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Perspective

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From Mussel Watch to Future Coastal Forecasting: Reframing Background Metal Baselines Across Baltic and Malaysian Coastal Waters

Chee Kong Yap[1]* and Piotr Szefer[2]

[1]Department of Biology, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Malaysia

[2]Department of Bromatology, Medical University of Gdańsk, Poland

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Author : Chee Kong Yap

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****Correspondence:***

Chee Kong Yap, Department of Biology, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Malaysia,

E-mail: yapchee@upm.edu.my

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Abstract

Marine mussels have long served as reliable sentinel organisms for assessing trace metal contamination in coastal ecosystems because they efficiently accumulate contaminants from surrounding waters and suspended particulates over time. Classical biomonitoring initiatives such as the Mussel Watch programme established the foundation for long term environmental surveillance and generated comparable records of coastal pollution across geographical regions. However, increasing environmental complexity associated with urbanization, climate change, and anthropogenic pressures now requires a broader interpretation of mussel derived information beyond conventional contamination assessment. This perspective reconsiders the significance of historical background metal data in marine mussels and proposes a transition from traditional monitoring toward predictive coastal forecasting. Drawing upon complementary evidence from the southern Baltic Sea and the west coast of Peninsular Malaysia, this paper discusses how soft tissues, byssus, and shells function as biological archives recording environmental conditions across different temporal scales. Rather than viewing background concentrations solely as static reference values, we argue that they represent environmental memory capable of supporting ecotoxicological forecasting, sustainability assessments, and environmental decision making. The integration of historical biomonitoring datasets with predictive frameworks offers opportunities for developing early warning systems, forecasting contamination trends, and strengthening Environmental, Social, And Governance (ESG) strategies. Within the broader planetary health framework, long term biological archives may facilitate stronger connections between environmental quality, ecosystem resilience, and human wellbeing. The transition from Mussel Watch to future coastal forecasting may therefore represent an important conceptual evolution in biomonitoring science, transforming marine mussels from passive recorders of environmental contamination into active contributors to environmental intelligence and sustainable coastal management.

Keywords: Mussel Biomonitoring; Coastal Forecasting; Background Metal Baselines; Environmental Archives; Sustainability

Introduction

Why background metal data matter beyond traditional biomonitoring? Marine ecosystems are increasingly subjected to multiple anthropogenic pressures arising from industrial activities, urban expansion, agricultural development, maritime transport, aquaculture practices, and climate driven environmental alterations. These pressures often introduce trace metals into coastal systems where contaminants may accumulate within sediments, seawater, and marine organisms. Because trace metals can persist for prolonged periods and undergo bioaccumulation within food webs, their monitoring remains an important component of marine environmental assessment and ecosystem management [1-3].

Among marine organisms, mussels have attracted considerable scientific attention because of their biological and ecological characteristics. Mussels are sessile filter feeders capable of integrating environmental exposure over time through continuous filtration of suspended particles and dissolved substances. Their relatively wide geographical distribution, abundance, ease of collection, and capacity for metal accumulation make them practical sentinel organisms for environmental monitoring programmes [4-6]. These characteristics led to the development of the classical Mussel Watch programme introduced by Goldberg (1975), representing one of the earliest global attempts

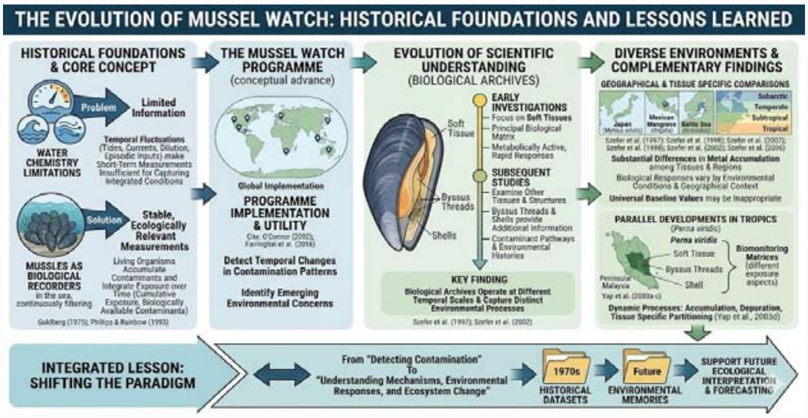

Figure 1: The Conceptual and Spatial Evolution of the Mussel Watch Programme. Note: This diagram is generated using Google Gemini based on the authors' perspectives and ideas.

to establish long term biological monitoring of marine contamination. Four decades later, reflections on the original programme continued to demonstrate its importance for understanding temporal changes in marine environmental quality and guiding management decisions [7].

Traditional biomonitoring approaches frequently focus on evaluating whether metal concentrations exceed established thresholds or background values. Such approaches are effective for identifying contamination hotspots and assessing ecological risks, yet they often interpret biological data as isolated measurements rather than components of larger environmental narratives. Historical datasets generated from biomonitoring programmes possess substantial scientific value extending beyond simple comparisons of contaminated versus uncontaminated sites. Long term biological archives contain environmental information that may reveal temporal trends, changing exposure pathways, ecosystem responses, and early indicators of environmental disturbance [2, 3].

The significance of background metal concentrations becomes particularly important in this context. Background concentrations represent natural or baseline conditions against which anthropogenic changes may be evaluated. However, such baselines are not universally constant because they vary according to regional geochemistry, hydrodynamic characteristics, climatic conditions, and species physiology [8-10]. Therefore, background data should not be considered merely as fixed threshold values but rather as dynamic environmental signatures reflecting ecological conditions and biological responses across space and time.

Recent developments in environmental science further support broader interpretations of biomonitoring information. Increasing emphasis on predictive environmental assessment, climate adaptation, sustainability initiatives, and planetary health perspectives requires environmental indicators capable of integrating complex interactions across biological and social systems [11-13]. Under these emerging frameworks, historical biomonitoring datasets may provide critical information for forecasting future environmental trajectories and supporting evidence-based decision making.

This perspective therefore argues that background metal datasets in marine mussels should be reframed from static contamination references toward dynamic ecological archives capable of informing future environmental forecasting. Using examples from Baltic and Malaysian coastal systems, this paper explores how mussel derived datasets may contribute to broader scientific and societal objectives including predictive biomonitoring, sustainability assessment, environmental governance, and planetary health.

The Evolution of Mussel Watch: Historical Foundations and Lessons Learned

The evolution of the Mussel Watch framework represents a significant paradigm shift in marine environmental monitoring, transitioning from volatile instantaneous data collection to integrated biological archiving (Figure 1). Initially established to overcome the limitations of traditional water chemistry - which is highly susceptible to temporal fluctuations from tides, currents, and episodic inputs - the core concept utilizes living organisms as continuous biological recorders of cumulative, bioavailable contaminant exposure [1, 4]. As the programme expanded globally, it demonstrated immense utility in tracking regional contamination patterns and flagging emerging environmental threats [5, 7]. Over subsequent decades, the scientific scope of Mussel Watch deepened through the realization that different anatomical structures, such as soft tissues, byssus threads, and shells, function as distinct biological archives operating across unique temporal scales and environmental pathways [8, 9]. Extensive geographical studies spanning subarctic to tropical climates - including pivotal research on *Perna viridis* in Peninsular Malaysia - highlighted how localized accumulation, depuration, and tissue-specific partitioning vary by environment, rendering universal baseline values inappropriate [14-16]. Ultimately, as illustrated in Figure 1, this multi-decade evolution shifts the focus of biomonitoring from merely detecting pollution to decoding the underlying mechanisms of ecosystem change, effectively transforming historical datasets into vital "environmental memories" capable of forecasting future ecological shifts.

The concept of using marine organisms as indicators of environmental contamination emerged from the recognition that direct measurements of pollutants in seawater often provide only limited information regarding ecological exposure. Water chemistry frequently exhibits substantial temporal fluctuations arising from tides, currents, dilution processes, and episodic inputs, making short term measurements insufficient for capturing integrated environmental conditions. In contrast, living organisms continuously accumulate contaminants from their surroundings and therefore reflect cumulative environmental exposure over extended periods [1, 4].

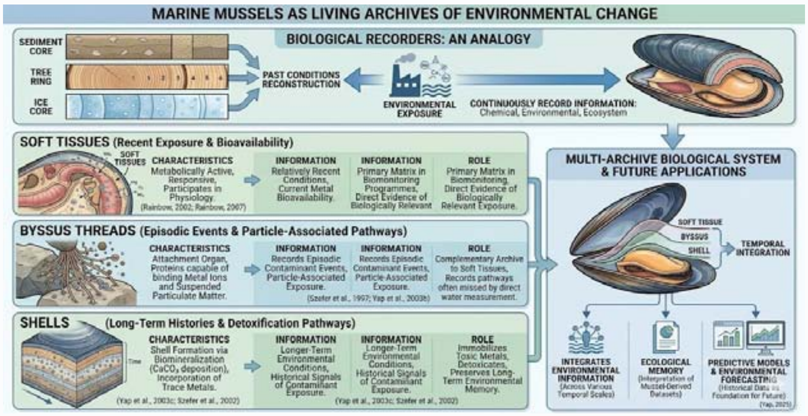

Figure 2: The Multi-Archive Biological System of Marine Mussels for Environmental Reconstruction. Note: This diagram is generated using Google Gemini based on the authors' perspectives and ideas.

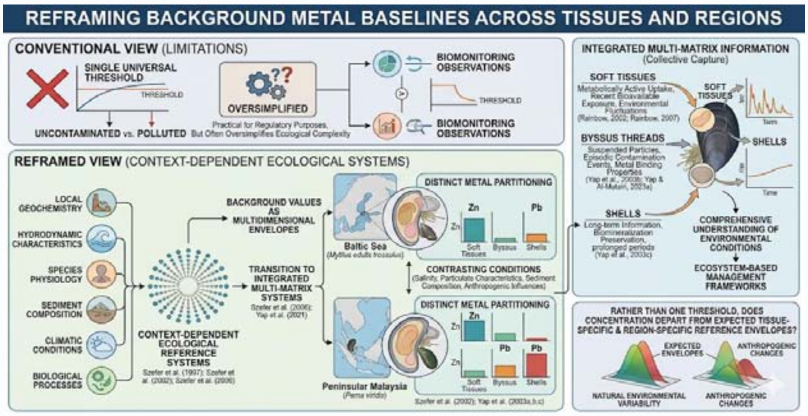

Figure 3: Reframing Static Background Metal Thresholds into Multidimensional Ecological Envelopes. Note: This diagram is generated using Google Gemini based on the authors' perspectives and ideas.

The Mussel Watch concept proposed by Goldberg (1975) represented a major conceptual advance in environmental monitoring. Rather than relying solely upon physical and chemical measurements of water quality, the programme utilized mussels as biological recorders capable of integrating contaminant exposure over time. This approach provided more stable and ecologically relevant measurements because accumulated concentrations reflected biologically available contaminants rather than instantaneous environmental conditions. Subsequent implementation of Mussel Watch programmes across different regions demonstrated their utility in detecting temporal changes in contamination patterns and identifying emerging environmental concerns [5, 7].

Over time, scientific understanding of mussel biomonitoring evolved considerably. Early investigations frequently focused on whole soft tissues as the principal biological matrix because metabolically active tissues often display rapid responses to environmental exposure. However, subsequent studies demonstrated that other tissues and structures including byssus threads and shells may provide additional information regarding contaminant pathways and environmental histories [8, 9]. These findings suggested that biological archives within mussels operate at different temporal scales and capture distinct environmental processes.

Research conducted across diverse marine environments further reinforced this understanding. Investigations involving *Mytilus edulis* from Japan, *Mytella strigata* from Mexican mangrove systems, and *Mytilus edulis trossulus* from the southern Baltic demonstrated substantial differences in metal accumulation patterns among tissues and regions [8, 9, 17]. Comparative studies extending across subarctic, temperate, subtropical, and tropical environments further showed that biological responses vary according to environmental conditions and geographical context [14]. Such observations emphasized that universal baseline values may be inappropriate and that local ecological conditions should be considered when interpreting biomonitoring results.

Parallel developments occurred in tropical regions, particularly involving *Perna viridis*. Studies from Peninsular Malaysia demonstrated the potential use of soft tissues, byssus threads, and shells as biomonitoring matrices capable of recording different aspects of environmental exposure [15, 18, 19]. Laboratory and field investigations further revealed dynamic processes of accumulation, depuration, and tissue specific partitioning that shape metal concentrations within biological systems [16].

These developments collectively illustrate an important lesson from several decades of Mussel Watch research. Biomonitoring should not merely focus on detecting contamination but should also seek to understand mechanisms governing environmental responses and ecosystem change. Historical datasets therefore become more than monitoring records. They become environmental memories

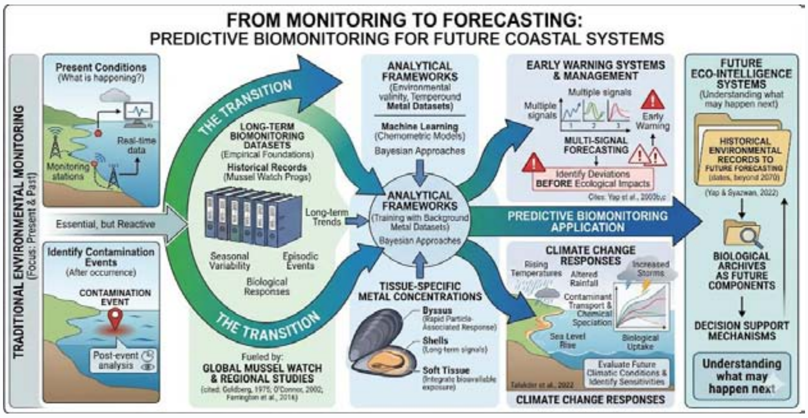

Figure 4: The Paradigm Shift from Reactive Coastal Monitoring to Predictive Environmental Intelligence.
Note: This diagram is generated using Google Gemini based on the authors' perspectives and ideas.

capable of supporting future ecological interpretation and forecasting.

Marine Mussels as Living Archives of Environmental Change

Marine mussels function as dynamic, living environmental archives capable of recording chemical exposure, fluctuating conditions, and ecosystem processes throughout their lifespans (Figure 2). Much like abiotic environmental proxies such as sediment cores, tree rings, or ice cores, mussels preserve distinct biological signatures that can be decoded to reconstruct historical baseline conditions [20]. As illustrated in Figure 2, this biological recording capacity is distributed across three primary structural matrices, each operating on a distinct temporal scale and capturing unique environmental pathways. The metabolically active soft tissues serve as a highly responsive matrix, rapidly accumulating pollutants to provide a direct snapshot of recent exposure and immediate metal bioavailability [2, 3]. In contrast, the proteinaceous byssus threads, which secure the organism to substrates, excel at binding metal ions and suspended particulate matter, thereby serving as unique recorders of episodic pollution events and particle-associated exposure pathways that soft tissues might miss [8, 21]. Extending further across the temporal spectrum, the shell matrix utilizes biomineralization processes ($CaCO_3$ deposition) to lock trace metals into stable carbonate structures over long periods; this not only preserves multi-year environmental histories but also serves as an active detoxification pathway where toxic elements are securely immobilized [9, 19]. Collectively, these compartmentalized archives form a cohesive, multi-scale monitoring system (Figure 2) that embeds deep ecological memory within the organism, shifting the utility of historical biomonitoring datasets from static pollution ledgers to foundational assets for future predictive modeling and environmental forecasting systems.

Marine mussels may be regarded as living environmental archives because they continuously record information concerning chemical exposure, environmental conditions, and ecosystem processes throughout their life histories. Similar to sediment cores, tree rings, or ice cores, biological structures within mussels preserve environmental signatures that may later be interpreted to reconstruct past conditions and understand environmental change [20].

Soft tissues represent one of the most responsive components within mussel biomonitoring systems because metabolically active tissues rapidly accumulate contaminants from surrounding waters and suspended particles. Since these tissues actively participate in physiological processes, they often reflect relatively recent exposure conditions and provide information concerning current bioavailability of metals [2, 3]. Consequently, soft tissues have traditionally served as the primary matrix in many biomonitoring programmes because they provide direct evidence of biologically relevant contaminant exposure.

However, soft tissues do not represent the only environmental archive within mussels. Studies conducted in both Baltic and Malaysian coastal systems demonstrated that byssus threads possess distinctive accumulation characteristics. Byssus structures function as attachment organs connecting mussels to substrates, yet they also contain proteins capable of binding metal ions and suspended particulate matter [8, 18, 21]. Such characteristics allow byssus tissues to record episodic contaminant events and particle associated exposure pathways that may not be fully reflected in soft tissues.

Similarly, shells provide another form of environmental archive with different temporal characteristics. Because shell formation occurs through biomineralization processes involving calcium carbonate deposition, trace metals may become incorporated within shell structures over extended periods [9, 19]. Shell matrices therefore frequently reflect longer term environmental conditions and may preserve historical signals of contaminant exposure. In certain cases, shells may even function as detoxification pathways where potentially toxic metals become immobilized within relatively stable carbonate structures.

The existence of multiple biological archives within mussels suggests that environmental information is distributed across tissues according to different physiological and environmental processes. Soft tissues may reflect recent exposure conditions, byssus may record particulate and episodic inputs, while shells may preserve longer term environmental histories. Together, these components create a multi archive biological system capable of integrating environmental information across various temporal scales.

This perspective suggests that marine mussels should therefore be interpreted not merely as contaminant accumulators but as environmental recorders possessing ecological memory. Historical biomonitoring datasets generated from these biological archives may subsequently provide the foundation for future predictive models and environmental forecasting systems.

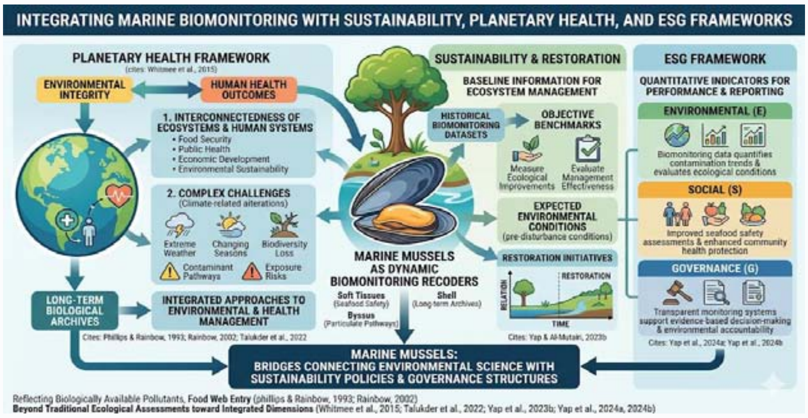

Figure 5: Integrating Mussel Biomonitoring within Sustainability, Planetary Health, and ESG Frameworks. Note: This diagram is generated using Google Gemini based on the authors' perspectives and ideas.

Reframing Background Metal Baselines Across Tissues and Regions

The interpretation of baseline metal contamination requires a conceptual shift away from rigid, single-threshold regulatory models toward dynamic, context-dependent ecological reference systems (Figure 3). Conventional environmental frameworks often treat background metal levels as static entities, oversimplifying the complex natural interactions driven by local geochemistry, hydrodynamics, species physiology, sediment composition, and fluctuating climatic conditions [8,14]. This limitation is clearly illustrated by comparative regional datasets shown in Figure 3; for example, *Mytilus edulis trossulus* from the Baltic Sea generally exhibits elevated zinc concentrations compared to Malaysian *Perna viridis* populations, while lead trends are frequently reversed due to localized variations in salinity, particulate matter, and anthropogenic pressures [9, 15, 18, 19]. Furthermore, these background baselines vary considerably within the organism itself, as the metabolically active soft tissues record recent bioavailable exposure [2, 3], the external byssus threads track episodic, particle-associated metal pulses [21], and the calcium carbonate shells preserve multi-year records of trace-metal incorporation [19]. By synthesizing these localized and anatomical variables, Figure 3 highlights how environmental assessments can transition from single-matrix compliance tracking to integrated multi-matrix monitoring. Ultimately, this reframes baseline data from a passive compliance metric into multidimensional "reference envelopes," establishing an ecosystem-based management tool that accurately accounts for natural variability while remaining highly sensitive to true anthropogenic change [6, 14].

Conventional interpretations frequently regard background metal concentrations as static values that distinguish uncontaminated environments from polluted systems. Such interpretations are practical for regulatory purposes but often oversimplify the ecological complexity underlying biomonitoring observations. Background concentrations are not fixed entities because they arise from interactions among local geochemistry, hydrodynamic characteristics, species physiology, sediment composition, climatic conditions, and biological processes. Consequently, the interpretation of background metal levels should move beyond the concept of universal thresholds toward context dependent ecological reference systems [8, 9, 14].

Evidence from Baltic and Malaysian studies clearly demonstrates this complexity. Investigations on *Mytilus edulis trossulus* from the southern Baltic and *Perna viridis* from Peninsular Malaysia revealed distinct differences in metal partitioning among soft tissues, byssus, and shells [8, 9, 14]. Zinc concentrations in Baltic mussels generally exceeded those observed in Malaysian populations, whereas lead concentrations frequently displayed the opposite trend. Such differences likely arise from contrasting environmental conditions between the two regions, including salinity regimes, particulate characteristics, sediment composition, and anthropogenic influences.

Differences among tissues also highlight important biological mechanisms controlling metal accumulation. Soft tissues frequently reflect metabolically active uptake and recent bioavailable exposure because contaminants absorbed into physiological systems may rapidly respond to environmental fluctuations [2, 3]. In contrast, byssus threads frequently accumulate metals associated with suspended particles and episodic contamination events because of their external location and metal binding properties [18, 21]. Shells often provide longer term information because metals incorporated during biomineralization processes may remain preserved for prolonged periods [19].

These observations suggest that background values should be considered multidimensional rather than singular measurements. Instead of asking whether metal concentrations exceed one universal threshold, a more appropriate question may be whether concentrations depart from expected tissue specific and region-specific reference envelopes. Such ecological envelopes acknowledge natural environmental variability while preserving the capacity to detect anthropogenic changes.

This perspective also supports a transition from single matrix monitoring approaches toward integrated multi matrix systems. Combining soft tissue, byssus, and shell information may provide a more comprehensive understanding of environmental conditions because different tissues collectively capture multiple exposure pathways and temporal scales. Similar approaches are increasingly consistent with broader ecosystem-based management frameworks that recognize interactions among biological, physical, and environmental components [6, 14].

The reinterpretation of background metal data therefore represents an important conceptual shift. Rather than viewing baseline concentrations as passive reference values, they may be considered dynamic ecological fingerprints capable of revealing environmental

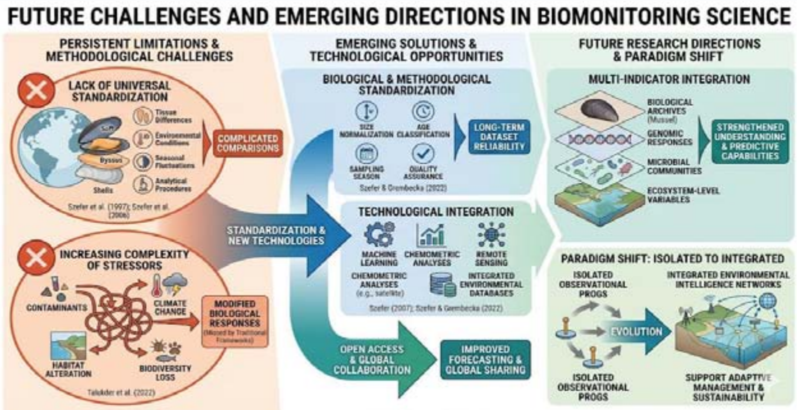

Figure 6: Overcoming Methodological Challenges through Technological Integration and Multi-Indicator Frameworks. Note: This diagram is generated using Google Gemini based on the authors' perspectives and ideas.

processes and supporting future predictive applications.

From Monitoring to Forecasting: Predictive Biomonitoring for Future Coastal Systems

Traditional environmental frameworks have historically focused on describing existing baseline conditions and logging contamination events after their occurrence, an approach that is increasingly insufficient against the escalating uncertainties of climate change, rapid coastal urbanization, and emerging pollutants (Figure 4). To establish a proactive stance, predictive biomonitoring integrates long-term empirical datasets from Mussel Watch programmes with modern forecasting methodologies to anticipate ecological responses before substantial degradation takes place [4, 5, 7, 22]. As mapped in Figure 4, decades of historical data tracking seasonal variability and biological trends serve as training matrices for advanced analytical frameworks, including Bayesian approaches, machine learning techniques, and chemometric models [10, 12]. By feeding tissue-specific concentrations alongside environmental variables - such as temperature, salinity, and hydrodynamics - into these systems, researchers can generate highly sensitive, multi-signal early warning thresholds [18, 19]. This predictive capacity is critical under shifting climate regimes, where rising sea levels, increased storm frequencies, and fluctuating rainfall alter contaminant transport, chemical speciation, and biological uptake pathways [12]. Ultimately, as visualized in Figure 4, extending Mussel Watch frameworks into future horizons transitioning toward 2070 transforms biological archives into core components of broader environmental intelligence systems, shifting the fundamental directive of coastal management from documenting historical degradation to predicting what may happen next [22].

Environmental monitoring has traditionally focused on describing present conditions and identifying contamination events after their occurrence. Although this approach remains essential, increasing environmental uncertainties associated with climate change, coastal urbanization, and emerging contaminants require more proactive frameworks capable of anticipating future ecological responses. Predictive biomonitoring represents one possible evolution of traditional monitoring approaches by integrating historical observations with forecasting methodologies [22].

Long term biomonitoring datasets possess several characteristics that make them suitable for predictive applications. Historical records generated through Mussel Watch programmes provide continuous environmental observations spanning multiple years or decades. Such records contain information concerning seasonal variability, long term trends, episodic contamination events, and biological responses under changing environmental conditions [4, 5, 7]. Consequently, these datasets provide empirical foundations for predictive analyses.

Background metal datasets may serve as training information for emerging analytical frameworks such as Bayesian approaches, machine learning techniques, and chemometric models [4, 5, 7]. For example, historical tissue specific metal concentrations combined with environmental variables including salinity, temperature, sediment characteristics, and hydrodynamic conditions may enable forecasting of contamination patterns under future scenarios.

Predictive applications may also improve early warning systems for environmental management. Byssus tissues may respond rapidly to short term particle associated contamination events, whereas shells may preserve longer term environmental signals and soft tissues may integrate biologically available exposure. Combining information from multiple biological archives may therefore generate multi signal forecasting systems capable of identifying deviations from expected conditions before substantial ecological impacts occur [18, 19].

Climate change further strengthens the need for predictive biomonitoring frameworks. Rising temperatures, altered rainfall regimes, sea level changes, and increasing storm frequencies may modify contaminant transport, chemical speciation, and biological uptake processes [12]. Historical biomonitoring records may therefore help identify environmental sensitivities and evaluate how coastal ecosystems may respond under future climatic conditions.

Recent discussions concerning Mussel Watch programmes extending beyond 2070 further support such perspectives by emphasizing the transition from historical environmental recording toward future forecasting applications [22]. Such developments suggest that biological archives generated through mussel biomonitoring may eventually become components of broader environmental intelligence systems linking ecological observations with decision support mechanisms. The future of biomonitoring may therefore extend beyond simply answering the question of what has happened toward understanding what may happen next.

Relevance to Sustainability, Planetary Health, and ESG

The application of marine mussel biomonitoring extends beyond traditional ecological assessments, serving as a vital bridge that connects environmental science with global sustainability, planetary health, and corporate governance structures (Figure 5). Within the planetary health framework, mussels illustrate the deep interconnectedness of environmental integrity and human welfare; because they directly capture bioavailable contaminants from the water column, their soft tissues provide critical data regarding pollution pathways entering the human food web via seafood consumption [1, 2, 11]. Under climate-induced stressors like shifting rainfall and rising temperatures, these biological archives track changing exposure risks to safeguard vulnerable food systems [12]. Furthermore, as outlined in Figure 5, historical biomonitoring datasets provide objective, pre-disturbance baseline benchmarks essential for evaluating the efficacy of ecosystem restoration initiatives and measuring long-term management success [23]. Finally, this multi-matrix approach fulfills the rigorous quantitative demands of Environmental, Social, and Governance (ESG) reporting frameworks [24, 25]. As systematically detailed in Figure 5, mussel-derived data satisfy the Environmental (E) criteria by quantifying contamination trends, enhance the Social (S) dimension by securing public health and seafood safety, and reinforce the Governance (G) sector by delivering transparent, reproducible, and evidence-based metrics for environmental accountability.

Environmental changes occurring within marine ecosystems increasingly influence broader societal systems including food security, public health, economic development, and environmental sustainability. Consequently, environmental monitoring approaches must evolve beyond traditional ecological assessments toward frameworks capable of integrating biological, social, and economic dimensions [11].

Marine mussels provide particularly valuable contributions within this context because they directly connect environmental quality with human wellbeing through seafood consumption pathways. Since mussels accumulate contaminants from their environments, concentrations measured within tissues reflect biologically available pollutants potentially entering food webs and affecting consumers [1, 2]. Historical background datasets therefore contribute not only to environmental assessment but also to public health protection.

Within sustainability frameworks, baseline metal information provides important reference conditions for ecosystem restoration and environmental management. Restoration initiatives frequently require objective benchmarks capable of evaluating ecological improvements and measuring management effectiveness. Historical biomonitoring datasets provide such benchmarks by identifying expected environmental conditions before major disturbances occur [23].

The emerging planetary health framework further strengthens these relationships by emphasizing the interconnectedness between environmental integrity and human health outcomes [11]. Climate related ecosystem alterations may affect biodiversity, food systems, contaminant pathways, and exposure risks, thereby creating increasingly complex environmental challenges [12]. Long term biological archives may therefore provide essential information supporting integrated approaches to environmental and health management.

The ESG frameworks also increasingly require quantitative indicators capable of demonstrating environmental performance and supporting transparent reporting systems. Biomonitoring data generated from marine mussels may satisfy many of these requirements because biological measurements provide objective and reproducible evidence regarding environmental quality [24, 25].

For environmental components, biomonitoring data may quantify contamination trends and evaluate ecological conditions. Social dimensions may benefit through improved seafood safety assessments and enhanced community health protection. Governance dimensions may be strengthened through transparent monitoring systems supporting evidence-based decision making and environmental accountability [24].

Consequently, marine mussels may function not only as ecological indicators but also as bridges connecting environmental science with sustainability policies and governance structures.

Future Challenges and Emerging Directions

Advancing the capabilities of marine biomonitoring requires resolving critical methodological challenges while integrating innovative technological tools to address escalating environmental complexities (Figure 6). A primary constraint within current frameworks is the lack of universal standardization across different regions and tissue types, where confounding variables - such as species differences, localized environments, shifting seasonal cycles, and disparate analytical procedures - frequently complicate cross-study comparisons [8, 14]. To build reliable long-term datasets, the discipline must prioritize the standardization of biological and procedural metrics, specifically optimizing size normalization, age classification, collection seasons, and quality assurance workflows [26]. As outlined in Figure 6, establishing these robust foundations is crucial for decoding modern marine ecosystems that face simultaneous, overlapping stressors from chemical pollution, climate alterations, habitat degradation, and biodiversity loss, which frequently warp biological responses in ways traditional observation models cannot interpret [12]. To map these intricate interactions, the framework leverages emerging digital assets, utilizing machine learning algorithms, chemometric profiling, remote sensing, and open-access global databases to facilitate broad-scale collaboration and enhance predictive forecasting [10, 26]. Ultimately, as visualized in Figure 6, aligning mussel tissue archives with complementary modern indicators - such as genomic responses, microbial profiles, and macro-level ecosystem dynamics - drives a crucial paradigm shift, evolving biomonitoring from isolated, reactive observational programs into interconnected environmental intelligence networks designed for adaptive coastal management and sustainable governance.

Despite substantial advances in biomonitoring science, several important challenges remain. One persistent limitation involves the absence of universally standardized approaches for integrating multiple tissues and regions into coherent monitoring frameworks. Variability arising from species differences, environmental conditions, seasonal fluctuations, and analytical procedures frequently complicates direct comparisons among studies [8, 14].

Standardization of biological and methodological variables therefore remains an important priority. Factors including size normalization, age classification, sampling season, and quality assurance procedures should be carefully considered when developing long term datasets. Such standardization may strengthen comparability and improve reliability of predictive analyses [26].

Another challenge concerns the increasing complexity of environmental stressors. Contemporary ecosystems experience simultaneous influences from contaminants, climate change, habitat alteration, and biodiversity loss. Interactions among these factors may modify biological responses in ways that traditional monitoring frameworks cannot fully capture [12].

Emerging technologies may provide opportunities to address such limitations. Machine learning approaches, chemometric analyses, remote sensing techniques, and integrated environmental databases may enhance interpretation of large biomonitoring datasets [10, 26]. Furthermore, the development of open access environmental databases may facilitate global collaboration and improve long term ecological forecasting.

Future research should also investigate how biological archives may interact with additional environmental indicators including genomic responses, microbial communities, and ecosystem level variables. Integrating such information may strengthen understanding of ecological processes and improve predictive capabilities.

Ultimately, future biomonitoring systems may evolve from isolated observational programmes toward integrated environmental intelligence networks capable of supporting adaptive management and sustainability initiatives.

Concluding Perspective

The evolution of marine mussel biomonitoring reflects a broader transition occurring within environmental science itself. Traditional monitoring approaches were primarily designed to identify contamination and evaluate environmental quality at specific locations and times. While these objectives remain essential, increasing environmental complexity now requires broader perspectives capable of integrating historical understanding with future prediction. The evidence synthesized from Baltic and Malaysian studies demonstrates that soft tissues, byssus threads, and shells function as complementary biological archives that record environmental information across different temporal scales. These archives preserve ecological memories concerning contaminant exposure, environmental variability, and biological responses. Consequently, background metal concentrations should not be regarded simply as static reference values but rather as dynamic ecological signatures capable of revealing environmental change.

Future applications of biomonitoring may increasingly involve predictive environmental assessment, sustainability planning, ESG implementation, and planetary health frameworks. Historical datasets generated through decades of Mussel Watch activities provide valuable opportunities for developing environmental forecasting systems capable of identifying emerging risks and supporting proactive decision making. The transition from Mussel Watch to future coastal forecasting therefore represents more than a methodological development. It represents a conceptual transformation in which marine mussels become not merely passive indicators of contamination but active contributors to environmental intelligence, sustainability, and the long-term protection of coastal ecosystems and human wellbeing.

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