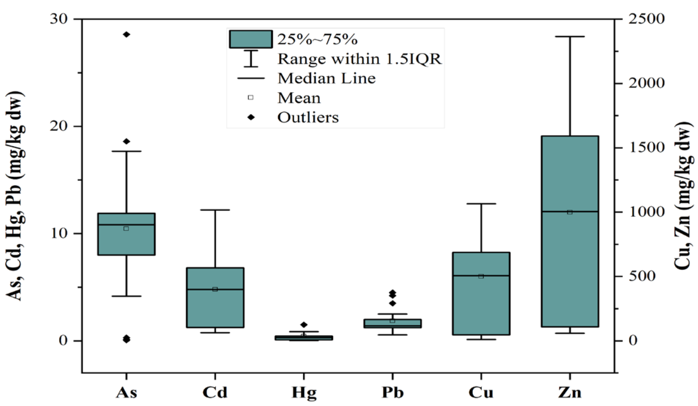

Figure 2. Heavy metal concentrations in bivalve molluscs from coastal waters of Northeastern Vietnam during the peri-od 2011–2022.

To provide a broad overview of the heavy metal con-centrations in bivalve mollusc samples across various locations in Quang Ninh Province and Hai Phong City, a radar diagram was constructed, offering a comprehensive comparative analysis that highlights significant regional dis-parities in Northeastern Vietnam (**Figure 3**). The diagram illustrates variations in As, Cd, Hg, and Pb concentrations, with Cat Ba displaying the highest level of arsenic (28.58 mg/kg dw) in *Saccostrea glomerata* samples, indicating lo-calized contamination possibly linked to industrial discharg-es or natural geological influences (**Figure 3A**) [25]. Cadmi-um levels are notably elevated in Do Son at 12.2 mg/kg in samples of *Saccostrea glomerata*, indicating potential indus-trial impact as well as contributions from maritime traffic activities [28]. Conversely, mercury and lead exhibit consis-tently low levels across most locations, with the highest con-centrations detected in Van Don, Quang Ninh, and Do Son, Hai Phong, at 1.50 mg/kg dw in clam (*Meretrix lyrata*) sam-ples and 4.50 mg/kg dw in mussel (*Perna viridis*) samples, respectively [4,28]. In terms of copper and zinc, Dinh Vu ex-hibits significantly higher concentrations in bivalve mollusc samples, specifically in *Saccostrea glomerata*, compared to other areas, at 1,065.3 mg/kg dw and 2,365.4 mg/kg dw, respectively (**Figure 3B**) [27]. This pronounced enrichment is likely attributable to the combined influence of rapid industrial activities, extensive port construction and maritime operations, and intensive agricultural practices in the Dinh Vu area. These variations suggest that specific environmental factors and industrial activities contribute to the differences observed. The marked regional disparities imply a pressing need for tailored environmental strategies and interventions to mitigate pollution sources. Continuous, site-specific monitoring is essential to protect the marine ecosystem, ensuring sustainable seafood safety and public health. Such efforts would help identify pollutant sources and facilitate effective management policies to safeguard the ecological balance of these coastal regions.

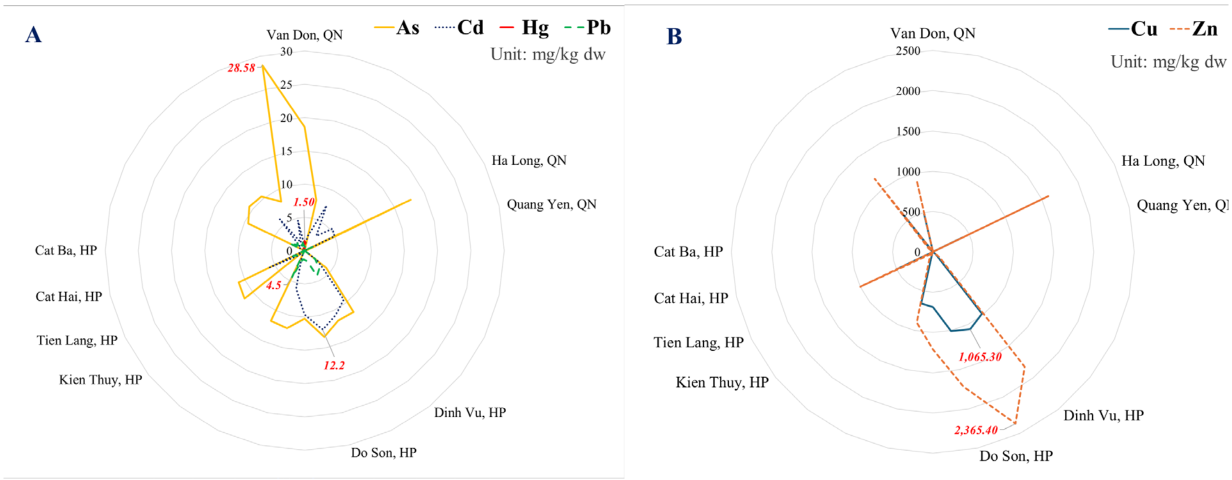

Figure 3. Comparison of Heavy metal concentrations in bivalve molluscs from different locations. (A) As, Cd, Hg and Pb. (B) Cu and Zn.

3.2.2. In Other Areas in Vietnam and around the World

The analysis of heavy metal concentrations in bivalve mollusks from various regions outside northeastern Vietnam reveals significant variations in contamination levels. The highest arsenic concentration was detected in *Meretrix meretrix* from Van Phong Bay, Khanh Hoa, at 19.0 mg/kg dw [32]. Cadmium accumulation was most pronounced in *Saccostrea sp.* collected from Cua Dai, Quang Nam, reaching 11.7 mg/kg dw. In *Crassostrea belcheri* from Can Gio, Ho Chi Minh, a substantial copper concentration was observed at 65.50 mg/kg dw [34]. Notably, the mercury content in *Corbicula subsulcata* from Thuan An, Thua Thien Hue, was the highest at 1.90 mg/kg dw [33]. *Meretrix meretrix*, also from Thuan An, recorded the peak lead level of 17.25 mg/kg dw [33]. Meanwhile, *Crassostrea rivularis* from the Gianh River, Quang Binh, exhibited an exceptional zinc concentration at 872.5 mg/kg dw [35]. This variation across species and locations under-scores the significant impact of environmental factors, such as pollution sources and species-specific uptake mechanisms, on metal accumulation. Regions like Khanh Hoa, Thua Thien Hue, and Quang Binh demonstrate higher contamination levels, potentially due to industrial activities, aquaculture, or urban runoff. These findings highlight the importance of ongoing monitoring of heavy metal pollution in coastal environments, particularly in areas with high seafood consumption, to assess ecological risks and ensure food safety.

Heavy metal accumulation in bivalve mollusks from China and Malaysia generally appears lower than in the northeastern coastal waters of Vietnam, with some exceptions. In Malaysia, *Crassostrea iredalei* showed notable Cu (13.22 mg/kg d.w) and Zn (397.2 mg/kg d.w) concentrations, but these values remain significantly lower than the highest Cu (1,065.3 mg/kg d.w) and Zn (2,365.4 mg/kg d.w) levels reported in Vietnam's Dinh Vu samples (*Saccostrea glomerata*) [27,36], possibly due to differences in environmental characteristics or the bioaccumulation capacities of the respective species. Cd levels in Malaysian bivalves, such as *Meretrix meretrix* (3.27 mg/kg d.w) were also much lower compared to the extreme values recorded in Do Son, Hai Phong, Vietnam (12.2 mg/kg d.w in *Saccostrea glomerata* sample) [28,36]. Contrary to other metals, Pb levels in bivalve mollusc samples from Malaysia reached 4.74 mg/kg d.w in *Anadara granosa*, slightly higher than the highest recorded levels in the study area of northeastern Vietnam, which were 4.5 mg/kg w.w in *Perna viridis* from Do So, Hai Phong [28,36].

In China, the highest concentrations of six heavy metals in bivalve molluscs from Laizhou Bay were all lower than the maximum values recorded in samples from northeastern Vietnam. The most significant differences were observed for copper and mercury, with the highest levels found in Laizhou Bay being 8.90 mg/kg d.w and 0.05 mg/kg d.w in *Ruditapes philippinarum*, which are significantly lower than the maximum levels in northeastern Vietnam, specifically 1,065.3 mg/kg d.w in *Saccostrea glomerata* and 1.5 mg/kg d.w in *Meretrix lyrata* [4,27,37]. These comparisons suggest that the northeastern coastal waters of Vietnam experience greater heavy metal contamination, likely due to higher industrial activity and environmental pollution.

Comparing heavy metal accumulation levels in bivalve molluscs (presented in **Table 2**) with established safety thresholds (as shown in **Table 3**) reveals that certain samples from Northeastern Vietnam exceed permissible limits set by several countries. For instance, cadmium (Cd) levels measured in many mollusc samples, particularly in *Saccostrea glomerata*, surpass the allowable limit of 2.0 mg/kg dry weight specified by Vietnam's QCVN 8-2:2011/BYT standard, emphasizing the significant health risks associated with Cd exposure and the urgent need for stricter regulatory measures to manage and mitigate this contamination in local seafood. However, these levels remain lower than the permissible limit of 25.0 mg/kg dry weight set by the United States (Food and Drug Administration of the United States - USFDA). Regarding Pb, when compared to Vietnam's current regulation of 1.5 mg/kg d.w, many samples exceed the permissible limit, notably *Meretrix lyrata* from Cat Ba (2.5 mg/kg d.w), *Saccostrea glomerata* from Dinh Vu (3.5 and 4.22 mg/kg d.w), and *Perna viridis* from Do Son (4.5 mg/kg d.w). However, compared to the permissible limits of Thailand (6.67 mg/kg d.w), Brazil (10.0 mg/kg d.w), and the US (11.5 mg/kg d.w), the Pb values in bivalve molluscs from the study area remain within safe limits. These differences underscore the variability in international safety standards, highlighting the critical need for continuous monitoring and the establishment of locally appropriate standards to protect public health and ensure the safety of seafood resources.

Table 3. Maximum permissible levels of heavy metals in bivalve mollusc foods by different countries/organizations (in mg/kg dry weight).

Country/Agencies	As	Cd	Cu	Hg	Pb	Zn
QCVN 8-2:2011/BYT, Vietnam [38]	-	2.0	-	0.5	1.5	-
Ministry of Public Health, Thailand (MPHT, 1986) [39]	-	-	133.0	0.5	6.67	667.0
AU/NZ* [40]	5.0**	10.0	-	2.5	10.0	-
Brazilian Ministry of Health (ABIA, 1991) [41]	-	5.0	150.0	-	10.0	250.0
Food and Drug Administration of the United States (USFDA, 1990) [42]	-	25.0	-	-	11.5	-
EU* [43]	-	5.0	-	2.5	7.5	-
FAO* [44]	-	5.0	-	2.5	5.0	-

Note: "*": Converted from wet weight (mg/kg w.w) to dry weight (mg/kg d.w) based on an assumed moisture content of 80%.; "**": Inorganic arsenic.

3.3. Biological Accumulation Factors for Selected Heavy Metals in Bivalve Molluscs

Table 4 below presents the Bioconcentration Factor (BCF) and Biota-Sediment Accumulation Factor (BSAF) values for selected heavy metals in bivalve molluscs collected from Northeastern Vietnam and other regions worldwide.

These data provide a scientific basis for comparing heavy metal accumulation levels and for evaluating the potential of molluscs as bioindicators reflecting environmental pollution levels.

Table 4. Biological accumulation factors of heavy metals in bivalve molluscs collected from coastal areas of Northeastern Vietnam from 2011–2022.

Location	Species	As	Cd	Cu	Hg	Pb	Zn	Reference
I. BCF								
1. Northeastern coastal waters of Vietnam								
Van Don, Quang Ninh	*Meretrix lyrata*	>750	>250	-	>1,300	-	-	[4]
Cat Ba, Hai Phong	*Meretrix lyrata*	~1,000	>300	-	>250	>500	-	[4]
Cat Hai, Hai Phong	*Meretrix lyrata*	-	-	-	333	-	-	[26]
Cat Hai, Hai Phong	*Meretrix lyrata*	-	-	-	20.5-303.2	-	-	[24]
Cat Hai, Hai Phong	*Meretrix lyrata*	-	-	-	21-307	-	-	[45]
Cat Ba, Hai Phong	*Saccostrea glomerata*	>800	>600	-	>450	>150	-	[4]
Van Don, Quang Ninh	*Saccostrea glomerata*	>1,900	>750	-	>750	-	-	[4]
Quang Yen, Quang Ninh	*Austriella corrugata*	83	-	-	-	-	-	[29]
Quang Yen, Quang Ninh	*Austriella corrugata*	-	-	-	1,344	-	-	[26]
Quang Yen, Quang Ninh	*Anadara granosa*	35	-	-	-	-	-	[29]
Quang Yen, Quang Ninh	*Anadara granosa*	-	-	-	344	-	-	[26]
Cat Ba, Hai Phong	*Lutraria rhynchaena*	26	-	-	-	-	-	[29]
Cat Ba, Hai Phong	*Lutraria rhynchaena*	-	-	-	158	-	-	[26]
Quang Yen, Quang Ninh	*Crassostrea spp.*	255	1,536	269	-	62	452	[31]
2. Other areas in Vietnam and around the world								
Gianh river, Quang Binh, Vietnam	*Crassostrea rivularis*	-	-	-	-	-	72.96-139.76	[35]
Likas estuary, Malaysia	*Meretrix meretrix*	-	550	160	-	17	2,500	[36]
Kota Belud estuary, Malaysia	*Meretrix meretrix*	-	420	440	-	110	2,700	[36]
Likas estuary, Malaysia	*Anadara granosa*	-	100	160	-	47	2,200	[36]
Likas estuary, Malaysia	*Crassostrea iredalei*	-	110	310	-	46	9,200	[36]
II. BSAF								
1. Northeastern Vietnam								
Cat Hai, Hai Phong	*Meretrix lyrata*	-	-	-	0.003	-	-	[18]
Quang Yen, Quang Ninh	*Anadara granosa*	31	-	-	-	-	-	[29]
Quang Yen, Quang Ninh	*Austriella corrugata*	49	-	-	-	-	-	[29]
Cat Ba, Hai Phong	*Lutraria rhynchaena*	-	-	-	-	-	-	[29]
Quang Yen, Quang Ninh	*Crassostrea spp.*	0.6	6.9	2.1	-	0.1	3.9	[31]
2. Other areas in Vietnam and around the world								
Likas estuary, Malaysia	*Meretrix meretrix*	-	0.8	0.1	-	0.1	0.3	[36]
Kota Belud estuary, Malaysia	*Meretrix meretrix*	-	4.2	0.1	-	0.1	0.6	[36]
Likas estuary, Malaysia	*Anadara granosa*	-	0.2	0.1	-	0.2	0.3	[36]
Likas estuary, Malaysia	*Crassostrea iredalei*	-	0.2	0.2	-	0.2	1.1	[36]
Laizhou Bay, China	*Scapharca subcrenata*	2.18	58.26	0.47	3.09	0.02	2.05	[37]
Laizhou Bay, China	*Mactra veneriformis*	1.20	14.34	0.64	4.53	0.09	1.73	[37]
Laizhou Bay, China	*Ruditapes philippinarum*	3.19	13.47	0.94	4.25	0.07	3.28	[37]

Regarding Bioconcentration Factor (BCF): The reported values for bioconcentration factors (BCF) in bivalve species from Northeastern Vietnam showed significant variability in the accumulation potential of heavy metals, reflecting biological differences among species and local environmental conditions. Samples from Van Don (Quang Ninh province) and Cat Ba (Hai Phong city) demonstrated notably high BCF values for arsenic (As), reaching the highest value of more than 1,900, indicating substantial absorption and accumulation of As within mollusc tissues [4]. For cadmium (Cd), BCF values surpassing 250 were observed in several samples, especially in *Crassostrea spp*. from Quang Yen, Quang Ninh, with the highest BCF reaching 1,536, indicating a bioaccumulation capacity classified by Arnot & Gobas (2006) within the range of 1,000 to 5,000 [46]. Samples collected from Quang Ninh, including species such as *Meretrix lyrata* and *Austriella corrugata*, exhibited elevated Hg bio-accumulation primarily driven by exposure to contaminated water, as evidenced by BCF values exceeding 1,300 [4,26]. In terms of Cu and Zn, studies evaluating BCF values in bivalve mollusk species within the study area remain limited. Specifically, in *Crassostrea spp*. samples collected from Quang Yen, Quang Ninh, BCF values reached 269 for Cu and 452 for Zn, suggesting a relatively low level of bioaccumulation for these metals [31]. These figures reflect species-specific differences in uptake mechanisms and accumulation efficiency, as well as the influence of environmental factors such as pollution sources and water characteristics. Interestingly, no clear trend emerges in BCF values when comparing bivalves cultured using sediment-exposure techniques (e.g., *Meretrix lyrata*, *Austriella corrugata*, *Anadara granosa*) with those utilizing non-sediment-contact methods (e.g., *Lutraria rhynchaena*, *Crassostrea spp*.). Collectively, high BCF values for As, Cd, and Hg in the studied locations confirm the potential of bivalve molluscs as bioindicators of heavy metal pollution in areas affected by anthropogenic activities, particularly industrial development, highlighting the importance of continuous monitoring programs to safeguard seafood resources and public health.

The variation in BCF values among different species and sampling locations underscores the complexity of metal bioaccumulation dynamics in bivalve molluscs. The exceptionally high BCF values for As, Cd, and Hg in several species from Northeastern Vietnam suggest prolonged exposure to significant contamination sources, likely stemming from industrial discharge, mining activities, and urban runoff. These elevated BCF values highlight the efficiency of certain bivalve species, such as *Crassostrea spp*., *Saccostrea glomerata*, and *Meretrix lyrata*, in accumulating metals from the water column, making them particularly suitable as biomonitoring organisms. Furthermore, the considerable variability observed in Cu, Pb and Zn accumulation may reflect differences in the bioavailability of these essential metals, which are subject to biological regulation in molluscs. The disparity in metal accumulation patterns also suggests that environmental factors, including water chemistry, metal speciation, and trophic interactions, play a crucial role in influencing bioconcentration efficiency. Notably, in the context of ongoing climate change, stressors such as alterations in salinity, rising sea temperatures, and ocean acidification are projected to modify these environmental conditions, thereby potentially enhancing the mobilization and bioavailability of heavy metals [47,48]. Indeed, such climate-driven modifications are expected to directly influence fundamental heavy metal contaminant pathways, including processes like volatilization, adsorption, biodegradation, hydrolysis, photo-enhanced toxicity, photodegradation, uptake, and metabolism [49,50]. Consequently, the interactive effects of climate change (increasing temperature, ocean acidification (decreasing pH), hypoxia) and pollutants are likely to exacerbate the bioaccumulation of heavy metals in marine organisms, including bivalves, in the foreseeable future [51-53]. Given these findings, future research should focus on the mechanisms driving metal uptake in different species, while long-term biomonitoring efforts should prioritize high-BCF species to better assess temporal trends in heavy metal pollution and their potential risks to aquatic ecosystems and human health.

Regarding Biota-Sediment Accumulation Factor (BSAF): The Biota-Sediment Accumulation Factor (BSAF) values presented in **Table 4** provide valuable insights into the relative contributions of sediment-bound metals to the overall accumulation in bivalve molluscs. The generally low BSAF values observed across various species in Northeastern Vietnam suggest that sediment exposure contributes less to metal accumulation compared to direct uptake from the water column. For instance, in Crassostrea spp. from Quang Yen, the BSAF values for As ranged from 0.6 to 49. Notably, bivalves cultured in continuous contact with sediment (e.g., *Anadara granosa* and *Austriella corrugata*) display markedly higher BSAF values for As (31–49) than *Crassostrea spp*., which rarely contact the sediment (0.6), implying that the cultivation method (bottom versus off-bottom) can affect arsenic bioaccumulation and, consequently, product safety. Additionally, these BSAF values are markedly lower than the BCF values observed for As in bivalve molluscs across Northeastern Vietnam, suggesting that sediment-associated As contributes substantially less to the arsenic levels within these organisms at this site compared to accumulation directly from the water column. Similarly, the relatively low BSAF values for the other studied metals (Cd, Cu, Hg, Pb and Zn) emphasize their primary uptake from the water column rather than from sediment particles in these organisms. These findings align with the observation that certain metals, like arsenic and mercury, are more bioavailable in the water phase, where they are dissolved and readily absorbed by bivalves through their gills and soft tissues. However, despite the general predominance of waterborne uptake, the extent of contribution from sediment-bound metals, as indicated by the BSAF values, is not uniform across species or under differing environmental conditions (e.g., different geographic areas and study periods). The variation in BSAF values can be attributed to several factors, including differences in sediment composition, metal speciation, and biological factors such as the molluscs' feeding behavior and metabolic processes. For example, *Austriella corrugata* may have a higher affinity for absorbing As from the sediment, possibly due to the nature of its feeding mechanism or a higher capacity to bioaccumulate metals from sediment particles. These observations highlight the complexity of metal bioaccumulation dynamics and the need to consider both sediment and waterborne sources of contamination in ecological risk assessments.

Moreover, comparisons with data from other regions, such as the Likas estuary in Malaysia, further underscore the site-specific variability in metal uptake from sediments. For instance, species like *Meretrix meretrix*, and *Crassostrea iredalei* from Likas estuary exhibit low BSAF values for cadmium (0.2 to 0.8) [36], which suggests that sediment is not a significant source of Cd for these organisms in this particular area. Similar trends are observed for copper and zinc, reinforcing the idea that sediment-derived metals may not always be as bioavailable to bivalves as metals dissolved in the water. In contrast, higher BSAF values reported from Laizhou Bay, China, particularly in species such as *Scapharca subcrenata* and *Ruditapes philippinarum*, suggest that sediment contamination may be a more prominent source of metal accumulation in those regions. For example, the BSAF for Cd in *Scapharca subcrenata* reached as high as 58.26, which is substantially higher than values observed in samples from Northeastern Vietnam and Malaysia. This disparity emphasizes regional differences in sediment-metal interactions and highlights the necessity of localized environmental assessments when evaluating the role of sediment in metal bioaccumulation across diverse ecosystems. This variability in BSAF values underscores the importance of considering both BCF and BSAF when evaluating the ecological risks associated with heavy metal contamination. The integration of these two factors provides a more comprehensive understanding of how pollutants accumulate in aquatic ecosystems and the potential for molluscs to serve as bioindicators of environmental health.

3.4. Proposed Solutions to Mitigate Health Risks Associated with Heavy Metals in Bivalve Molluscs

Environmental remediation measures for heavy metal contamination: The issue of heavy metal conta-mination in aquatic environments is pressing, especially in countries like Vietnam, where rapid industrial growth and urbanization significantly contribute to pollution levels. Toxic metals, including lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), are hazardous pollutants that persist in the environment and can bioaccumulate through the food chain, leading to serious ecological and public health consequences. These metals can enter water bodies through various sources, including industrial effluents, agricultural runoff, and untreated sewage. To effectively mitigate the impact of heavy metals, a combination of control and remediation strategies is essential. Among the most common technologies, chemical precipitation is widely used to remove metal ions by forming insoluble compounds, which are subsequently removed through sedimentation or filtration. Coagulation-flocculation is another common method, involving the use of chemicals to aggregate suspended particles and metals, allowing for their removal from water. Membrane filtration, which em-ploys semipermeable membranes with optimized pore sizes, effectively traps metal ions and other contaminants, while ion exchange and electrochemical treatments help-remove specific contaminants by exploiting the affinity between metals and ion-exchange resins or electrodes. Oxidation-reduction techniques are also valuable, espe-cially for converting toxic metals into less harmful forms. However, each of these methods has limitations based on water chemistry, the specific characteristics of pollutants, and the economic feasibility of large-scale application. In contrast, constructed wetlands provide an ecologically sustainable and economically viable solution for heavy metal remediation by using biological processes to filter and degrade pollutants [54]. More specifically, these systems utilize natural energies from the sun, wind, soil, plants, and animals to convert pollutants into harmless byproducts or essential nutrients, minimizing fossil fuel usage. In Vietnam, their implementation is promising due to cost-effectiveness and low maintenance requirements. Investment costs for wetlands include land acquisition, site investigation, system design, earthwork excavation, liners, filtration media, vegetation, hydraulic control structures, and miscellaneous expenses such as fencing and access roads. In a comprehensive analysis of investment costs for horizontal-flow constructed wetlands in the United States, the Czech Republic, Spain, and Portugal, Vymazal and Kröpfelová found that capital expenditures were distributed as follows: excavation 7–27.4%; gravel media 27–53%; liners 13–33%; vegetation establishment 2–12%; plumbing 6–12%; control structures 3.1–5.7%; and miscellaneous items 1.8–12% [55]. Total capital expenditures exhibit even greater regional variability, ranging from 29 USD per m² in India to 33 USD per m² in Costa Rica, and up to 257 EUR per m² in Belgium [56-58], highlighting their adaptability to diverse budgets in contrast to the typically substantial fixed costs of conventional treatments. In summary, by flexibly combining constructed wetlands with physico-chemical treatments, Vietnam can more effectively remediate heavy metal pollution, thereby reducing its accumulation in marine organisms and safeguarding aquatic ecosystem health.

Technical solutions to limit heavy metal entry and accumulation in marine organisms: To reduce the harmful impact of heavy metals in marine organisms, a multifaceted approach is necessary. The entry and accumulation of heavy metals in marine life pose significant risks to both ecosystems and human consumers, especially given the importance of seafood in many diets. One of the key strategies involves enhancing environmental management frameworks to ensure better pollution control and to reduce metal emissions from both terrestrial and marine sources. This includes improving regulatory policies, strengthening environmental monitoring systems, and promoting sustainable development practices. Conducting detailed inventories of pollution sources, both point-source and non-point-source, helps to identify and mitigate risks at their origin. Establishing regular monitoring of environmental quality, including water, sediment, and biota, is crucial for early detection of heavy metal contamination and for enabling timely interventions. Another vital strategy is to prioritize aquaculture practices in regions with relatively lower pollution levels and to implement zoning regulations that limit aquaculture activities in contaminated areas. This minimizes the exposure of marine organisms to high levels of metals. Additionally, the application of advanced aquaculture technologies, including selective breeding and genetic modification, can significantly reduce metal exposure and accumulation in farmed organisms. Genetic advancements can lead to the development of species or strains that grow rapidly, have shorter life cycles, and possess enhanced abilities to metabolize or excrete heavy metals. However, these genetic interventions must be approached cautiously. It is crucial that such approaches, especially when considering the genetic modification of key aquaculture species like bivalves, are preceded by thorough research into their ecological implications, including comprehensive ecological risk assessments, and that they strictly adhere to biosafety standards to avoid unintended environmental consequences. These technical solutions, when implemented in combination with effective environmental management and sustainable aquaculture practices, can significantly reduce the risks associated with heavy metal accumulation in marine organisms and ensure safer seafood for consumption.

Solutions for ensuring seafood safety: Ensuring seafood safety from heavy metal contamination requires a comprehensive approach that spans the entire supply chain, from harvesting to processing, and even to consumer consumption. Seafood products, particularly bivalve molluscs, are vulnerable to contamination by heavy metals, which can accumulate to harmful levels over time. One of the most critical components of ensuring safety is setting and enforcing safety thresholds, such as Maximum Residue Limits (MRL), Maximum Permissible Levels (MPL), and Acceptable Daily Intake (ADI) for toxic metals like mercury, cadmium, arsenic, and lead. These thresholds are designed to limit exposure and ensure that contaminants do not reach harmful levels in the food supply. Regular testing and analysis of seafood at specialized laboratories are essential for verifying compliance with these safety limits and for detecting contamination early. In addition to scientific testing, the establishment of comprehensive seafood traceability systems is vital for ensuring trans-parency and safety throughout the seafood supply chain. These systems track the origin of seafood products, providing consumers with information about where and how their food is sourced, harvested, and processed. This not only fosters consumer confidence but also enables quick responses in case of contamination. Public communication and education are equally important in ensuring the safety of seafood. Campaigns that raise awareness about the risks of heavy metal contamination and provide consumers with clear guidance on selecting safe, high-quality seafood are crucial. Leveraging modern information technologies, such as mobile apps and online platforms, enables consumers to access real-time information about seafood safety and product origins. Additionally, periodic training programs for consumers and industry stakeholders can help ensure that safe seafood handling and storage practices are followed. By combining strict regulatory frameworks, advanced monitoring tech-niques, and effective public outreach, the risks associated with heavy metal contamination in seafood can be signi-ficantly reduced, protecting both public health and the seafood industry.

4. Conclusions

The study revealed that bivalve molluscs from coastal areas of Northeastern Vietnam exhibit significant variability in heavy metal accumulation, depending on species and sampling locations. High bio-concentration factors (BCF) were recorded for arsenic (As), cadmium (Cd), and mercury (Hg), particularly from samples collected at Van Don, Quang Yen and Cat Ba, highlighting the predominance of metal uptake through contaminated water sources. Conversely, lower biota-sediment accumulation factors (BSAF) reflect the limited role of sediment in transferring heavy metals to mollusc tissues. These findings underline the substantial impact of industrial, urban, and agricultural waste sources on marine environmental quality, directly affecting seafood safety and public health. Consequently, establishing continuous monitoring programs and developing region-specific food safety standards are critically necessary. Improved pollutant source management systems and effective treatment solutions to prevent heavy metal infiltration into marine ecosystems will protect biodiversity and ensure seafood resource safety for consumers. Further research should focus on assessing the long-term impacts of heavy metal accumulation on food chains, providing essential baseline data to inform environmental management and safeguard public health.

Author Contributions

S.X.L.: Conceptualization, methodology, validation, data curation, writing - original draft preparation, writing - review and editing, supervision. B.V.N.: data curation, writing - original draft preparation, writing - review and editing. H.T.M.B.: writing - review and editing. N.V.L.: writing - review and editing. H.V.D.: writing - review and editing; K.D.L.: writing - review and editing; S.T.C.: writing - review and editing; K.N.: writing - review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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