State of the art of trace metal detection in the mediterranean coastal marine environment, combinatorial approach using *mytilus galloprovincialis* and surface sediments

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Abstract. This literature review focuses on the use of *Mytilus galloprovincialis*, a common Mediterranean bivalve, as a bio-indicator for the detection of trace metals in the Mediterranean coastal marine environment. By analyzing various studies, we examined the ability of *Mytilus galloprovincialis* to bioaccumulate trace metals and its effectiveness as an environmental monitoring tool. We explored the methodologies employed, the levels of contamination detected, and the ecological and health implications. This review highlights current trends, gaps in knowledge, and proposes recommendations for future research. It offers a global perspective on the importance of *Mytilus galloprovincialis* in assessing the quality of the Mediterranean coastal marine environment, and highlights its potential role in environmental management strategies.
Keywords. Trace Metals, Mediterranean Coastal Marine, Mytilus galloprovincialis, Surface Sediments.

1 Introduction

The Mediterranean, with its vast 46,000 km of coastline, is a region of immense ecological and cultural importance, home to some of the planet's most precious coastal ecosystems [1-5]. Despite their importance, Mediterranean coastal zones are among the most vulnerable to environmental threats, facing various anthropogenic pressures contributing to pollution, including contamination by trace metals [6].

Trace metals in marine environments are a growing concern because of their ability to accumulate in ecosystems and affect the health of both marine organisms and humans. These metals, including mercury, lead, cadmium, copper and zinc, come from a variety of sources, both natural and anthropogenic. Industrial activities, agriculture, urban waste and mining are all major anthropogenic sources, while soil erosion and rock weathering also contribute to their presence in the marine environment [7]. Their impact on marine ecosystems is profound, affecting biological and ecological processes and potentially leading to bioaccumulation in the food chain, thus posing a direct risk to human health [8-11].

The Mediterranean coastal marine environment, remarkable for its rich biodiversity and vital importance too many human societies, is today facing increasing challenges due to the presence of trace metals [12]. These metals, from anthropogenic sources such as industry, agriculture and urbanization, as well as natural sources such as soil erosion, accumulate in marine ecosystems [13-15]. Their presence can have adverse effects on the health of marine ecosystems, affecting not only marine flora and fauna but also, by extension, public health through the food chain [5]. This situation underlines the urgency of adopting management and environmental monitoring measures to mitigate metallic contamination and preserve the health of Mediterranean marine ecosystems, as well as the well-being of the communities that depend on them [16].

In terms of detection and monitoring, traditional techniques such as spectrometry and chemical methods are complemented by emerging approaches that exploit bioindicators and sediments [17]. Bioindicators, such as certain mollusc species like *Mytilus sp.*, are particularly valued for their ability to accumulate trace metals, reflecting environmental contamination without the need for invasive or large-scale sampling [18-20]. Sediments, on the other hand, serve as a historical archive of metal contamination, making it possible to trace the evolution of metal inputs into the marine environment [21-24]. By providing precise data on contamination levels, these techniques are crucial to the development of management and mitigation strategies aimed at protecting marine ecosystems and public health [25].

In this context, an accurate and comprehensive assessment of trace metal contamination in the Mediterranean coastal environment is crucial. This paper proposes an innovative approach for the detection of these metals, using a combination of analyses on the mussel *Mytilus galloprovincialis*, widely distributed on Mediterranean coasts, and on surface sediments, in order to provide a holistic view of metal contamination

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in this environment and contribute to the development of effective management strategies to preserve marine ecosystem health and food security.

2 The importance of detection

The presence of trace metals in Mediterranean coastal areas can be attributed to a variety of natural processes. Here are some of the natural sources of trace metals in several areas.

Trace metals are necessary for the proper functioning of many biochemical and physiological processes in humans, animals and plants. For example, over 300 enzymes and 200 transcription factors require zinc as a cofactor for the maintenance of membrane integrity, auxin metabolism and reproduction [26]. Molybdenum (Mo), vanadium (V), nickel (Ni) and cobalt (Co), as critical constituents of nitrogenase, an enzyme for the reduction of dissolved N2 to NH3, for the synthesis of vitamin B12 or as cofactors for photosynthetic enzymes, could play a key role in N2 fixation and thus in the growth of diazotrophic species [27-29]. Cobalt is also essential to the metabolism of living organisms. It plays a role in the synthesis of fatty acids, DNA, RNA and in energy production [30]. Cobalt (Co) and zinc (Zn) are involved in carbon and hydrogen transfer reactions during phytoplankton respiration, and thus play a key role in the development of several planktonic species ranging from coccolithophores to diatoms. Cadmium (Cd) could replace Zinc (Zn) for several phytoplanktonic species and enhance their growth when Zn is limited. Studies have also shown that certain TMEs, such as copper, can promote the growth of beneficial bacteria that contribute to the degradation of organic matter and nutrient cycling. The significant effect of copper (Cu) on the growth of coastal and oceanic diatoms has been observed, while the availability of cobalt (Co) is a key factor in the growth of the cyanobacterium Prochlorococcus. The importance of Nickel (Ni) in nitrogen fixation by the diazotrophic species Trichodesmium has been demonstrated under high light conditions [31].

Trace metals can have toxic effects on marine organisms, including fish, mollusks and micro-organisms. These organisms, present in water, are particularly sensitive to the effects of heavy metals; for example Certain trace metals such as cadmium (Cd) and lead (Pb), when introduced at concentrations above 0.11mg.L-1 into natural communities sampled in the Mediterranean or North Seas, inhibit cell abundance and growth rates in all phytoplankton populations [32]. In fish, copper toxicity leads to disruption of membrane lipids and the formation of reactive oxygen species [33, 34], altering fish gills and delaying spawning. This can disrupt marine food chains and affect biodiversity, leading to changes in marine community structure and reduced biodiversity [35, 36]. Heavy metals can alter the physico-chemical characteristics of marine environments, such as salinity, pH and oxygen content, with consequences for the survival of marine species [37-39]. For example, copper can inhibit the nitrogen-fixing processes of marine bacteria, disrupting the availability of essential nutrients for marine organisms [10, 23, 40].

Populations that depend on marine resources for their food can be exposed to toxic trace metals present in marine organisms, leading to risks for human health, as these elements, such as Hg, Pb , Cd ,As ,Ni and Cr, accumulate over time and become a threat to human life, causing various types of illness, such as increased blood pressure, brittle bones, joint pain, as well as dysfunction of the hepatic, gastrointestinal, renal and reproductive systems, such as infertility in women and serious problems for the foetus, cell apoptosis [41, 42]. Many have long-term carcinogenic effects [5, 43, 44]. High concentrations of heavy metals in Mediterranean coastal water can also pose challenges for the production of drinking water in desalination plants [45, 46].

Monitoring heavy metals in the coastal marine environment helps ensure compliance with environmental standards and regulations. These include water quality standards, heavy metal concentration limits in fishery products, and protected area management guidelines. Early detection and monitoring of heavy metals facilitates the implementation of corrective measures and environmental policies to ensure compliance with regulations. Heavy metal monitoring helps control industrial discharges and local sources of pollution [3, 36, 47]. This promotes more sustainable management of the coastal marine environment, by identifying sources of contamination and imposing pollution prevention and abatement measures where heavy metal discharges can be frequent [48-50].

3 Anthropogenic sources and marine pollution

Human activities along the Mediterranean coast play a key role in marine contamination by trace metals (TMEs) such as mercury, lead, cadmium, copper and zinc. The sources of this contamination vary widely, including heavy industries such as metallurgy and chemicals, agriculture with its intensive use of fertilizers and pesticides, and dense maritime traffic around Mediterranean ports [51]. These activities lead to the release of metals into the coastal environment, either directly through discharges into water, or indirectly through atmospheric deposition and runoff. In addition, urban and industrial areas also contribute to this pollution through inadequate waste management and atmospheric deposition, while coastal mining operations and sewage and desalination plants add to the complexity of the problem. Even tourism and recreational activities do not escape this list, introducing metals into the marine environment by various means [52].

Accidental spills and waste represent another significant facet of TME pollution in the Mediterranean. Ship accidents can release hydrocarbons that dissolve trace metals, while industrial failures and waste, whether plastic or industrial, exacerbate the situation by dispersing these contaminants into coastal ecosystems. Plastic waste, in particular, plays a worrying role in

adsorbing and dispersing metals in the marine environment. This complexity of TME pollution sources calls for an integrated approach to understanding and mitigating their impact on the Mediterranean coastal environment.

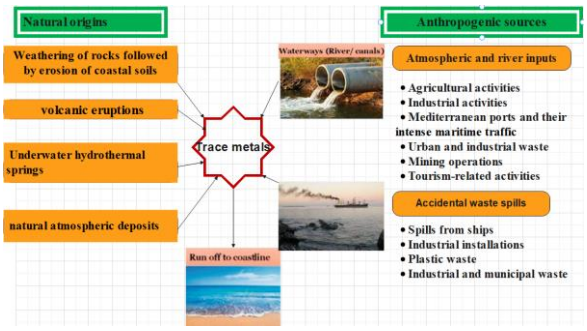

Fig. 1. Main pathways of trace metal contamination of the marine coastal environment

4 Factors influencing trace metal detection

Trace metal detection in the coastal marine environment is a complex subject, and several factors can influence the accuracy and sensitivity of detection methods. Here are some of the main factors to consider.

4.1 Human activities and metal conditions

Human activities along the coasts of the Mediterranean, including increasing urbanization, industrial expansion, intensive agricultural practices, coastal development, flourishing tourism, and fishing, as well as incidents of accidental spills, play a major role in increasing levels of trace metals in the coastal marine environment. These activities release a range of pollutants, including trace metals, directly into coastal waters via industrial discharges and wastewater, making their identification and quantification particularly challenging in areas where human impact is most pronounced. The complexity of detecting these metals is accentuated by several factors, including the diversity of metals present, their different physicochemical properties which influence their reactivity and detectability, and the level of their concentration in the environment.

The sensitivity of detection methods varies significantly according to metal type, with unique properties such as electrical conductivity, susceptibility to corrosion, and interaction with specific detection wave frequencies, playing a key role in this variability. Metals present in large quantities are generally easier to identify, while the detection of minute traces requires the use of highly sensitive and specific analytical techniques. Furthermore, the presence of other substances in water, such as salts, organic compounds and suspended particles, can further complicate the task by introducing interferences that affect the reliability of results, potentially leading to measurement errors [53].

The analytical methods employed for the analysis of metals in the marine environment each have their own strengths and limitations, including varying detection thresholds, necessitating judicious selection according to the specific objectives of the study [54]. In addition, the temporal dynamics of metal concentrations, influenced by factors such as seasonal cycles, tides and variations in human activities throughout the year, require meticulous planning of sampling campaigns to accurately capture these fluctuations [55]. Thus, to optimize the accuracy and efficiency of trace metal detection in coastal marine environments, it is essential to combine suitable analytical methods, a well-designed sampling strategy, and a thorough understanding of local and regional influences. This holistic approach ensures effective and reliable monitoring of metal pollution, essential for the management and protection of Mediterranean marine ecosystems.

4.2 Geographic and oceanographic conditions

Geographic and oceanographic conditions are keys to understanding the influence on trace metal detection in the Mediterranean coastal marine environment. The topography of the seabed, with its submarine canyons and landforms, plays a role in the dispersion and accumulation of trace metals, with certain geographical areas becoming hot spots for their concentration. Sea currents, upwelling winds, wave fields and surface current convergences transport trace metals over long distances, despite pollution sources concentrated in coastal areas. Environmental conditions such as climate, tides and other factors, as well as water salinity and temperature, also influence the dispersion of metals in water [56]. Variations in salinity, due to evaporation and freshwater inflow, can affect the solubility of trace metals, just as rising temperatures can reduce the adsorption of certain metals to ligands and promote the degradation of the organic compounds that bind them [57]. The properties of marine sediments, such as their composition and retention capacity, as well as marine biomass, through bioaccumulation by organisms such as *Mytilus galloprovincialis*, influence the distribution of trace metals. Finally, atmospheric circulation plays a role in the introduction of these metals into the Mediterranean Sea from distant regions. Understanding these multiple factors enables scientists to more accurately interpret the results of trace metal detection analyses at marine coastal level.

5 Indicators used

5.1 Bivalves as biological models

Marine bivalves, notably *Mytilus galloprovincialis*, *Donax trunculus*, and *Mactra corallina*, have been used as bioindicators for metals, a method validated by various research studies since the 1970s. Their wide geographical distribution along the coasts of the Mediterranean basin, their well-known biology, their sessile lifestyle, and their resilience to various environmental stresses make them particularly well suited to this use [58]. These mussels are found on a variety of substrates, from rocks to artificial structures, enabling them to colonize numerous coastal habitats.

Their ability to accumulate high concentrations of pollutants, combined with a diversified diet and stable population, makes them ideal sentinels for pollution monitoring.

Environmental monitoring using these bivalves offers multiple benefits. They act as sentinel species, allowing metal concentrations to be detected in their tissues, reflecting water quality and the presence of pollutants [59]. Their sedentary nature facilitates integrated temporal and spatial monitoring of specific areas, while the ease of sampling makes this method economical for regular monitoring. As components of many marine food chains, mussels provide insight into contaminant transfer in food webs. Their wide distribution allows comparisons between different coastal zones, helping to identify areas of high contamination and direct environmental management efforts. Finally, this monitoring contributes to the assessment of regulatory compliance, essential for the protection of the marine ecosystem and human health [60].

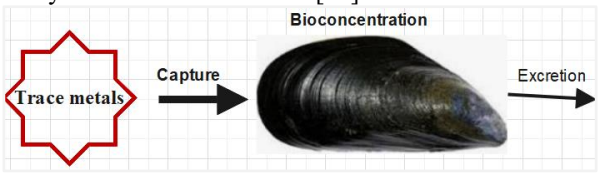

Fig. 2. Bioconcentration process

The process of bioaccumulation, where living organisms accumulate contaminants to levels above those in their environment, is crucial in this monitoring [61,62].

Mussels capture trace metals by dietary filtration, adsorption to the gills, endocytosis, and ligandation and complexation, with specific mechanisms enabling uptake and storage in various organs. Accumulation in excretory and reserve organs is an integral part of this process, reflecting the ability of mussels to sequester and eliminate metals. Bioaccumulation is influenced by many factors, including the physico-chemical characteristics of the environment, the chemical properties of contaminants, and the biological factors of the organism, resulting in significant seasonal and spatial variations. Understanding these variations is vital for assessing the impact of trace metals on the environment, requiring in-depth studies and regular monitoring for effective management of coastal ecosystems.

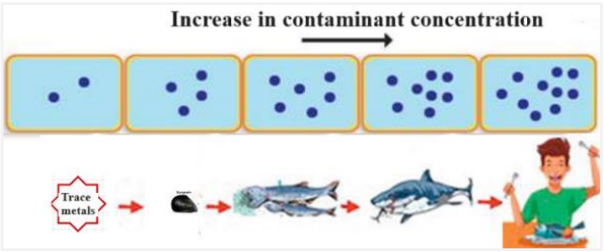

Fig. 3. Biomagnification process

5.2 Surface sediments as historical witnesses

Continuous analysis of marine sediments plays a key role in understanding trace metal contamination, acting as a long-term reservoir for these substances. Through the study of sediments, it is possible to trace the history of contamination, identify potential sources and assess temporal variations in metal pollution [63].

The interaction processes between marine sediments, seawater and metal cycles are complex but essential to the dynamics of coastal ecosystems. These interactions include adsorption and desorption, where sediment particles capture or release metal ions; complexation, which sees certain metal ions form chemical bonds with organic or inorganic ligands; and ion exchange, where there is substitution between metal cations and ions present in sediments, influencing their concentration in seawater. Other processes such as precipitation-coprecipitation and dissolution also play a role in the fate of metals in aquatic environments [64].

These interactions are strongly influenced by factors such as sediment pH, redox potential, grain size and chemical composition, as well as by the ionic composition of pore waters, which can either trap metals in sediments or release them into the water column. In addition, the sediment dynamics of trace metals are controlled by processes such as early diagenesis, diffusion, bioturbation and sediment resuspension. These processes influence not only the deposition and sedimentation of metal particles, but also their remobilization, release or fixation in sediments, as well as the transport of metals to other environments [65].

Marine sediments function as reservoirs accumulating trace metals over time, with important environmental implications. The bioavailability of remobilized metals, their bioaccumulation in marine organisms, and the contamination of benthic organisms living in close contact with sediments, are critical factors affecting water and sediment quality. The analysis of metals in sediments serves as an indicator of this quality, making it possible to assess the impact of human activities on coastal environments. The management of trace metals in coastal environments requires a thorough understanding of the mechanisms of metal storage, release and transport in marine sediments, underlining the need for regular monitoring programs and appropriate management strategies to protect coastal ecosystems [66].

Marine sediments, influenced by factors such as pH, redox potential, grain size and chemical composition, play a key role in the speciation and mobility of trace metals (TMEs), trapping or releasing them into the water column. Sediment dynamics and TME mobility are governed by four key processes: early diagenesis, elemental diffusion, bioturbation and sediment resuspension. These processes include deposition and sedimentation of metal particles by gravity, influenced by water turbidity and suspended particle properties; diagenesis, which can bind or release metals in sediments; remobilization of metals in seawater via desorption; and bioturbation, where biological activity in sediments reshuffles particulate material, affecting metal distribution. In addition, sediments act as temporary reservoirs, influencing the transport of metals to other environments [67].

Coastal marine sediments are essential as reservoirs and sources of TMEs, contributing to the dynamics of biogeochemical cycles. MTEs accumulate in marine

sediments due to their affinity for the particulate phase, potentially leading to high concentrations in contaminated areas.

This accumulation has important environmental implications, particularly in terms of bioavailability and bioaccumulation, affecting marine organisms and food chains, as well as contamination of benthic organisms. The analysis of metals in sediments also serves as an indicator of water and sediment quality, making it possible to assess the impact of human activities on the coastal environment [68]. Effective management of TMEs in coastal environments requires a thorough understanding of the mechanisms by which metals are stored, released and transported in marine sediments. To minimize the impact of metals on coastal ecosystems, regular monitoring programs and appropriate management strategies are essential.

This comprehensive approach is crucial for assessing and managing metal contamination in marine ecosystems, thereby safeguarding the health of coastal ecosystems and food security. In-depth studies and constant monitoring are needed to understand the impact of human activities on these cycles and to implement effective management strategies.

6 Techniques, assessment methods and results

6.1 Sampling and sample preparation

Mussel samples were collected along the coast and brought back to the laboratory, where they were stored at -10°C for analysis. Sampling locations covered a variety of environmental contexts, including agricultural, recreational, port, industrial and urban areas. At the same time, superficial sediment samples (3 to 5 cm deep) were collected in the vicinity of mussel habitats, with several replicas taken at each site. These sediment samples were stored in acid-washed polyethylene bags before being frozen for analysis. For preparation, the mussels were thawed at room temperature, the soft tissues extracted from the shells, and the samples oven-dried to standardize measurements and reduce variability in metal concentrations.

Sediments underwent a similar treatment, with sieving to remove large particles. Digestion of mussel soft tissues was carried out in concentrated nitric acid, with an initial step at low temperature followed by complete digestion at high temperature for at least three hours. For sediments, approximately 1 g of each dry sample was digested in a mixture of concentrated nitric and perchloric acid, also started at low temperature before being brought to a higher temperature.

Digested samples were diluted with double distilled water (DDW), filtered, and the filtrate stored for metals analysis.

The data collected for this study have been presented in the MED POL database for different countries and matrices, highlighting mussel and sediment sampling over several years, and illustrating the geographical and temporal diversity of sampling in the Mediterranean basin.

These data provide valuable insight into the presence and concentration of trace metals in the coastal marine environment, underlining the importance of continuous monitoring to assess the health of marine ecosystems.

6.2 Main techniques used

Atomic absorption spectrometry (AAS) is a technique that measures the UV/visible light energy absorbed by vaporized metal atoms at a specific wavelength, corresponding to the energy required to excite their electrons to a higher energy level. This absorption is directly proportional to the concentration of the element in the sample, making AAS particularly useful for quantifying many metals with sensitivity down to 1 ppb. Flame atomic absorption spectrometry (FAAS) is favored for its simplicity and ability to analyze a wide range of metals in diverse samples. Conversely, electrothermal atomic absorption spectrometry (SAAET) requires a graphite furnace for high atomization temperatures, offering increased sensitivity even with small sample volumes, but limited to the analysis of a single metal at a time.

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is distinguished by its ability to analyze multiple elements simultaneously at trace levels, with high precision and accuracy. It requires digestion of solid samples prior to analysis, typically using HNO_3 or a mixture of HNO_3 and H_2O_2, before atomizing and ionizing the material in argon plasma.

The ions produced are then sorted according to their mass-to-charge ratio before detection, enabling sensitive and detailed analysis of many elements, although this technique is costly and requires specialized technical expertise. Finally, X-ray fluorescence spectrometry (XRF) offers a non-destructive analytical method that analyzes the radiation emitted by a sample excited by X-rays. This radiation, specific to the composition of the sample, enables qualitative and quantitative identification of the elements present, although the technique is limited to certain elements and requires prior calibration with standard concentrations. XRF stands out for its speed and the ability to analyze several metals simultaneously without destroying the sample.

6.3 Evaluation methods

The method employed was the evaluation of the most recent MED POL datasets available, concerning levels of chemical contaminants in relation to established environmental criteria (for different matrices) and on a regional scale. Heavy metals were initially assessed using the MED POL database of coastal monitoring networks by country. Contamination levels in the various matrices examined: mussels and sediments were compared with BAC thresholds (Assessment of Reference Concentrations),(UNEP/MAP, 2016). For indicative purposes, an EEB assessment effort was carried out based on the thresholds adopted by COP19 in February 2016 for the Mediterranean Sea

(UNEP/MAP, 2016). These are based on European biota policy (EC/EU Directives 1881/2006 and 629/2008 on maximum levels for certain contaminants in foodstuffs) and US Low-Range Effects (LRE) values (The Toxicological Criteria for Low-Range Effects on Sediment - in force in the USA - Table 1) although the former may not be environmentally accurate.
Apart from this limiting fact, this is in line with the approach observed by other regional seas (i.e. OSPAR). This is the case for passive biomonitoring, carried out by RNO (Réseau National d'Observation de la Qualité du Milieu Marin), Mussel Watch, and active biomonitoring carried out by RINBIO (Réseau Intégrateurs Biologiques).

6.4 Results obtained

Data from the MED POL program for the assessment and control of marine pollution in the Mediterranean region, as well as recent publications, were analyzed to assess the presence of heavy metals in bivalves and marine sediments. These data, supplied annually by various countries, enabled a precise assessment based on µg/kg dry weight units for mussel soft tissues and sediments. Analysis of heavy metals in bivalves revealed that 8% of the stations studied had lead (Pb) levels above the thresholds set by the European Commission (EC), mainly due to mining and industrial activities along the Spanish, Italian and Croatian coasts. On the other hand, cadmium (Cd) and mercury (Hg) levels remain below these thresholds, indicating that, despite high Pb concentrations in certain hot spots, environmental conditions remain generally satisfactory in relation to the maximum limits set for foodstuffs by the EC. In the case of marine sediments, the situation is somewhat different, particularly for Hg and Pb. Pb and Cd levels are generally below the thresholds for toxic effects, with slightly elevated Cd levels near the Strait of Gibraltar attributed to natural water influx processes from the Atlantic. However, Hg levels exceed these thresholds in several regions, notably in the north-western Mediterranean, the Adriatic Sea, the Aegean Sea and the Levant Sea basins, mainly due to industrial mining. These regional analyses of heavy metal levels in bivalves and sediments highlight the need for ongoing monitoring and management measures to preserve the health of Mediterranean marine ecosystems.

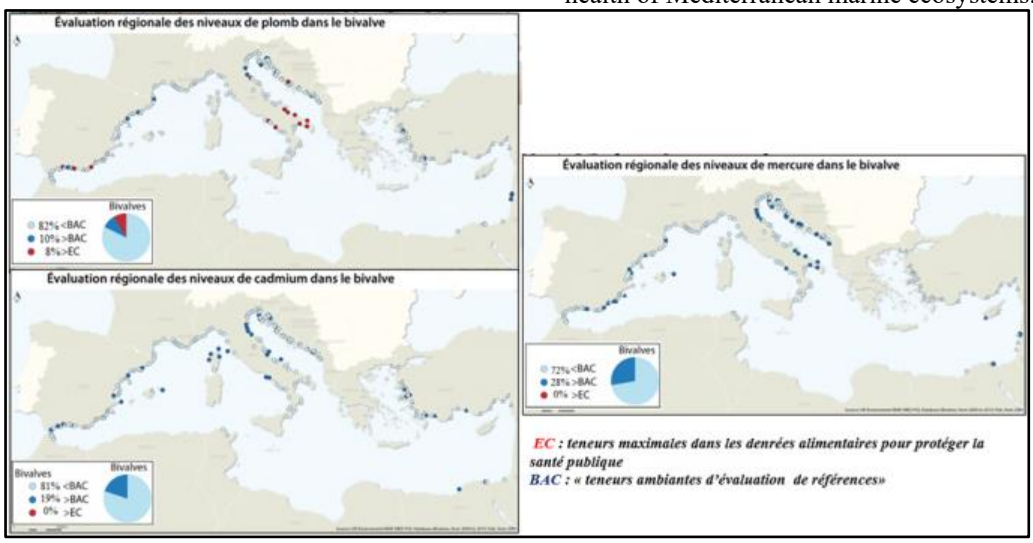

Fig. 4. Regional assessment of heavy metal levels in relation to BAC/EC criteria in bivalves (*Mytilus galloprovincialis*)

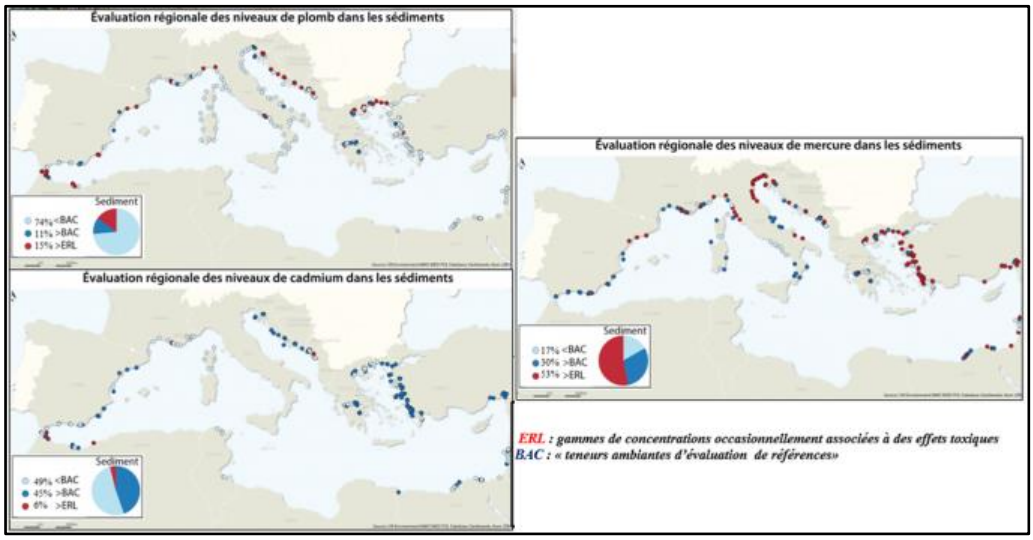

Fig. 5. Regional assessment of heavy metal levels in relation to BAC/ERL criteria in sediments

7 Exploring the combinatorial approach: *Mytilus sp.* and sediments

7.1 Benefits and challenges of the approach

The integration of analyses of two distinct environmental matrices, encompassing both living organisms (*Mytilus galloprovincialis*) and their environment (surface sediments), offers a comprehensive perspective on metal contamination, essential for environmental monitoring.

This approach makes it possible to assess contamination by identifying the trace metals of greatest concern, whether of anthropogenic or natural origin, and to monitor metal bioavailability and bioaccumulation in food chains. Mussels, by bioaccumulating trace metals (TMEs) in their tissues, reflect historical exposure and respond to recent variations in TME concentrations, providing both a short- and long-term view of contamination. At the same time, sediments act as a long-term reservoir for these metals, providing a historical overview of the area's contamination.

This method is easily adapted to local conditions, using specific bioindicators and sediment sampling sites to enhance regional relevance. It also provides valuable indicators of water and sediment quality, and helps assess compliance with environmental standards, facilitating risk management and regulatory decision-making.

The data collected supports scientific research into biogeochemical cycles and the complex interactions between sediments and marine organisms. Nevertheless, this approach has limitations, such as the spatial and temporal variability of TMEs in sediments and the mobility of mussels, which can introduce uncertainties. Interactions between mussels, sediments and ETMs can be complex, making precise attribution of contamination sources difficult.

In addition, environmental factors such as salinity, temperature and season can influence results, adding to the complexity of data interpretation. Although bioaccumulation in mussels is measurable, this approach does not provide direct information on metal mobility in sediments, underlining the need for a holistic and multidimensional approach for accurate and comprehensive interpretation of monitoring results.

7.2 Integration of bioaccumulation and sediment data

The combined approach of bioaccumulation and sediment analysis plays a crucial role in assessing trace metal (TME) contamination in coastal marine environments. The methodology for integrating these data involves several essential steps. Initially, it is necessary to gather data on the concentration of TMEs both in marine sediments and in living organisms such as fish, mussels and crabs, based on field sampling and laboratory analysis.

To enable adequate comparison between the different matrices, the data collected must be normalized according to the mass or dry weight of the samples. It is also crucial to compare these concentrations with regulatory thresholds defined by environmental authorities to identify areas at risk. The use of spatial mapping tools enhances this analysis by geographically locating high concentrations of ETMs, while statistical analyses can detect correlations between ETM concentrations in sediments and in organisms, thus revealing contamination mechanisms and potential sources of ETMs.

The use of predictive models is another key step, making it possible to estimate ETM concentrations based on different environmental parameters and to better understand bioaccumulation dynamics. Finally, the establishment of a continuous monitoring program is essential for observing temporal trends in ETM concentrations, assessing the effectiveness of environmental management strategies and anticipating changes in coastal marine environments. This integrated approach provides a comprehensive and in-depth view of TME contamination, facilitating effective and preventive management of marine resources and the coastal environment.

7.3 Reliability of results

Adopting a combined approach to the analysis of *Mytilus galloprovincialis* and sediments in the assessment of trace metal contamination in Mediterranean coastal areas represents an effective strategy for obtaining a comprehensive overview of the environmental situation. For results to be reliable and meaningful, it is crucial to follow rigorous sampling and preparation protocols. Standardized methods not only ensure the consistency of the data collected, but also guarantee that measurements are reproducible and comparable across different studies. This step is fundamental to establishing a solid basis for contamination assessment.

The judicious choice of analytical methods also plays a decisive role in the accuracy and reliability of results. Advanced techniques such as ICP-MS and XRF spectrometry are particularly valued for their sensitivity and ability to detect low concentrations of trace metals. The implementation of rigorous quality controls, including the use of certified reference materials and the performance of duplicate checks, is essential to validate the accuracy of measurements and to identify any contamination or procedural deviations that could affect results.

Interpreting the data collected requires a thorough understanding of the environmental context specific to the study area. Taking into account the natural variability of metals in the Mediterranean environment and distinguishing anthropogenic influences from natural background levels are critical aspects for an accurate assessment of contamination. In addition, analysis of correlations between metal concentrations in sediments and in mussels can provide valuable insights into contamination pathways and accumulation processes.

Cross-validation of the results obtained with other environmental indicators enriches the analysis and

confirms the validity of the trends observed. Setting up long-term monitoring programs is beneficial for tracking changes in metal concentrations and assessing the impact of environmental management measures. Transparency in the communication of results, including full disclosure of the methods used and associated uncertainties, reinforces confidence in the conclusions and promotes evidence-based management. In short, by carefully integrating these various elements into trace metal contamination studies, it is possible to provide accurate and reliable data on the ecological status of Mediterranean coastal zones.

This information is essential to support conservation efforts and guide environmental management decisions, thus contributing to the protection and preservation of marine ecosystems.

Conclusion

The investigation into trace metal detection within the Mediterranean coastal marine environment underscores a pivotal need for a multi-faceted strategy that leverages both biological indicators, like *Mytilus galloprovincialis* (mussels), and the analysis of surface sediments. This dual approach not only sheds light on the intricate web of interactions linking human endeavors, marine ecosystems, and metal pollutants but also emphasizes the imperative of continual surveillance and forward-thinking stewardship of marine resources.

Utilizing mussels as bioindicators offers a real-time window into the bioavailability of trace metals, reflecting the immediate impact of these substances on the marine environment. This method stands in contrast to sediment analysis, which archives historical data on trace metal accumulation and hints at the potential origins of such contamination. The marriage of these two methodologies facilitates a holistic understanding of the environmental threats posed by trace metals, fostering a more nuanced assessment of risk.

Nonetheless, this field faces numerous hurdles, including the vast array of pollution sources, the geographical and seasonal fluctuations in metal deposition, and the evolving nature of contamination pathways.

Addressing these challenges demands an enhancement of existing detection methods, an expansion in the spectrum of metals under scrutiny, and a deeper exploration into the dynamics of metal transport and accumulation within marine organisms and ecosystems. Future endeavors must pivot towards honing these detection technologies, widening the metal detection spectrum, and unraveling the complex processes of metal transport and bioaccumulation. Such efforts are critical for advancing our comprehension of how these metals interact with marine environments and affect biological systems.

Ultimately, this comprehensive analysis underscores the paramount significance of persistent monitoring of the Mediterranean's coastal waters. It advocates for an integrated approach that combines the strengths of bioindicator species and sediment analysis to forge a deeper understanding of, and devise effective strategies against, the pollution by trace metals. By doing so, it aims to safeguard the vitality of marine ecosystems and ensure the continued viability of human activities in this essential region, thereby contributing to the broader goal of preserving marine health and ecological integrity in the face of ongoing environmental challenges.

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