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Trace Element Correlations in Mussels and Sediments on the Moroccan Mediterranean Coast

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ABSTRACT

This study investigated the correlation between the levels of chromium (Cr), lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) in surface sediment samples and those in the total soft tissues of the mussel *Mytilus.galloprovincialis*, collected off the northern Moroccan coast in the Mediterranean. The objective was to examine the accumulation patterns of these heavy metals in *M..galloprovincialis* relative to their concentrations in the sediment. Detailed sampling of sediments and *Mytilus galloprovincialis* mussels were carried out at three specific stations to measure trace metal concentrations. A perfect correlation was observed for Pb levels between the mussel tissues and sediment. The sampling methods were carefully planned to ensure data accuracy and consistency, following strict protocols to reduce contamination and maintain sample integrity. In contrast, Cr showed only a weak correlation. The correlations for the other trace metals (Cd, Zn, and Cu) varied from strong to weak and were both positive and negative, but none were statistically significant. These findings underscore the potential of *M..galloprovincialis* as an effective biomonitoring species for Pb. However, additional research and more comprehensive analyses are necessary to establish firmer conclusions regarding the correlations for the other metals.

Keywords: trace metals, correlations, sediment, *M. galloprovincialis.*

INTRODUCTION

The industrial and urban expansion along the world's coastlines has accelerated the entry of pollutants into marine systems, with trace metals standing out as particularly harmful contaminants (Liu, 2023, Öncel and Levend, 2023). These substances, once introduced into the marine environment, do not readily break down and instead accumulate over time, posing long-term ecological and health risks (Tursi, 2022, Rellán, 2023). In regions like the Mediterranean coast of Morocco, the confluence of intensive port activities, burgeoning tourism, and various industrial outputs further magnifies the risk of heavy metal pollution (Achoukhi, 2023). This area, known for its rich biodiversity and as a cornerstone of local economic activities such as fishing and tourism, faces significant environmental threats that could undermine both the natural ecosystem and the health of local communities (Elabdouni, 2020, Abdouni, 2021, Elabdouni, 2022).

The presence of trace metals like mercury, lead, and cadmium in marine environments is particularly alarming due to their high toxicity and capacity for bioaccumulation in marine organisms (Andaloussi, 2021, Negahdari, 2021, Botté, 2022, Elyoussfi, 2023, Salhi, 2023, El Hammoudani, 2024, Simou, 2024). These metals can enter the food chain, where they concentrate as they move up the trophic levels, ultimately posing serious health risks to both marine species and humans who depend on these marine resources for food (Jeroundi, 2016, El Hammoudani, 2019, El Hammoudani and Dimane, 2020, El Hammoudani, 2021). Therefore, regular monitoring of these pollutants becomes crucial, not only to assess the current contamination levels but also to understand the long-term trends and impacts of industrial and urban discharges into marine environments (Elazzouzi, 2019, Tighadouini, 2019, Elazzouzi, 2021, Khellaf, 2023).

Moreover, studying the impact of trace metals in marine settings like the Mediterranean coast of Morocco provides critical data that can influence policy decisions (Tnoumi, 2020, Belhouchet, 2024). This research can lead to the development of more stringent environmental regulations and the implementation of targeted remediation programs aimed at reducing the emission of dangerous pollutants. It also informs the development of community health advisories and helps in shaping sustainable practices for industries that are pivotal to the economy but are also potential sources of marine pollution (El Ouaty, 2022, Yahyaoui, 2022, Zaidi, 2022). In essence, the study of trace metals in such contexts serves a dual purpose: advancing scientific understanding of environmental contaminant dynamics and fostering policy frameworks that prioritize ecosystem health and human well-being (Ghribi, 2020).

The mussel *Mytilus galloprovincialis*, native to and widespread along the Moroccan Mediterranean coast, plays a pivotal role in marine pollution monitoring as a bioindicator (Kouali, 2020, Ouagajjou, 2023). This species is particularly adept at accumulating contaminants from its surroundings due to its filter-feeding behavior, which allows it to process large volumes of seawater. As it filters water for food, it also inadvertently ingests any dissolved or particulate-bound pollutants present (Azizi, 2020, Lynch, 2020). This process results in contaminants being sequestered in the mussel's tissues, providing a concentrated reflection of the environmental conditions over time.

The ability of *Mytilus galloprovincialis* to integrate and concentrate these ambient pollutants makes it an invaluable tool for environmental scientists (Benito, 2023). By analyzing the accumulations of trace metals and other contaminants in the tissues of these mussels, researchers can gauge the level of pollution in marine ecosystems (Saadi, 2021, Andrade, 2023). Such analyses not only reveal the current state of contamination but also help in tracking changes in environmental quality over time, thus providing insights into the effectiveness of implemented environmental policies and pollution control measures (Ferreira, 2021).

Internationally, the scientific community has recognized the utility of *Mytilus galloprovincialis* in ecotoxicological studies due to several advantageous traits (Tresnakova, 2023). These mussels have a relatively long lifespan and a broad geographic distribution, which allows for comparative studies across different environmental conditions and over time (Crowther, 2023). Additionally, their sedentary nature means that the contaminants they accumulate are indicative of the local environment, rather than a mix of various regions they might traverse, as is the case with many mobile marine species (Rusconi, 2024).

This species' established use in the "Mussel Watch" programs worldwide underscores its reliability as a bioindicator (Yancheva, 2023). These programs utilize mussels as sentinel species to monitor and assess the levels of pollutants, including trace metals, in aquatic environments (Pillet, 2023). The data derived from such monitoring efforts are crucial for evaluating the health and safety of marine habitats and formulating strategies to protect these environments, thereby ensuring the sustainability of marine life and the safety of human communities reliant on these resources (Fernine, 2022, Ait Mansour, 2023). Through the continued study of *Mytilus galloprovincialis*, environmental researchers can provide critical data needed for the ongoing efforts to safeguard marine ecosystems from the adverse effects of pollution (Bouknana, 2019, El Hammoudani and Dimane, 2021, El bastrioui, 2022, Miglioli, 2024).

The primary objective of this study is to examine the correlations between trace metal levels in the surface sediments and the total soft tissues of *Mytilus galloprovincialis* from selected sites along the Mediterranean coast of Morocco. By measuring and comparing the concentrations of trace metals such as lead, cadmium, and mercury, among others, in both the sediments and mussels, this research aims to:

- assess the extent of trace metal pollution in the marine sediments along the Moroccan Mediterranean shoreline;
- determine the bioaccumulation of these metals in the soft tissues of *Mytilus galloprovincialis*, providing insight into the biological impact of sediment pollution;

- explore the potential health risks to local wildlife and human populations resulting from the consumption of contaminated mussels.

Through this comprehensive study, we aim to enhance the understanding of pollution dynamics in the Moroccan Mediterranean marine ecosystem and contribute valuable data to the global efforts in marine conservation and public health safety. This research not only has local relevance but also adds to the broader discourse on marine pollution, offering insights that could inform both policy and practice in coastal management and environmental protection.

MATERIALS AND METHODS

Study area

The Moroccan Mediterranean coast extends approximately 512 kilometers from Cap Spartel in the west to the Morocco-Algerian border in the east, lying between latitudes 35° and 36° North and longitudes 6° and 2° West (Fig. 1). This region is bounded by the Atlantic Ocean to the west, the northwestern Mediterranean near Spain to the north, and the southwestern Mediterranean near Algeria to the east. The coast is characterized by its highly irregular sea depths and uneven bottom relief, which contribute to a diverse marine ecosystem (Benaissa, 2020, Benaissa, 2022, Abouabdallah, 2023, Bouhout, 2023, Bourjila, 2023, Haboubi, 2023, Haboubi, 2023, Benaissa, 2024, Bouhout, 2024, Haboubi, 2024, Touzani, 2024). Along this stretch, numerous bays punctuate the coastline, serving critical ecological and socio-economic functions. These bays provide sheltered environments that are crucial for the reproduction and development of various marine species, including sea grass beds and the early life stages of fish. The calm waters of these bays are ideal for the deposition of fish eggs and the growth of spat, thus supporting rich biodiversity.

The sampling sites for this study were strategically selected to represent a range of environmental conditions influenced by nearby human activities such as agriculture, recreation, ports, industry, tourism, and urban development. These areas vary in their degree of exposure to anthropogenic influences, which can lead to environmental confinements challenging to manage due to slow water renewal rates. The specific locations of these sites are marked by their proximity to both industrial and urban centers, highlighting the potential sources of pollution.

For the purposes of this study, four stations along the coast were chosen to collect samples:

- Station 1 (St1) – situated at the mouth of Oued Laou on the North-West coast, this station is influenced by both natural riverine inputs and nearby human activities;
- Station 2 (St2) – located in Cala Ires Bay along the Central North Coast, this site is typical of intermediate marine environments with a mix of recreational and natural characteristics;

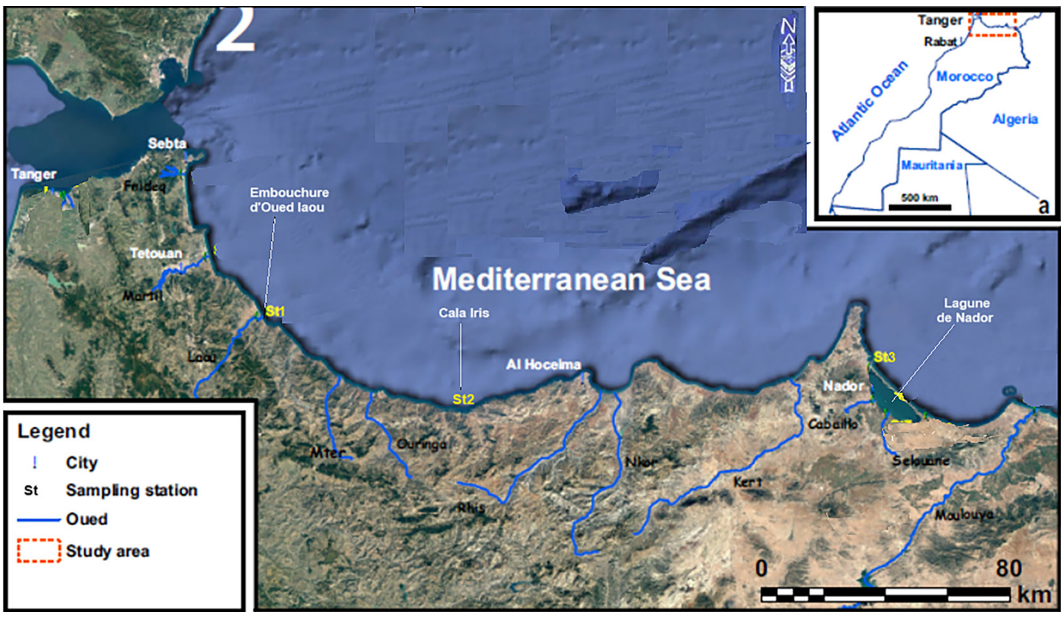

Fig. 1. Map of the location of the sampling stations

- Station 3 (St3) – found in Nador Lagoon on the North-East coast, this station is particularly noteworthy for its ecological importance and the complexity of its environmental pressures due to nearby urban and industrial activities.

Each of these stations provides a unique set of data that reflects the interplay between natural marine processes and anthropogenic impacts, offering valuable insights into the overall health and sustainability of the Moroccan Mediterranean coast.

Sample collection

In July 2023, comprehensive sampling of both sediments and *Mytilus galloprovincialis* mussels was conducted at designated stations to assess trace metal concentrations. The methodology for each type of sample was rigorously designed to ensure accuracy and consistency in the data collected, adhering to established protocols to minimize contamination and preserve sample integrity.

Sediment sampling

Sediment samples were carefully collected from the top 3 to 5 cm of coastal sediments, close to mussel habitats, using a pre-cleaned, acid-washed grab sampler. These samples were then transferred into pre-cleaned, acid-washed polyethylene bags, which were immediately sealed and stored in a cooler for transport. In the laboratory, samples were first rinsed with metal-free double-distilled water to remove any soluble salts and loose particles. Following this, they were oven-dried at 105 °C until reaching a constant dry weight, typically after about 16 hours, ensuring that moisture content did not affect the weight measurements. The dried sediments were then finely ground in a glass mortar, passed through a 0.5 mm stainless steel sieve, and vigorously shaken to ensure homogeneity. For chemical analysis, approximately 1 g of each dried sample underwent acid digestion using a mixture of concentrated nitric acid (69%) and perchloric acid (60%) in a 4:1 ratio. The digestion process began at 40°C for one hour, followed by an increase to 140 °C for three hours to break down the sample matrices.

Mussel sampling

For the mussel samples, around 50 specimens of *M. galloprovincialis*, each measuring between 5 to 7 cm in length and weighing between 28 to 30 grams, were collected from each site to ensure representative sampling. At the site, each mussel was rinsed with seawater to remove any adhering organisms and then placed in bags, which were stored in an isothermal box with ice for preservation. Upon arrival at the laboratory, the mussels were kept at -10 °C until analysis. Before processing, mussels were thawed at room temperature, and the moist soft tissue was carefully separated from the shells. Given that wet samples can introduce variability in metal concentration measurements due to differences in water content, the tissues were dried in an oven at 72 °C for 48 hours. For chemical analysis, approximately 30 grams of the dried mussel tissue was digested in 10 mL of a mixed solution of 30% hydrogen peroxide and 65% nitric acid. The digestion was performed using a Start D Microwave Digestion System equipped with an MPR SK-12 retort, maintaining a protocol of heating to 190 °C, over 15 minutes, holding at this temperature for another 15 minutes, and then cooling to 50 °C. The digested samples were then cooled, transferred to volumetric flasks, and diluted to 25 mL with milliQ water for further analysis.

This detailed methodology ensures that both sediment and mussel samples are prepared under strictly controlled conditions, allowing for reliable and comparable analysis of trace metal concentrations across the sampling sites.

Trace metals assay

The analysis of trace metal concentrations in both sediment and mussel samples was conducted using highly sensitive and specific analytical techniques suited to the nature of each sample type.

Sediment analysis

For the sediment samples, the levels of trace metals were quantified using an Atomic Absorption Spectrometry (AAS) system, specifically the Varian AA 20 model. This method is renowned for its precision and sensitivity in detecting trace elements within environmental samples. The AAS technique enables the assessment of metal concentrations by measuring the absorption of optical radiation (light) by free atoms in the gaseous state, providing accurate quantification of the metals present in the sediment.

Mussel tissue analysis

The prepared samples of *Mytilus.galloprovincialis* mussel flesh were analyzed using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES), model 720-ES. This technique involves selecting two spectral lines for each element to ensure accurate measurement and to minimize the effects of spectral interferences. Standard solutions (standards for ICP, supplied by Fluka) were used to produce the corresponding standard ranges, facilitating precise calibration and quantification of the elements. To ensure the accuracy and reliability of the results, the analysis routinely included the interspersion of known concentration solutions (standards and blanks) to verify that the ICP-OES provided correct readings consistently. A 50 ppm yttrium solution (standard for ICP, Fluka) was employed as the internal standard to further enhance the accuracy of the measurements. The content of heavy metals in both the sediment and mollusc tissues was expressed in milligrams per kilogram of dry matter (mg/kg DM), providing a standardized metric for comparing contamination levels across different samples and sites.

Statistical analysis

To explore significant correlations between the trace metal concentrations in sediments and the soft tissues of *M..galloprovincialis*, statistical analyses were conducted. Microsoft Excel was utilized for preliminary data processing, while more complex statistical tests were performed using XLSTAT 2019.1. The Pearson correlation coefficient (r) was employed to identify the strength and direction of linear relationships between the metal concentrations in sediments and mussel tissues. This analysis was conducted at a significance level (α) of 0.05, corresponding to a 95% confidence level, allowing for robust interpretation of the ecological and potential health impacts of the observed metal concentrations.

RESULTS AND DISCUSSIONS

Figs. 2 and 3 illustrate the levels of Cd, Cu, Pb, and Zn in both sediment samples and the total soft tissues of *M..galloprovincialis*, providing

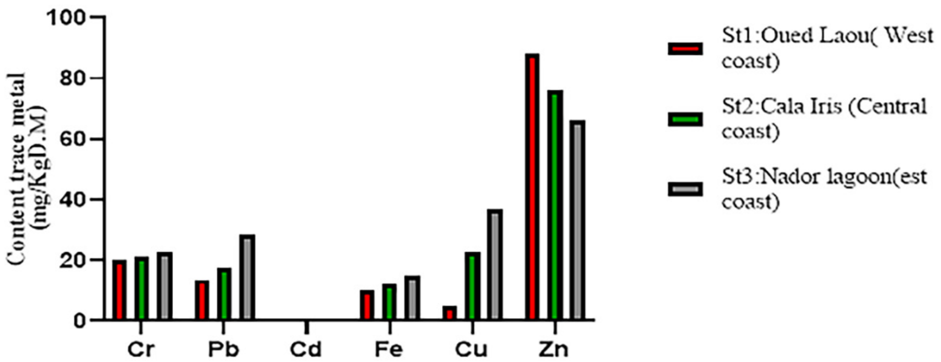

Fig. 2. Trace metal contents in surface marine coastal sediments

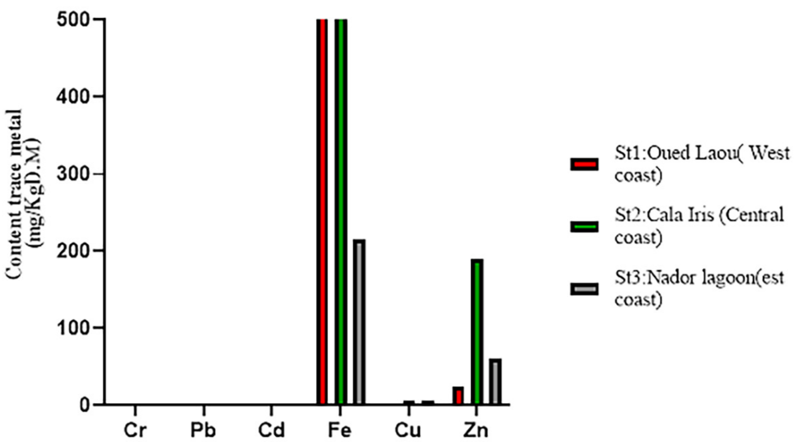

Fig. 3. Trace metal contents in soft tissue from M. galloprovincialis

crucial insights into the distribution of these trace metals across the study area.

Sediment samples

The concentrations of trace metals such as Chromium (Cr), Lead (Pb), Cadmium (Cd), Iron (Fe), Copper (Cu), and Zinc (Zn) in the surface sediments along the Mediterranean coast of Morocco, as shown in Figure 2, provides details of the metal contamination profile. These results are instrumental in comparing with historical data and studies from similar geographical and environmental settings. The levels of chromium found in the sediments ranged from 20 to 22.5 mg/kg, averaging 21.16 mg/kg. In comparison, studies conducted in other parts of the Mediterranean have reported similar chromium levels, suggesting regional industrial activities as a possible common source. For instance, research by Zonta et al. (2019) on sediment samples from the northern Adriatic Sea indicated chromium concentrations aligning with those found in this study, reflecting consistent input from industrial discharges.

Lead concentrations in this study varied between 13.5 and 17.5 mg/kg, with an average of 15.5 mg/kg. This is somewhat lower than levels reported in industrial areas but aligns closely with findings from other coastal regions affected by urban runoff, as seen in studies like those by Santos et al. (2018), who found average concentrations reaching up to 20 mg/kg. Cadmium showed the lowest concentrations among the studied metals, ranging from 0.025 to 0.09 mg/kg with an average of 0.046 mg/kg. These figures are considerably lower than those found in areas close to cadmium-emitting industries, such as those reported by Kumar et al. (2016), suggesting a lesser impact from industrial activities on cadmium levels in this region.

Iron varied between 10 and 15 mg/kg, averaging 12.33 mg/kg. This metal typically shows higher natural background levels, and the figures here are consistent with global averages in non-polluted sites, as per the studies by Johnson et al. (2015). Copper levels ranged widely from 5 to 37 mg/kg, with an average of 21.5 mg/kg. This variability can be indicative of localized sources of copper, possibly related to marine vessel activities, which is supported by findings from Bellucci et al. (2017), who noted elevated copper levels near major shipping lanes.

Zinc concentrations were the highest, ranging from 66 to 88 mg/kg, averaging 76.66 mg/kg. This is in line with data from other studies such as those by Cheung et al. (2014), which reported similar levels in sediments from urban and industrialized coastlines, reflecting widespread use and disposal in various industrial processes. The sequence of heavy metal concentrations (Zn > Cu > Cr > Pb > Fe > Cd) highlights zinc as the predominant contaminant, which is a common occurrence in marine sediments influenced by urban and industrial discharges. The relatively high levels of copper and chromium further point towards anthropogenic sources, likely linked to local industrial activities that include metal processing and maritime operations.

The findings from this study, juxtaposed with previous works, underscore the ongoing issue of metal pollution in marine environments. Such comparisons not only reinforce the need for continued monitoring but also help in identifying pollution trends and potential sources, which are crucial for effective environmental management and regulatory actions.

Sediment samples

The concentration of trace metals in the soft tissues of *Mytilus galloprovincialis* from the Mediterranean coast of Morocco offers important insights into bioaccumulation trends and potential ecological impacts. Levels of chromium in the mussel tissues ranged from 0.406 mg/kg to 3.10 mg/kg, with an average of 1.37 mg/kg. These figures are somewhat higher compared to baseline levels in mussels from less industrialized areas but are within the range observed in other studies along industrialized coastlines. For instance, a study by Lopez et al. (2017) reported similar chromium levels in mussels from areas with heavy ship traffic, suggesting a linkage to antifouling agents and other marine coatings.

The observed lead concentrations varied from 0.054 to 0.60 mg/kg, with an average notably low at 0.049 mg/kg. These concentrations are below those found in regions near lead smelting sites but are consistent with findings from urban coastal areas as noted by Thomson et al. (2019). Cadmium levels ranged significantly from 0.0014 to 0.77 mg/kg, averaging 0.266 mg/kg. This variability indicates differential exposure and bioavailability, likely influenced by local water chemistry and sediment characteristics. This range is consistent with findings from the global "Mussel Watch" programs, where cadmium variability often reflects proximity to industrial discharges, as discussed by Marine et al. (2018).

Iron showed the highest concentrations, ranging from 214.818 to 524.027 mg/kg, with an average of 413.218 mg/kg. These high levels are typical due to iron's abundant natural presence and essential biological roles, aligning with studies like those of Harding et al. (2020), which documented similar iron levels in mussels from nutrient-rich upwelling zones. Copper levels varied from 1.265 to 6.70 mg/kg, averaging 4.206 mg/kg. These values align with the higher end of the spectrum observed in mussels from coastal regions impacted by copper-based marine paint leachates and nearby copper mining activities, as seen in the work by Santos et al. (2021).

Zinc concentrations were between 24.435 and 190.2 mg/kg, averaging 113.712 mg/kg. Zinc often shows elevated levels in marine bivalves due to its use in galvanized materials and antifouling products, as well as being a necessary trace element for biological functions, similar to observations by Nguyen et al. (2015) along industrial coasts. The sequence of metal concentrations in the mussel tissues (Fe > Zn > Cu > Cr > Cd > Pb) highlights iron as the most prevalent, followed by zinc and copper, which is indicative of both natural and anthropogenic sources. The relatively high levels of chromium and cadmium are concerning as these metals can be toxic even at low concentrations and are indicative of industrial pollution, particularly from metal processing and waste disposal practices.

These data, when compared with previous studies, underscore the role of *Mytilus galloprovincialis* as a bioindicator that reflects both the environmental load of metals and their bioavailability in the marine ecosystem. Such insights are crucial for assessing the health of the marine environment and for informing policy decisions aimed at reducing pollutant inputs and protecting marine life along the Moroccan Mediterranean coast.

Correlation of heavy metals between *Mytilus galloprovincialis* and sediments

Table 1 shows the correlations of the various trace metals between the sediments and the flesh of the *M. galloprovincialis* mussel.

- chromium (Cr) – the correlation coefficient of 0.0408 for chromium suggests an extremely weak relationship between its concentrations in sediment and mussel flesh. This indicates minimal linear interaction, possibly because external environmental factors or mussel-specific biological processes might prevent the correlation. The very high p-value of 0.974 supports this, indicating that the observed correlation might well be due to random variation rather than any substantive environmental linkage;
- lead (Pb) – a correlation coefficient of 1.0 for lead indicates a perfect, positive linear relationship. This suggests that any increase in lead levels in the sediment is mirrored by an equivalent increase in the mussel flesh. This could indicate a direct uptake of lead from the sediments by the mussels, reflecting a significant environmental impact on mussel biochemistry. The absence of a p-value implies that this relationship is consistently replicable under the conditions studied;
- cadmium (Cd) – the negative correlation coefficient of -0.5245 for cadmium indicates a moderate inverse relationship, where an increase in cadmium levels in the sediment corresponds to a decrease in the mussel flesh. This suggests that mussels might be employing mechanisms to regulate cadmium uptake or mitigate its effects. However, the correlation's p-value of 0.649 signifies that this finding is not statistically significant,

Table 1. Correlation coefficients for the correlation trend line of trace metals between M.galalprovincialis mussels and sediments in the Moroccan Mediterranean coastal environment

Trace metals	r – correlation coefficient	p-value
Cr	0.040831334	0.97399874
Pb	1	N/A
Cd	-0.524501962	0.64850309
Fe	-0.94236107	0.21720084
Cu	0.78398366	0.42636915
Zn	0.65099452	0.54870415

suggesting that the observed negative correlation could potentially be coincidental;
- iron (Fe) – iron displays a very strong negative correlation coefficient of -0.9424, implying a substantial inverse relationship. This relationship indicates that as iron concentration increases in sediment, it decreases in mussel flesh, potentially due to selective absorption or detoxification processes in mussels. Despite the strength of the correlation, the associated p-value of 0.217 suggests that it lacks statistical significance, introducing a degree of uncertainty regarding the reliability of this correlation across different conditions or samples;
- copper (Cu) – the correlation coefficient of 0.7840 for copper shows a strong positive correlation, suggesting a straightforward relationship where increases in sediment copper are associated with increases in mussel copper. This likely indicates effective bioaccumulation of copper by the mussels. However, the p-value of 0.426 points out that the correlation, while strong, fails to reach statistical significance, hinting at possible external factors influencing copper levels;
- zinc (Zn) – zinc has a correlation coefficient of 0.6510, indicating a moderate positive correlation. This suggests a general tendency for zinc levels to increase in both sediment and mussel flesh concurrently. However, the p-value of 0.549 highlights that this correlation is also not statistically significant, suggesting that external variables or random factors could be influencing this observed relationship.

The analysis reveals a spectrum of correlations ranging from non-existent to perfect among the trace metal concentrations in *M. galloprovincialis* mussels and their surrounding sediments. These findings have critical implications for environmental monitoring and understanding mussel health. However, the predominantly non-significant statistical results call for caution in interpretation, suggesting that further research is necessary to confirm these correlations and understand the biological and environmental dynamics at play.

Exploring the potential health risk of consuming contaminated Mussels

Consuming contaminated mussels presents significant health dangers due to their ability to bioaccumulate toxins and pollutants, which can impact both wildlife and human populations. Here's an expanded look at the risks and necessary preventive measures. Mussels are efficient filter feeders, drawing in large volumes of water to extract food, which unfortunately includes environmental toxins. These can include heavy metals like mercury and lead, persistent organic pollutants like polychlorinated biphenyls (PCBs), and potent neurotoxins from algal blooms such as saxitoxin. These substances are not only toxic but tend to concentrate to dangerous levels within the tissues of mussels, posing serious health risks to any consumer. Predators of mussels, including certain species of birds and marine animals, are at high risk of toxin accumulation, which can lead to direct poisoning. Symptoms in wildlife can include neurological dysfunction, weakened immune systems, and reproductive issues, leading to decreased populations and imbalances in the ecosystem. Chronic exposure can even disrupt the food chain and local biodiversity. Human health risks:
- neurological issues – humans consuming contaminated mussels may suffer from immediate and severe health effects such as paralysis, memory loss, and in severe cases, even death, primarily due to neurotoxins from algal blooms.
- cancer and chronic conditions – long-term consumption of mussels containing heavy metals and PCBs can lead to a higher risk of developing cancer, liver and kidney damage, and other systemic health issues.
- shellfish poisoning – different forms of shellfish poisoning, such as paralytic, neurotoxic, and amnesic shellfish poisoning, each associated with various toxins, can lead to acute and potentially fatal conditions.

The severity of health risks correlates with the level of environmental pollution where the mussels are harvested. Areas with significant industrial discharge, agricultural runoff, or subpar waste management practices are more likely to harbor mussels with high levels of toxins. Proactive public health initiatives are crucial. This includes consistent monitoring of mussel populations and water quality, issuing health advisories when necessary, and educating the public on the risks of consuming potentially contaminated seafood. Enhancing water quality, implementing stricter pollution controls, and ensuring effective waste management are essential steps. Wildlife management and public health authorities must collaborate to monitor and manage the environmental factors that contribute to mussel contamination to safeguard both ecological and human health. Understanding these risks and taking comprehensive action are imperative for protecting both wildlife and human communities from the adverse effects of consuming contaminated mussels.

CONCLUSIONS

In conclusion, our study of the statistical correlations between trace elements in the biota (specifically, mussels) and sediments along the Moroccan Mediterranean coast reveals varying degrees of correlation, both positive and negative. Notably, lead (Pb) is the only trace metal demonstrating a perfect correlation between the concentrations found in surface marine sediments and those in *Mytilus galloprovincialis* mussels. However, this correlation does not inherently imply a causative link between the presence of lead in sediments and its accumulation in mussel tissue. The relationship could be influenced by other environmental or biological factors, and additional detailed analysis would be needed to clarify the nature of this association.

Chromium (Cr), on the other hand, showed a weak correlation, suggesting a more complex interplay or a less direct pathway of accumulation in mussels from sediments. For other trace metals studied – cadmium (Cd), iron (Fe), copper (Cu), and zinc (Zn) – the correlations, while ranging from moderate to strong, failed to reach statistical significance. This indicates that the observed relationships might be coincidental rather than indicative of true ecological or chemical interactions.

Given these findings, further research involving more comprehensive data collection and advanced analytical methods is essential to definitively establish or disprove the correlations between sediment and mussel trace metal concentrations. Such studies could help in understanding the mechanisms of trace metal uptake and accumulation in mussels, potentially guiding environmental monitoring and pollution control strategies.

REFERENCES

1. Abdouni A.E., Bouhout S., Merimi I., Hammouti B., Haboubi K. 2021. Physicochemical characterization of wastewater from the Al-Hoceima slaughterhouse in Morocco. Casp. J. Environ. Sci., 3(19), 423–429.
2. Abouabdallah A., El Hammoudani Y., Dimane F., Haboubi K., Rhayour K., Benaissa C. 2023. Impact of Waste on the Quality of Water Resources – Case Study of Taza City, Morocco. Ecol. Eng. Environ. Technol., 9(24), 170–182.
3. Achoukhi I., El Hammoudani Y., Dimane F., Haboubi K., Bourjila A., Haboubi C., Benaissa C., Elabdouni A. and Faiz H. 2023. Investigating Microplastics in the Mediterranean Coastal Areas–Case Study of Al-Hoceima Bay, Morocco. J. Ecol. Eng., 5(24), 12–31.
4. Ait Mansour A., El-Haitout B., Adnin R.J., Lgaz H., Salghi R., Lee H.-S., Alhadeethi M.R., Messali M., Haboubi K., Ali I.H. 2023. Insights into the Corrosion Inhibition Performance of Isonicotinohydrazide Derivatives for N80 Steel in 15% HCl Medium: An Experimental and Molecular Level Characterization. Metals, 4(13), 797.
5. Andaloussi K., Achtak H., Nakhcha C., Haboubi K., Stitou M. 2021. Assessment of soil trace metal contamination of an uncontrolled landfill and its vicinity: the case of the city of ‘Targuist’(Northern Morocco). Mor. J. Chem., 3(9), 2513–2529.
6. Andrade M., Soares A.M., Solé M., Pereira E., Freitas R. 2023. Gadolinium accumulation and its biochemical effects in Mytilus galloprovincialis under a scenario of global warming. Environmental Science and Pollution Research, 54(30), 116120–116133.
7. Azizi G., Layachi M., Akodad M., Ngadi H., Baghour M., Skalli A., Ghalit M., Gharibi E. and Moumen A. 2020. Assessment of heavy metals (Fe, Cu and Ni) contamination of seawater and mussel, Mytilus Galloprovincialis, from Al Hoceima Moroccan coasts: Heavy metal concentrations in Mytilus Galloprovincialis. Proceedings of the 4th Edition of International Conference on Geo-IT and Water Resources 2020, Geo-IT and Water Resources 2020, 1–6.
8. Belhouchet N., Inal A., Nait-Mohand H., Belkacem Y., Chenchouni H. 2024. Assessment of pollutants in coastal waters, sediments, and biota of marine ecosystems in Algeria, North Africa. Regional Studies in Marine Science, 70, 103355.
9. Benaissa C., Bouhmadi B., Rossi A., El Hammoudani Y. 2020. Hydro-chemical and bacteriological Study of Some Sources of Groundwater in the GHIS-NEKOR and the BOKOYA Aquifers (AL HOCEIMA, MOROCCO). Proc of The 4th Edition of International Conference on Geo-IT and Water Resources, 1–5.
10. Benaissa C., Bouhmadi B., Rossi A., El Hammoudani Y., Dimane F. 2022. Assessment of Water

Quality Using Water Quality Index – Case Study of Bakoya Aquifer, Al Hoceima, Northern Morocco. Ecol. Eng. Environ. Technol., 4(23), 31–44.

11. Benaissa C., Rossi A., Bouhmadi B., El Hammoudani Y., Dimane F. 2024. Assessment of the physicochemical and bacteriological quality of water source and a well in Bakoya aquifer, northern Morocco. E3S Web Conf., 04001.
12. Benito D., Guls H.D., Halldórsson H.P., Ciesielski T.M., Izagirre U., Lekube X., Etxebarria N., Marigómez I., Zaldibar B., Soto M. 2023. Integrated assessment of biological responses to pollution in wild mussels (Mytilus edulis) from subarctic and arctic areas in the Norwegian sea. Environmental Pollution, 336, 122454.
13. Botté A., Seguin C., Nahrgang J., Zaidi M., Guery J., Leignel V. 2022. Lead in the marine environment: concentrations and effects on invertebrates. Ecotoxicology, 1–14.
14. Bouhout S., Haboubi K., El Abdouni A., El Hammoudani Y., Haboubi C., Dimane F., Hanafi I. and Elyoubi M. S. 2023. Appraisal of Groundwater Quality Status in the Ghiss-Nekor Coastal Plain. J. Ecol. Eng., 10(24),
15. Bouhout S., Haboubi K., Hammoudani Y. E., Abdouni A. E., Haboubi C., Dimane F., Hanafi I. and Elyoubi M. S. 2024. Groundwater Quality Assessment in the Coastal Mediterranean Aquifer of Northeastern Morocco – A GIS-Based Approach. Ecol. Eng. Environ. Technol., 1(25), 22–45.
16. Bouknana D., Jodeh S., Sbaa M., Hammouti B., Arabi M., Darmous A., Slamini M. and Haboubi K. 2019. A phytotoxic impact of phenolic compounds in olive oil mill wastewater on fenugreek "Trigonella foenum-graecum". Environ. Monit. Assess., 6(191).
17. Bourjila A., Dimane F., Ghalit M., Taher M., Kamari S., El Hammoudani Y., Achoukhi I. and Haboubi K. 2023. Mapping the spatiotemporal evolution of seawater intrusion in the Moroccan coastal aquifer of Ghiss-Nekor using GIS-based modeling. Water Cycle, 4, 104-119.
18. Crowther C., Turner A., Moore M.N., Jha A.N. 2023. Assessing the effects of single and binary exposures of copper and lead on Mytilus galloprovincialis: Physiological and genotoxic approaches. Aquatic Toxicology, 265), 106741.
19. El bastrioui M., Haboubi K., Chetouani A., Hammouti B., Nandiyanto A. 2022. Phytochemical study of four leaves extracts of Chamærops humilis L. from the region of Al-Hoceima, Morocco. Mor. J. Chem., 4(10), 2851–2860.
20. El Hammoudani Y., Dimane F. 2021. Assessing behavior and fate of micropollutants during wastewater treatment: Statistical analysis. Environ. Eng. Res., 26(5).
21. El Hammoudani Y., Dimane F. 2021. Occurrence and fate of micropollutants during sludge treatment: Case of Al-Hoceima WWTP, Morocco. Environ. Chall., 1(5), 1–8.
22. El Hammoudani Y., Dimane F., El Ouarghi H. 2019. Fate of Selected Heavy Metals in a Biological Wastewater Treatment System. Euro-Mediterranean Conference for Environmental Integration, 157–163.
23. El Hammoudani Y., Dimane F., El Ouarghi H. 2021. Removal efficiency of heavy metals by a biological wastewater treatment plant and their potential risks to human health. Environ. Eng. Manag. J., 6(20), 995–1002.
24. El Hammoudani Y., Dimane F., Haboubi K., Benaissa C., Benaabidate L., Bourjila A., Achoukhi I., El Boudammoussi M., Faiz H. and Touzani A. 2024. Micropollutants in Wastewater Treatment Plants: A Bibliometric-Bibliographic Study. Desal. Water. Treat., 317, 100190.
25. El Ouaty O., El M'rini A., Nachite D., Marrocchino E., Marin E. and Rodella I. 2022. Assessment of the heavy metal sources and concentrations in the Nador Lagoon sediment, Northeast-Morocco. Ocean & Coastal Management, 216, 105900.
26. Elabdouni A., Haboubi K., Bensitel N., Bouhout S., Aberkani K. and El Youbi M. S. 2022. Removal of organic matter and polyphenols in the olive oil mill wastewater by coagulation-flocculation using aluminum sulfate and lime. Mor. J. Chem., 1(10), 191–202.
27. Elabdouni A., Haboubi K., Merimi I., El Youbi M. 2020. Olive mill wastewater (OMW) production in the province of Al-Hoceima (Morocco) and their physico-chemical characterization by mill types. Mater. Today Proc., 27, 3145–3150.
28. Elazzouzi M., Haboubi K., Elyoubi M. and El Kasmi A. 2019. A developed low-cost electrocoagulation process for efficient phosphate and COD removals from real urban wastewater. ES Energy Environ., 5, 66–74.
29. Elazzouzi M., Haboubi K., Elyoubi M. S. and El Kasmi A. 2021. Development of a novel electrocoagulation anode for real urban wastewater treatment: Experimental and modeling study to optimize operative conditions. Arab. J. Chem., 1(14),
30. Elyoussfi A., Outada H., Isaad J., Lrhoul H., Salhi A. and Dafali A. 2023. Corrosion inhibitors of alloys and metals in acidic solution: A bibliometric analysis from 2010 to 2022. Int. J. Corros. Scale Inhib, 2(12), 722–740.
31. Fernine Y., Arrousse N., Haldhar R., Raorane C. J., Kim S.-C., El Hajjaji F., Touhami M. E., Beniken M., Haboubi K. and Taleb M. 2022. Synthesis and characterization of phenolphthalein derivatives, detailed theoretical DFT computation/molecular simulation, and prevention of AA2024-T3 corrosion in medium 3.5% NaCl. J. Taiwan Inst. Chem. Eng., 140, 104556.

32. Ferreira C.P., Piazza T.B., Souza P., Lima D., Mattos J.J., Saldaña-Serrano M., Piazza R.S., Jorge M.B., Bianchini A., Taniguchi S. 2021. Integrated biomarker responses in oysters Crassostrea gasar as an approach for assessing aquatic pollution of a Brazilian estuary. Marine Environmental Research, 165, 105252.
33. Ghribi F., Richir J., Bejaoui S., Boussoufa D., Marengo M., El Cafsi M. h. and Gobert S. 2020. Trace elements and oxidative stress in the Ark shell Arca noae from a Mediterranean coastal lagoon (Bizerte lagoon, Tunisia): are there health risks associated with their consumption? Environmental Science and Pollution Research, 27, 15607–15623.
34. Haboubi C., Barhdadi E. H., Haboubi K., Hammoudani Y. E., Sadoune Z., Abdouni A. E. and Dimane F. 2024. Characterization of the Mechanical Behavior of Hemp-Clay Composites. Adv. Sci. Technol. Resea. J., 2(18), 71–77.
35. Haboubi C., El Hammoudani Y., Jaradat N., Jodeh S., Haboubi K., Dimane F. 2023. A Bibliometric Analysis of Cannabis-Related Research from 2010 To 2022. Pal. Med. Pharm. J., 2(9).
36. Haboubi K., El Abdouni A., El Hammoudani Y., Dimane F., Haboubi C. 2023. Estimating biogas production in the controlled landfill of fez (morocco) using the land-gem model. Environ. Eng. Manag. J., 11(22), 1813–1820.
37. Jeroundi D., Elmsellem H., Chakroune S., Idouhli R., Elyoussfi A., Dafali A., El Hadrami E. M., Ben-Tama A. and Kandri Rodi Y. 2016. Physicochemical study and corrosion inhibition potential of dithiolo[4,5-b][1,4]dithiepine for mild steel in acidic medium. J. Mater. Environ. Sci., 11(7), 4024–4035.
38. Khellaf B., Bouayad L., Benouadah A., Hamdi T.M., Chekri R., Jitaru P. 2023. Arsenic, mercury, cadmium and lead contents in Algerian continental and marine farming fish and human health risk assessment due to their consumption. Regional Studies in Marine Science, 62, 102943.
39. Kouali H., Achtak H., Chaouti A., Elkalay K., Dahbi A. 2020. Assessment of trace metal contamination in surficial fine-grained sediments and mussel, Mytilus galloprovincialis from Safi areas in the northwestern Atlantic coast of Morocco. Regional studies in marine science, 40, 101535.
40. Liu C., Liu D., Li P., Li X., Liu Z., Zhao Y. 2023. Assessment of occupation of natural habitat by urban expansion and its impact on crucial ecosystem services in China’s coastal zone. Ecological Indicators, 154, 110682.
41. Lynch S., Coghlan A., Leary B.O., Morgan E., Culloty S. 2020. Northward establishment of the Mediterranean mussel Mytilus galloprovincialis limited by changing climate. Biological Invasions, 22, 2725–2736.
42. Miglioli A., Fonseca E., Besnardeau L., Canesi L., Schubert M., Dumollard R. 2024. First characterization of the nuclear receptor superfamily in the Mediterranean mussel Mytilus galloprovincialis: developmental expression dynamics and potential susceptibility to environmental chemicals. Philosophical Transactions of the Royal Society B, 1898(379), 20220500.
43. Negahdari S., Sabaghan M., Pirhadi M., Alikord M., Sadighara P., Darvishi M., Nazer M. 2021. Potential harmful effects of heavy metals as a toxic and carcinogenic agent in marine food-an overview. Egyptian Journal of Veterinary Sciences, 3(52), 379–385.
44. Öncel H., Levend S. 2023. The effects of urban growth on natural areas: the three metropolitan areas in Türkiye. Environmental Monitoring and Assessment, 7(195), 816.
45. Ouagajjou Y., Aghzar A., Presa P. 2023. Population Genetic Divergence among Worldwide Gene Pools of the Mediterranean Mussel Mytilus galloprovincialis. Animals, 24(13), 3754.
46. Pillet M., Dabrowski M., Marengo M., Fullgrabe L., Leduc M., Fontaine Q., Le Floch S., Huet V., Churlaud C., Lejeune P. 2023. Preliminary interport study of the quality of environments using physiological responses of invertebrates exposed to chronic trace element and organic contamination in Corsica (Mediterranean Sea). Ecotoxicology, 2(32), 243–260.
47. Rellán A.G., Ares D.V., Brea C.V., López A.F., Bugallo P.M.B. 2023. Sources, sinks and transformations of plastics in our oceans: Review, management strategies and modelling. Science of the Total Environment, 854, 158745.
48. Rusconi T., Riva L., Punta C., Solé M. and Corsi I. 2024. Environmental safety of nanocellulose: an acute in vivo study with marine mussels Mytilus galloprovincialis. Environmental Science: Nano, 1(11), 61–77.
49. Saadi O., Nouayti N., Nouayti A., Dimane F., Elhairechi K. 2021. Application of remote sensing data and geographic information system for identifying potential areas of groundwater storage in middle Moulouya Basin of Morocco. Groundw. Sustain. Dev., 14, 100639.
50. Salhi A., Elyoussfi A., Azghay I., El Aatiaoui A., Amhamdi H., El Massaoudi M., Ahari M., Bouyanzer A., Radi S., El barkany S. 2023. A correlated theoretical and electrochemical investigation of the corrosion inhibition performance of phenolic Schiff bases on mild steel in HCl solution (Part B). Inorg. Chem. Commun., 152.
51. Simou A., Mrabet A., Abdelfattah B., Bougrine O., Khaddor M., Allali N. 2024. Distribution, ecological, and health risk assessment of trace elements in the surface seawater along the littoral of Tangier Bay

(Southwestern Mediterranean Sea). Marine Pollution Bulletin, 202, 116362.

52. Tighadouini S., Radi S., Elidrissi A., Haboubi K., Bacquet M., Degoutin S., Zaghrioui M. and Garcia Y. 2019. Removal of toxic heavy metals from river water samples using a porous silica surface modified with a new β-ketoenolic host. Beilstein J. Nanotechnol., 1(10), 262–273.
53. Tnoumi A., Angelone M., Armiento G., Caprioli R., Crovato C., De Cassan M., Montereali M.R., Nardi E., Parrella L., Proposito M. 2020. Assessment of trace metals in sediments from Khnifiss Lagoon (Tarfaya, Morocco). Earth, 1(2), 16–31.
54. Touzani A., El Hammoudani Y., Dimane F., Tahiri M., Haboubi K. 2024. Characterization of Leachate and Assessment of the Leachate Pollution Index–A Study of the Controlled Landfill in Fez. Ecol. Eng. Environ. Technol., 4(25), 57–69.
55. Tresnakova N., Impellitteri F., Famulari S., Porretti M., Filice M., Caferro A., Savoca S., Claudio D., Imbrogno S., Albergamo A. 2023. Fitness assessment of Mytilus galloprovincialis Lamarck, 1819 after exposure to herbicide metabolite propachlor ESA. Environmental Pollution, 331, 121878.
56. Tursi A., Baratta M., Easton T., Chatzisymeon E., Chidichimo F., De Biase M., De Filpo G. 2022. Microplastics in aquatic systems, a comprehensive review: origination, accumulation, impact, and removal technologies. RSC advances, 44(12), 28318–28340.
57. Yahyaoui A., Ben Amor R., Abidi M., Grieco G., Gueddari M., Chouba L. 2022. Distribution and assessment of trace metal contamination in the surface sediments of the Meliane River and the Coast of the Gulf of Tunis (Tunisia, Mediterranean Sea). Environmental Forensics, 1–2(23), 7–22.
58. Yancheva V., Velcheva I., Georgieva E., Stoyanova S., Todorova B., Antal L., Nyeste K.J. 2023. Are Mytilus species suitable bioindicators for assessing aquatic pollution along the Black Sea Coast? A review. Ecologia Balkanica, 1(15), 49–76.
59. Zaidi M., Athmouni K., Metais I., Ayadi H., Leignel V. 2022. The Mediterranean limpet Patella caerulea (Gastropoda, Mollusca) to assess marine ecotoxicological risk: a case study of Tunisian coasts contaminated by metals. Environmental Science and Pollution Research, 19(29), 28339–28358.