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Original Article

Accumulation of Heavy Metal in Marine Bivalve

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Abstract:

Marine bivalves, including mussels, oysters, clams, and scallops, are widely recognized as effective biomonitors of heavy metal contamination in coastal and estuarine environments. This comprehensive literature review synthesizes findings from 192 peer-reviewed studies to examine the mechanisms, patterns, and implications of heavy metal bioaccumulation in bivalve molluscs. The review reveals that bivalves accumulate metals such as cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), mercury (Hg), and arsenic (As) through filter-feeding activities, with concentrations often exceeding regulatory limits for human consumption. Key factors influencing accumulation include species-specific physiology, environmental conditions (salinity, temperature, pH), metal bioavailability, and anthropogenic pollution sources. The evidence demonstrates that bivalves serve dual roles as sentinel organisms for environmental monitoring and as potential vectors for human exposure to toxic metals through seafood consumption. This review identifies critical knowledge gaps and provides recommendations for future research and monitoring programs.

Introduction:

Heavy metal contamination in marine ecosystems represents a persistent and growing environmental challenge with significant implications for ecosystem health and human well-being. Marine bivalve molluscs—including mussels (*Mytilus spp.*), oysters (*Crassostrea spp.*), clams (*Ruditapes*, *Meretrix*, *Tivela spp.*), and scallops (*Pecten spp.*)—have emerged as particularly valuable organisms for monitoring metal pollution due to their sedentary nature, filter-feeding behaviour, wide geographic distribution, and capacity to bioaccumulate contaminants [1], [2], [3]. These organisms concentrate heavy metals from both the water column and sediments, often achieving tissue concentrations several orders of magnitude higher than ambient environmental levels [4], [5].

The accumulation of heavy metals in bivalves is of dual concern: first, as indicators of environmental contamination reflecting anthropogenic inputs from industrial discharge, urban runoff, agricultural activities, and mining operations [1], [6]; and second, as a food safety issue, given that bivalves constitute an important protein source for coastal populations worldwide [7], [8]. Metals such as cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), copper (Cu), and zinc (Zn) can exert toxic effects on both the organisms themselves and on humans who consume contaminated shellfish [9], [10].Despite extensive research over the past five decades, significant questions remain regarding the mechanisms governing metal uptake and storage, the factors modulating bioaccumulation across species and environments, and the most effective approaches for using bivalves in environmental monitoring programs [7], [11]. The objectives are to: (1) characterize patterns of metal bioaccumulation across bivalve species and geographic regions; (2) evaluate the environmental and biological factors influencing accumulation; (3) assess methodological approaches and analytical techniques; (4) examine human health risks associated with consumption of contaminated bivalves; and (5) identify critical knowledge gaps and future research priorities.

Background and Theoretical Foundations:

- **Heavy Metals in Marine Environments**

Heavy metals are naturally occurring elements with high atomic weights and densities greater than 5 g/cm³.

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In marine environments, metals originate from both natural sources (weathering of rocks, volcanic activity, atmospheric deposition) and anthropogenic activities (industrial effluents, mining, agricultural runoff, urban wastewater, and shipping) [1], [12]. The most commonly studied metals in bivalve research include cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) [13], [14].

These metals persist in marine systems due to their non-biodegradable nature and can exist in various chemical forms that differ in bioavailability and toxicity [15]. Metal speciation, influenced by factors such as pH, salinity, dissolved organic matter, and redox conditions, determines the fraction available for biological uptake [16], [17]. Unlike organic pollutants that can be metabolized and eliminated, heavy metals tend to accumulate in biological tissues over time, leading to biomagnification through food webs [2], [18].

The toxic effects of heavy metals on marine organisms include oxidative stress, DNA damage, disruption of enzyme systems, interference with calcium metabolism, and impairment of reproductive and immune functions [6], [19]. At the ecosystem level, metal contamination can alter community structure, reduce biodiversity, and impair ecosystem services [20].

- **Bivalves as Biomonitors**

Bivalve molluscs possess several characteristics that make them ideal biomonitors for assessing heavy metal contamination in coastal and estuarine environments [16], [21]. First, their sedentary lifestyle means they reflect local contamination conditions rather than integrating exposures across large geographic areas [9], [22]. Second, as filter feeders, bivalves process large volumes of water (up to several liters per hour), concentrating particulate-bound and dissolved metals from both the water column and resuspended sediments [4], [23].

Third, bivalves exhibit relatively slow metal elimination rates compared to uptake rates, resulting in bioaccumulation factors (BAF) often exceeding 10,000 for certain metals like cadmium [24], [25]. Fourth, many bivalve species are cosmopolitan, facilitating comparisons across geographic regions and environmental gradients [7], [26]. Fifth, bivalves are economically important as food resources, making their contamination status directly relevant to human health risk assessment [8], [27].

The use of bivalves in biomonitoring programs has been formalized through initiatives such as the International Mussel Watch Program, which has tracked temporal and spatial trends in coastal contamination since the 1970s [28]. However, effective interpretation of biomonitoring data requires understanding the multiple factors that influence metal accumulation beyond simple environmental exposure [11], [29].

- **Bioaccumulation Mechanisms**

Heavy metal bioaccumulation in bivalves occurs through multiple pathways and is regulated by complex physiological processes [15], [30]. The primary uptake routes include: (1) absorption of dissolved metals across gill epithelia during respiration and filter-feeding; (2) ingestion of metal-laden particulate matter (phytoplankton, detritus, sediment particles); and (3) direct contact with contaminated sediments [4], [31].

Once absorbed, metals are distributed among various tissues and organs, with the digestive gland (hepatopancreas) typically serving as the primary storage site [19], [32]. Bivalves have evolved several detoxification mechanisms to manage metal exposure, including the synthesis of metal-binding proteins such as metallothioneins (MTs), which sequester metals in non-toxic forms [29], [33]. Metallothioneins are low-molecular-weight, cysteine-rich proteins that bind metals like Cd, Cu, Zn, and Hg with high affinity, reducing their availability for toxic interactions [34].

Additional detoxification strategies include compartmentalization of metals in lysosomes, formation of insoluble metal-rich granules, and incorporation into shell structures [26], [35]. The balance between uptake, internal distribution, detoxification, and elimination determines the net accumulation of metals in bivalve tissues [36]. Elimination pathways include excretion through kidneys, loss during spawning (gamete release), and incorporation into shell material during growth [37].

Bioaccumulation kinetics can be described by two-compartment models that account for uptake rate constants (ku) and elimination rate constants (ke), with steady-state concentrations reached when uptake and elimination rates are balanced [27], [38]. However, many bivalve populations in contaminated environments do not reach steady state due to temporal variability in metal exposure and physiological condition [39].

Methodological Approaches in the Literature:

- **Analytical Techniques**

The accurate quantification of heavy metals in bivalve tissues requires rigorous analytical methods. The literature reveals a predominance of atomic spectroscopy techniques, with Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Atomic Absorption

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Spectroscopy (AAS) being the most widely employed [30], [40]. ICP-MS offers superior sensitivity, multi-element capability, and low detection limits (typically in the parts-per-billion range), making it particularly suitable for trace metal analysis [41], [42]. Studies have also utilized ICP-Optical Emission Spectrometry (ICP-OES), Flame AAS (FAAS), and Graphite Furnace AAS (GFAAS), each with specific advantages for different metals and concentration ranges [43], [44].

Sample preparation protocols typically involve tissue dissection, drying (freeze-drying or oven-drying at 60-105°C), homogenization, and acid digestion using concentrated nitric acid (HNO_3), hydrogen peroxide (H_2O_2), or mixtures thereof [30], [45]. Microwave-assisted digestion has gained popularity due to reduced digestion times and lower contamination risks [46]. Quality assurance measures include the use of certified reference materials (CRMs), procedural blanks, replicate analyses, and spike recovery tests to ensure data accuracy and precision [47], [48].

For mercury analysis, Cold Vapor AAS (CVAAS) or Direct Mercury Analyzers (DMA) are often preferred due to mercury's volatility [49]. Arsenic speciation studies employ techniques such as High-Performance Liquid Chromatography coupled with ICP-MS (HPLC-ICP-MS) to distinguish between toxic inorganic arsenic and less toxic organic arsenicals [50].

- **Study Designs**

The reviewed literature encompasses diverse study designs, each addressing different research questions. Field surveys constitute the majority of studies, involving collection of bivalves from multiple sites along contamination gradients to assess spatial patterns of metal accumulation [18], [23], [51]. These studies often correlate tissue metal concentrations with environmental variables (sediment metal content, water quality parameters, proximity to pollution sources) to identify contamination hotspots and sources [52], [53].

Temporal monitoring studies track seasonal and inter-annual variations in metal concentrations, revealing the influence of physiological cycles (spawning, growth), environmental fluctuations (temperature, salinity, food availability), and changes in pollution inputs [54], [55]. Such studies are essential for distinguishing natural variability from anthropogenic trends [56].

Laboratory exposure experiments provide controlled conditions to investigate uptake kinetics, dose-response relationships, and the effects of environmental variables on bioaccumulation [57], [58]. These studies typically expose bivalves to known metal concentrations in seawater or spiked sediments and measure tissue accumulation over time [59]. Depuration experiments examine elimination kinetics by transferring contaminated bivalves to clean water and monitoring metal loss [60].

Comparative studies examine multiple species collected from the same locations to evaluate species-specific differences in accumulation capacity and suitability as biomonitors [19], [61]. Meta-analyses and systematic reviews synthesize data from multiple studies to identify global patterns, establish baseline concentrations, and assess temporal trends [11], [62].

- **Sampling Strategies**

Effective sampling strategies are critical for generating representative and comparable data. Most studies collect adult bivalves of similar size ranges to minimize the confounding effects of age and growth on metal concentrations [63], [64]. Sampling is typically conducted during specific seasons to control for physiological variability associated with reproductive cycles [55], [65].

Site selection considers environmental gradients (e.g., distance from pollution sources, salinity gradients in estuaries) and includes reference sites in relatively pristine areas for comparison [66], [67]. Sample sizes vary widely, with most studies analysing 10-30 individuals per site, often pooled into composite samples to reduce analytical costs while maintaining statistical power [68].

Tissue selection also varies: some studies analyse whole soft tissues, while others focus on specific organs such as the digestive gland, gills, or adductor muscle [32], [69]. The digestive gland typically exhibits the highest metal concentrations due to its role in detoxification and storage, whereas muscle tissue is more relevant for human consumption risk assessment [70], [71].

Key Findings and Comparative Analysis:

- **Species-Specific Accumulation Patterns**

Significant interspecific variation in metal accumulation capacity has been documented across bivalve taxa. Mussels, particularly *Mytilus galloprovincialis* and *Mytilus edulis*, are among the most extensively studied species and consistently demonstrate high bioaccumulation potential for multiple metals [9], [25], [72]. These species are the foundation of many biomonitoring programs due to their wide distribution, tolerance of environmental stress, and strong accumulation capacity [73].

Oysters, including *Crassostrea virginica*, *Crassostrea gigas*, and *Saccostrea cucullata*, also exhibit substantial metal accumulation, with particularly high concentrations of zinc and copper, which are essential micronutrients involved in

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enzyme function and shell formation [6], [29], [74]. Studies have shown that oysters can accumulate cadmium through an inducible metallothionein-like protein, with concentrations influenced by salinity and seasonal physiological activity [29], [75].

Clam species display more variable accumulation patterns. *Ruditapes philippinarum*, *Meretrix meretrix*, and *Tivela mactroides* have been studied across diverse geographic regions, with accumulation capacity influenced by habitat type (sandy vs. muddy substrates) and burrowing depth [24], [26], [76]. The hard clam *Meretrix meretrix* has been investigated for its potential as a bioindicator, with studies suggesting that shell composition may also reflect environmental metal exposure [26].

Comparative studies reveal that accumulation hierarchies vary by metal. For cadmium, mussels and oysters typically show higher concentrations than clams, while for lead and mercury, patterns are more species- and site-specific [19], [61]. These differences reflect variations in feeding behaviour, gill surface area, metabolic rates, and detoxification mechanisms [77].

- **Metal-Specific Bioaccumulation**

Cadmium (Cd): Cadmium consistently emerges as one of the most bioaccumulative metals in bivalves, with bioconcentration factors often exceeding 10,000 [24], [25], [29]. Cadmium accumulation is strongly influenced by salinity, with inverse relationships observed in several studies—higher accumulation at lower salinities due to increased metal bioavailability and reduced competition from calcium ions [29], [78]. Seasonal patterns in cadmium concentrations correlate with reproductive cycles, with peaks often observed during gametogenesis when metallothionein synthesis is elevated [54], [79]. The digestive gland serves as the primary storage site, accounting for 60-80% of total body burden [32].

Lead (Pb): Lead accumulation in bivalves is generally lower than cadmium but still of concern due to its neurotoxicity. Concentrations vary widely depending on proximity to anthropogenic sources such as industrial areas, harbors, and urban runoff [80], [81]. Lead tends to bind strongly to particulate matter, making sediment-dwelling species potentially more exposed than those in the water column [82]. Studies have documented lead concentrations exceeding regulatory limits in bivalves from industrialized coastal areas [83].

Copper (Cu) and Zinc (Zn): These essential metals are actively regulated by bivalves to maintain physiological functions, resulting in relatively narrow concentration ranges compared to non-essential metals [84], [85]. However, in highly contaminated environments, regulatory mechanisms can be overwhelmed, leading to toxic accumulation [86]. Copper is particularly elevated in oysters due to its role in hemocyanin (the oxygen-carrying protein in molluscan blood) [74]. Zinc concentrations typically follow the order: Zn > Cu > other metals in tissue analyses [30], [87].

Mercury (Hg): Mercury bioaccumulation in bivalves is of particular concern due to its neurotoxicity and potential for biomagnification. Methylmercury, the most toxic form, can constitute a significant fraction of total mercury in bivalve tissues [88]. Accumulation patterns are influenced by sediment characteristics, with anoxic sediments promoting methylation by sulfate-reducing bacteria [89]. Bivalves from contaminated sites (e.g., near chlor-alkali plants, gold mining areas) can exhibit mercury concentrations exceeding food safety limits [90].

Arsenic (As): Arsenic in marine bivalves exists predominantly in organic forms (arsenobetaine, arsenosugars), which are less toxic than inorganic arsenic [50], [91]. However, total arsenic concentrations can be high, and speciation analysis is necessary for accurate risk assessment [92]. Studies have reported arsenic concentrations exceeding regulatory limits in bivalves from certain regions, particularly in Southeast Asia [30], [93].

- **Geographic Variations**

Global patterns of metal contamination in bivalves reflect regional differences in industrialization, urbanization, and environmental regulations. Asian coastal regions, particularly in China, India, Malaysia, and Indonesia, frequently report elevated metal concentrations in bivalves, associated with rapid industrial development, inadequate wastewater treatment, and intensive aquaculture [23], [30], [94]. Studies from Laizhou Bay (China), Daya Bay (China), and the Sunderban mangrove wetlands (India) document multiple metals exceeding food safety standards [18], [22], [23].

Mediterranean coastal areas show variable contamination patterns, with hotspots near major ports, industrial zones, and river mouths [25], [95]. Studies on *Mytilus galloprovincialis* from Greek, Spanish, and Italian coasts reveal site-specific accumulation influenced by local pollution sources and hydrodynamic conditions [25], [96].

In contrast, bivalves from relatively pristine areas such as remote Pacific islands, Antarctic regions, and protected marine reserves exhibit baseline metal concentrations several orders of magnitude lower than those from contaminated sites [11], [97]. These baseline data are essential for establishing reference conditions and assessing the magnitude of anthropogenic impacts [62].

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Estuarine environments represent particularly dynamic systems where metal bioavailability is modulated by salinity gradients, sediment resuspension, and mixing of freshwater and marine waters [98]. Studies in estuaries consistently show elevated metal concentrations in bivalves near river mouths and industrial discharge points [99].

- **Environmental and Biological Factors**

Salinity: Salinity exerts complex effects on metal bioaccumulation through multiple mechanisms. Lower salinity generally increases the bioavailability of metals like cadmium and lead by reducing competition from major ions (Ca^{2+}, Mg^{2+}) for binding sites on gill surfaces [29], [100]. However, salinity also affects bivalve physiology, including filtration rates and osmoregulation, which can indirectly influence metal uptake [101].

Temperature: Temperature influences metabolic rates, filtration activity, and the kinetics of metal uptake and elimination [102]. Seasonal temperature variations contribute to temporal patterns in tissue metal concentrations, with higher accumulation often observed during warmer months when feeding activity is elevated [54], [103]. However, temperature effects are often confounded with reproductive cycles and food availability [104].

pH and Redox Conditions: Acidification can increase metal bioavailability by enhancing desorption from sediments and altering metal speciation [105]. Redox conditions in sediments affect the mobility of metals like mercury and arsenic, with reducing conditions promoting methylation and mobilization [106].

Reproductive Cycle: Spawning events can significantly reduce tissue metal concentrations through gamete release, leading to seasonal minima post-spawning [54], [107]. Conversely, gametogenesis may be associated with increased metallothionein synthesis and metal sequestration [79].

Size and Age: Larger and older bivalves generally exhibit higher metal concentrations due to longer exposure times and cumulative accumulation [63], [108]. However, growth dilution can occur when growth rates exceed metal uptake rates, resulting in lower concentrations in rapidly growing individuals [109].

Food Availability and Quality: The quantity and quality of suspended particulate matter influence both filtration rates and the dietary pathway of metal exposure [110]. Phytoplankton blooms can enhance metal uptake by increasing the particulate-bound metal fraction available for ingestion [111].

Health Risk Assessment and Food Safety:

- **Regulatory Standards and Exceedances**

International food safety standards for heavy metals in bivalves have been established by organizations including the Food and Agriculture Organization/World Health Organization (FAO/WHO), European Commission, and national regulatory agencies [112]. Common maximum permissible limits include: cadmium (1.0 mg/kg wet weight), lead (1.5 mg/kg), mercury (0.5 mg/kg), and arsenic (variable, depending on speciation) [113].

Numerous studies report metal concentrations exceeding these limits in bivalves from contaminated areas. For example, research in Kuala Perlis (Malaysia) found arsenic, cadmium, and copper concentrations in *Marcia marmorata* exceeding FAO/WHO standards, leading to recommendations against consumption [30]. Similarly, studies in Daya Bay (China) documented cadmium and lead levels in multiple bivalve species above regulatory thresholds [23]. In Timsah Lake (Egypt), recent investigations revealed elevated concentrations of multiple metals in edible bivalves, posing health risks to local consumers [21].

However, metal concentrations in bivalves from well-managed aquaculture systems and pristine coastal areas typically fall within safe limits [114]. Geographic variation in contamination underscores the importance of site-specific monitoring and risk assessment [115].

- **Human Health Implications**

Consumption of metal-contaminated bivalves poses several health risks, particularly for populations with high shellfish consumption rates [8], [116]. Chronic exposure to cadmium can cause kidney damage, bone demineralization (itai-itai disease), and has been classified as a human carcinogen [117]. Lead exposure affects neurological development in children and cardiovascular function in adults [118]. Mercury, particularly methylmercury, is neurotoxic and can impair cognitive development in fetuses and young children [119]. Arsenic exposure is associated with increased cancer risk, cardiovascular disease, and diabetes [120].

Health risk assessments typically employ hazard quotients (HQ) and target hazard quotients (THQ), calculated by dividing estimated dietary intake by reference doses [121]. Studies in Kota Kinabalu (Malaysia), Laizhou Bay (China), and Sunderban wetlands (India) have calculated HQ values exceeding 1 for certain metals, indicating potential health risks for regular consumers [20], [22], [23]. Vulnerable populations, including pregnant women, children, and subsistence fishing communities, face elevated risks [122].

However, risk assessment is complicated by several factors: (1) metal speciation affects toxicity (e.g., organic vs. inorganic arsenic); (2)

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cooking methods can alter metal bioavailability; (3) nutritional benefits of bivalve consumption (high-quality protein, omega-3 fatty acids, micronutrients) must be weighed against contamination risks; and (4) individual consumption patterns vary widely [123], [124].

- **Risk Assessment Methodologies**

Risk assessment methodologies in the literature include deterministic approaches (using mean or maximum concentrations and average consumption rates) and probabilistic approaches (Monte Carlo simulations incorporating variability in both exposure and toxicity parameters) [125]. Target cancer risk (TCR) calculations are employed for carcinogenic metals like cadmium and arsenic [126].

Consumption advisories based on risk assessments recommend limiting intake of bivalves from contaminated areas, with specific guidance for vulnerable populations [23], [127]. Some studies propose maximum safe consumption rates (e.g., meals per month) based on site-specific contamination levels [128].

Biomonitoring programs that integrate environmental monitoring, tissue analysis, and human health surveillance provide the most comprehensive approach to managing risks associated with contaminated seafood [129].

Discussion:

- **Synthesis of Major Findings**

This comprehensive review of 192 studies reveals several overarching patterns in heavy metal accumulation in marine bivalves. First, bivalves consistently demonstrate their utility as biomonitors, with tissue concentrations reflecting both spatial and temporal patterns of environmental contamination [2], [7], [16]. The capacity to bioconcentrate metals by factors of 10^3 to 10^5 makes them sensitive indicators of even low-level pollution [24], [25].

Second, metal accumulation is governed by a complex interplay of environmental factors (salinity, temperature, pH, metal bioavailability), biological factors (species, size, reproductive status, detoxification capacity), and anthropogenic factors (pollution sources, land use patterns) [130]. No single factor dominates; rather, accumulation patterns emerge from the integration of multiple influences [131].

Third, significant geographic disparities exist, with bivalves from rapidly industrializing regions in Asia often exhibiting metal concentrations exceeding those from Europe and North America, where environmental regulations have been in place longer [132]. This pattern highlights the global nature of coastal metal contamination and the need for international cooperation in monitoring and management [133].

Fourth, the dual role of bivalves as environmental sentinels and food resources creates a direct link between ecosystem health and human health [8], [134]. Contamination patterns documented through biomonitoring programs have immediate implications for food safety and public health policy [135].

- **Limitations and Challenges**

Despite the extensive literature, several limitations and challenges persist. First, methodological inconsistencies across studies (different analytical techniques, tissue types, size classes, seasons) complicate direct comparisons and meta-analyses [136]. Standardization of protocols, as advocated by programs like Mussel Watch, would enhance data comparability [137].

Second, most studies focus on total metal concentrations rather than metal speciation, which is critical for assessing bioavailability and toxicity [50], [138]. Expanded use of speciation techniques (e.g., HPLC-ICP-MS) would improve risk assessments [139].

Third, the literature exhibits geographic bias, with extensive coverage of European, North American, and East Asian coasts but limited data from Africa, South America, and remote island nations [140]. Filling these geographic gaps is essential for understanding global contamination patterns [141].

Fourth, temporal monitoring programs are often short-term (1-2 years), limiting the ability to detect long-term trends and distinguish natural variability from anthropogenic changes [142]. Long-term datasets spanning decades are needed to assess the effectiveness of pollution control measures [143].

Fifth, most studies examine individual metals in isolation, yet bivalves in natural environments are exposed to complex mixtures [144]. Interactive effects (synergistic, antagonistic, or additive) among metals and between metals and other contaminants (organic pollutants, microplastics) remain poorly understood [145].

Sixth, the mechanistic understanding of metal uptake, distribution, and detoxification at the molecular level is still developing [6]. Integration of omics approaches (genomics, transcriptomics, proteomics, metabolomics) with traditional ecotoxicology would advance mechanistic knowledge [28], [146].

- **Implications for Environmental Management**

The findings synthesized in this review have several important implications for environmental management and policy. First, bivalve biomonitoring programs should be

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expanded and standardized globally to provide early warning of contamination trends and assess the effectiveness of pollution control measures [147]. Integration with sediment and water quality monitoring would provide a more complete picture of ecosystem health [148].

Second, site-specific risk assessments should inform consumption advisories and aquaculture site selection [149]. Areas with consistently elevated metal concentrations should be designated as unsuitable for shellfish harvesting, with efforts directed toward identifying and remediating pollution sources [150].

Third, regulatory frameworks should consider metal speciation and bioavailability rather than relying solely on total concentrations [151]. Risk-based standards that account for population-specific consumption patterns and vulnerable subgroups would improve public health protection [152].

Fourth, pollution prevention strategies targeting major sources (industrial effluents, mining waste, agricultural runoff, urban stormwater) are essential for reducing metal inputs to coastal waters [153]. Best management practices, wastewater treatment upgrades, and enforcement of discharge limits can significantly reduce contamination [154].

Fifth, climate change may alter metal bioaccumulation patterns through effects on temperature, ocean acidification, and coastal hydrology [155]. Monitoring programs should be designed to detect and respond to these emerging changes [156].

Conclusion:

Marine bivalves serve as critical sentinels of heavy metal contamination in coastal and estuarine environments, integrating exposure over time and space through their filter-feeding lifestyle and bioaccumulative capacity. This comprehensive review of 192 studies demonstrates that bivalves worldwide accumulate metals such as cadmium, lead, copper, zinc, mercury, and arsenic, with concentrations often reflecting anthropogenic pollution sources and posing potential risks to both ecosystem health and human consumers [1], [2], [7].

The evidence reveals substantial interspecific variation in accumulation patterns, with mussels and oysters generally exhibiting the highest bioconcentration factors [9], [25]. Metal-specific patterns reflect differences in bioavailability, essentiality, and detoxification mechanisms, with cadmium consistently emerging as one of the most bioaccumulative elements [24], [29]. Geographic variations underscore the global nature of coastal metal contamination, with particularly elevated concentrations documented in rapidly industrializing regions of Asia [23], [30].

Environmental factors including salinity, temperature, and sediment characteristics, along with biological factors such as reproductive status and size, modulate accumulation patterns in complex and interactive ways [54], [100]. The integration of advanced analytical techniques (ICP-MS, speciation analysis) with diverse study designs (field surveys, laboratory experiments, long-term monitoring) has advanced understanding of bioaccumulation processes [40], [47].

From a human health perspective, consumption of contaminated bivalves represents a significant exposure pathway for toxic metals, with numerous studies documenting concentrations exceeding regulatory limits and calculated health risks above acceptable thresholds [21], [23], [30]. These findings emphasize the need for robust biomonitoring programs, site-specific risk assessments, and consumption advisories to protect public health [127], [149].

Looking forward, priority research areas include mechanistic studies employing molecular approaches, investigation of metal mixture effects and climate change interactions, expansion of geographic coverage, and development of predictive models [6], [160], [170]. Standardization of methods and integration of environmental monitoring with human health surveillance will enhance the utility of bivalves as biomonitors and improve risk management [172], [168].

Ultimately, effective management of heavy metal contamination in coastal ecosystems requires a multifaceted approach combining pollution prevention at sources, comprehensive environmental monitoring using bivalves and other indicators, science-based risk assessment, and targeted interventions to protect both ecosystem integrity and human health [153], [154]. The extensive body of research synthesized in this review provides a strong foundation for evidence-based policy and management decisions, while also highlighting critical knowledge gaps that warrant continued investigation.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

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