Sanitary Quality of Cultured Mytilus galloprovincialis from an Algerian Aquaculture Site and Its Implications for Co-product Valorization

Hichem Benhamou[1*], Sabrine Louala[2]

[1]Department of Biology, Laboratory of Clinical and Metabolic Nutrition, Faculty of Natural and Life Sciences, University of Oran 1 Ahmed Ben Bella, Oran, Algeria. Email: benhamouhichem439@gmail.com, ORCID: 0009-0002-6217-8368
[2]Department of Biology, Laboratory of Clinical and Metabolic Nutrition, Faculty of Natural and Life Sciences, University of Oran 1 Ahmed Ben Bella, Oran, Algeria. Email: S.louala79@gmail.com, ORCID: 0000-0003-4175-8777

Received: 17-06-2026 **Accepted:** 27-08-2026 **Published:**18-09-2026

Abstract
Mediterranean mussel farming has become an important component of sustainable aquaculture owing to the high nutritional value of Mytilus galloprovincialis and its recognized role as a bioindicator of coastal environmental quality. This study evaluated the physicochemical and microbiological quality of farming water together with the sanitary safety of mussels collected from the Kristel aquaculture site (Oran, Algeria) to determine their suitability for human consumption and their potential valorization as a safe source of protein-rich co-products.
Physicochemical parameters, microbiological indicators, and trace metals (Cu, Pb, and Hg) were determined in farming water, whereas mussel flesh was analyzed for regulatory microbiological criteria and eight trace elements (Ni, Pb, Hg, Cd, Cr, Cu, Zn, and As). Food safety was further assessed using bioconcentration factor (BCF), Heavy Metal Pollution Index (HPI), cumulative contamination degree (CD), Metal Pollution Index (MPI), estimated daily intake (EDI), target hazard quotient (THQ), hazard index (HI), and comparison with provisional tolerable intake values established by international authorities.
All microbiological indicators in both water and mussel flesh complied with Algerian regulatory requirements or remained below the analytical detection limits. Trace metal concentrations in mussel tissues were well below the maximum limits established by Commission Regulation (EU) 2023/915. Human health risk assessment revealed negligible non-carcinogenic risk, with THQ values below 1 for all investigated metals and a cumulative HI of approximately 0.046.
Overall, these findings demonstrate that mussels cultivated at the Kristel aquaculture site meet current sanitary safety requirements and constitute a safe biological resource for human consumption and for the sustainable valorization of aquaculture co-products. Nevertheless, additional seasonal monitoring is recommended to confirm the long-term environmental and sanitary status of the farming area.

Keywords: Mytilus galloprovincialis; Aquaculture; Trace metals; Food safety; Human health risk assessment; Bioaccumulation; Mediterranean Sea.

1. Introduction

Mediterranean shellfish aquaculture has become an increasingly important component of the blue economy and sustainable coastal development, particularly in countries where marine resources contribute substantially to food security and local economic growth (FAO 2024). Among cultivated bivalves, Mytilus galloprovincialis is one of the most economically valuable species because of its high nutritional value, broad consumer acceptance, rapid growth, and relatively low environmental footprint (FAO 2024; Meloni et al. 2022). In addition to its commercial importance, this species is widely recognized as an effective sentinel organism for environmental monitoring owing to its remarkable filter-feeding capacity, which enables the accumulation of microorganisms and chemical contaminants from the surrounding environment (Goldberg 1975; Rainbow 1995, 2002). Consequently, Mytilus galloprovincialis serves not only as an important seafood resource but also as a reliable bioindicator of coastal environmental quality and aquaculture sustainability (Andral et al. 2011; Guendouzi et al. 2024).
Trace metals are among the most persistent and hazardous contaminants in marine ecosystems because they are non-biodegradable, can accumulate in aquatic organisms, and may be transferred through the food chain, posing potential risks to both ecosystem integrity and human health (Ali et al. 2019). Owing to their sessile lifestyle, long lifespan, and continuous filter-feeding activity, mussels readily accumulate dissolved and particulate contaminants, thereby integrating environmental exposure over extended periods (Rainbow 1995, 2002). Consequently, Mytilus galloprovincialis has become one of the most extensively used bioindicator species in marine pollution monitoring programmes since the establishment of the global "Mussel Watch" programme (Goldberg 1975; Andral et al. 2011). Although essential trace elements such as copper and zinc are partially regulated through physiological homeostasis, non-essential metals including lead, cadmium, and mercury may accumulate according to their environmental bioavailability and represent a potential concern for seafood safety (Rainbow 2002; Bat et al. 2023).

In addition to chemical contamination, filter-feeding bivalves may concentrate pathogenic microorganisms originating from wastewater discharges, agricultural runoff, and other anthropogenic sources. Consequently, microbiological contamination remains a major public health concern because mussels can accumulate fecal indicator bacteria as well as enteric viruses, including norovirus and hepatitis A virus, which are among the leading causes of shellfish-associated foodborne outbreaks (Lees 2000; Food and Agriculture Organization of the United Nations (FAO), World Health Organization (WHO) 2022). To protect consumers, the sanitary classification of shellfish harvesting areas is primarily based on the determination of Escherichia coli in bivalve molluscs according to European legislation, including Regulation (EU) 2017/625 and its implementing regulations, together with the Codex Standard for Live and Raw Bivalve Molluscs (Codex Alimentarius Commission 2022). Therefore, the combined assessment of microbiological quality and chemical contamination represents the cornerstone of sanitary surveillance programmes for shellfish production areas.

Recent investigations conducted throughout the Mediterranean basin have demonstrated considerable spatial and temporal variability in trace metal accumulation by Mytilus galloprovincialis, mainly reflecting differences in local environmental conditions and anthropogenic pressures (Meloni et al. 2022; Bat et al. 2023; Bruno et al. 2024; El Mourabit et al. 2024; Guendouzi et al. 2024; Hacısalihoglu 2025). Although most studies have reported contaminant concentrations below the maximum limits established by European legislation, significant differences in bioaccumulation patterns and human health risk indices have been observed among production areas. These findings highlight the importance of continuous site-specific monitoring, particularly in rapidly expanding aquaculture regions where environmental conditions may change over time. Despite the growing development of shellfish farming in Algeria, comprehensive studies integrating farming-water quality, microbiological safety, trace metal contamination, and quantitative human health risk assessment remain scarce.

The present study was conducted to provide a comprehensive sanitary assessment of Mytilus galloprovincialis cultivated at the Kristel aquaculture site (Oran, Algeria). Specifically, the objectives were to (i) evaluate the physicochemical and microbiological quality of farming water; (ii) determine the microbiological safety and trace metal concentrations in mussel tissues in relation to Algerian and European regulatory standards; and (iii) assess potential human health risks associated with mussel consumption using internationally recognized contamination and exposure indices, including the bioconcentration factor (BCF), Heavy Metal Pollution Index (HPI), cumulative contamination degree (CD), Metal Pollution Index (MPI), estimated daily intake (EDI), target hazard quotient (THQ), and hazard index (HI). By integrating environmental monitoring, food safety evaluation, and quantitative health risk assessment within a single framework, this study provides scientific evidence supporting the sanitary status of Algerian mussel aquaculture and the sustainable valorization of mussel co-products as a safe protein resource.

2. Materials and Methods

2.1 Study site and sampling

The study was conducted at the commercial mussel farming site of Kristel, located in Gdyel (Oran Province, northwestern Algeria; 35°49′18″ N, 0°28′59″ W), on the southern Mediterranean coast. Sampling was performed during March 2024 under routine farming conditions.

Representative seawater samples were collected aseptically in sterile polyethylene bottles from the vicinity of the cultivation ropes and transported to the laboratory under refrigerated conditions for immediate physicochemical and microbiological analyses.

Adult specimens of Mytilus galloprovincialis of commercial size were manually harvested from suspended culture ropes. After collection, mussels were placed in insulated containers containing ice packs, transported to the laboratory within the same day, and processed immediately for microbiological examination and trace element determination.

2.2 Physicochemical analyses of seawater

Water temperature, pH (20 °C), electrical conductivity (20 °C), and turbidity were measured immediately after sampling using calibrated analytical instruments according to standardized procedures. Hydrocarbon concentration was determined by gas chromatography (GC). Total phosphorus, nitrites, nitrates, unionized ammonia, and residual chlorine were quantified following ISO 6878, ISO 7890-3, the Rodier method (Rodier et al. 2009), and the Algerian standard NA 2063, respectively. All analyses were performed in triplicate, and the results are expressed as mean values.

2.3 Microbiological analyses

The microbiological quality of seawater and Mytilus galloprovincialis samples was assessed according to internationally recognized ISO standard methods. Water samples were analyzed for total coliforms, fecal coliforms, intestinal enterococci, sulfite-reducing anaerobes, and Salmonella spp., whereas mussel samples were examined for Escherichia coli, coagulase-positive Staphylococcus, Salmonella spp., and sulfite-reducing anaerobic bacteria.

Briefly, total and fecal coliforms were enumerated using the membrane filtration technique in accordance with ISO 9308-1, intestinal enterococci according to ISO 7899-2, sulfite-reducing anaerobes following ISO 15213, and Salmonella spp. according to ISO 6579. Microbiological analyses of mussel tissues were performed using the corresponding ISO reference methods and the results were interpreted according to the microbiological criteria established by Algerian regulations and relevant European legislation. All microbiological determinations were carried out under aseptic laboratory conditions, and the results were expressed as colony-forming units (CFU) or most probable number (MPN), depending on the analytical method used.

2.4 Determination of trace metals

Trace metal concentrations were determined in both seawater and mussel soft tissues. For mussel samples, soft tissues were carefully dissected from the shells, pooled, homogenized, and subjected to acid digestion according to **NF EN 14082:2003**, using concentrated analytical-grade acids under controlled temperature conditions. The investigated elements : nickel (Ni), lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), copper (Cu), zinc (Zn), and arsenic (As), were subsequently quantified by inductively coupled plasma optical emission spectrometry (ICP-OES) and expressed as $\mu g\ g^{-1}$ dry weight (DW). For seawater samples, appropriate acidification and pre-concentration procedures were applied prior to instrumental analysis, and metal concentrations were expressed as $\mu g\ L^{-1}$. Throughout the analytical procedure, instrument calibration was performed using certified standard solutions, and analytical quality was ensured through the use of reagent blanks, procedural blanks, and certified reference materials. The measured concentrations in mussel tissues were compared with the maximum permissible levels established by Commission Regulation (EU) 2023/915.

2.5 Quality assurance and quality control (QA/QC)

Analytical quality was ensured through the use of reagent blanks, duplicate analyses, calibration with certified multi-element standard solutions, and periodic verification of instrument performance. Recovery tests were performed on spiked samples, and all analyses were conducted in triplicate. Limits of detection (LOD) and quantification (LOQ) were established according to the analytical procedure employed.

2.6 Contamination and human health risk indices

Potential health risks associated with the consumption of Mytilus galloprovincialis were evaluated using internationally accepted exposure assessment models. Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), Hazard Index (HI), Bioconcentration Factor (BCF), Heavy Metal Pollution Index (HPI), Cumulative Degree (CD), and Metal Pollution Index (MPI) were calculated according to the equations reported below. The parameters used in these calculations were selected from internationally recognized guidelines and previous studies to facilitate comparison with similar investigations.

2.6.1 Bioconcentration factor (BCF)

The bioconcentration factor for Cu, Pb, and Hg was calculated as:

$BCF = C_{xresh} / C_{rater}$

where C_{eresh} is expressed in µg/kg DW and C_{rater} in µg/L, yielding BCF values in L/kg.

2.6.2 Heavy Metal Pollution Index (HPI)

HPI was calculated according to Mohan et al. (1996):

$HPI = \Sigma(W_i \times Q_i) / \Sigma W_i;\ W_i = k / S_i;\ Q_i = (M_i / S_i) \times 100$

where M_i is the measured concentration of metal i, S_i the corresponding guideline value, and W_i the unit weight. In the absence of specific shellfish-water standards, WHO drinking water guideline values were used as reference concentrations (World Health Organization (WHO) 2017).

2.6.3 Cumulative contamination degree (CD)

An adapted contamination factor, derived from the contamination factor concept originally proposed by Håkanson (1980), was calculated for each metal as the ratio between the measured concentration and the corresponding European maximum limit:

$CF_i = C_i$ measured / C_i limit; CD_adapted = ΣCF_i

2.6.4 Metal Pollution Index (MPI)

MPI was determined using the geometric mean approach described by Usero et al. (1996):

$MPI = (C_1 \times C_2 \times \ldots \times C_n)$^(1/n)

where C_i is the concentration of metal i and n = 8.

2.6.5 Estimated Daily Intake (EDI)

EDI was calculated following the USEPA methodology (USEPA 1989, 2013):

$EDI = (C_{eresh}(fw) \times IR) / BW$

where $C_{eresh}(fw)$ is the concentration on a fresh-weight basis, IR = 20 g/day is the ingestion rate, and BW = 70 kg is the reference body weight (USEPA 2011).

2.6.6 Target Hazard Quotient (THQ) and Hazard Index (HI)

THQ was calculated as:

THQ = EDI / RfD

where RfD is the oral reference dose established by the USEPA for each metal. The cumulative Hazard Index was calculated as $HI = \Sigma THQ_i$ (USEPA 2000).

2.6.7 Comparison with tolerable intakes

Weekly or monthly estimated intakes were compared with the provisional tolerable intake values established by the Joint FAO/WHO Expert Committee on Food Additives (JECFA): Cd PTMI = 25 µg/kg bw/month (JECFA 2011), Hg PTWI = 1.6 µg/kg bw/week (JECFA 2003), and the historical reference values for Pb and As (JECFA 1986) commonly used for comparative purposes in the literature.

2.7 Sanitary classification of the production area

E. coli results obtained from mussel flesh were compared with the shellfish production area classification criteria established by Regulation (EC) No. 854/2004. The interpretation was performed according to the thresholds defining Zone A for direct human consumption.

2.8 Statistical analysis

All analyses were performed in triplicate, and the results are presented as mean ± standard deviation (SD). Statistical analyses were carried out using IBM SPSS Statistics software. Differences between measured values and regulatory limits were evaluated where appropriate. A significance level of $p < 0.05$ was considered statistically significant.

3. Results

3.1 Physicochemical and microbiological quality of farming water

The physicochemical characteristics of the farming water are presented in Table 1. The water exhibited typical marine conditions, with an alkaline pH (8.34), low turbidity (1.55 NTU), and low hydrocarbon concentration (0.66 µg/L). Total phosphorus, nitrites, nitrates, and residual chlorine were not detected, whereas unionized ammonia was 0.015 mg/L.

Table 1 Physicochemical characteristics of the farming water (Kristel, March 2024)

Parameter	Measured value
Temperature	23 °C
pH (20 °C)	8.34
Electrical conductivity (20 °C)	97,200 µS/cm
Turbidity	1.55 NTU
Hydrocarbons	0.66 µg/L
Total phosphorus	Not detected
Nitrites	Not detected
Nitrates	Not detected
Unionized ammonia	0.015 mg/L
Residual chlorine	Not detected

Trace metal concentrations in seawater were below the analytical detection limits. No fecal coliforms, fecal streptococci, or Escherichia coli were detected (Table 2).

Table 2 Trace metals and microbiological quality of farming water

Parameter	Result
Copper	<0.02 µg/L
Lead	<0.05 µg/L
Mercury	<1.0 µg/L
Fecal coliforms	Absent
Fecal streptococci	Absent
Escherichia coli	Absent

3.2 Sanitary quality of mussel flesh

The concentrations of trace metals in mussel flesh are summarized in Table 3. All measured concentrations were below the maximum levels established by Commission Regulation (EU) 2023/915.

Table 3 Trace metal concentrations in Mytilus galloprovincialis flesh (mean ± SD, n = 3)

Metal	Concentration (µg/g DW)	EU limit
Ni	0.025 ± 0.001	<2.0
Pb	0.19 ± 0.01	0.30
Hg	0.039 ± 0.002	0.10
Cd	0.29 ± 0.01	0.50
Cr	0.075 ± 0.003	<1.0
Cu	0.63 ± 0.02	<2.0
Zn	0.019 ± 0.001	<0.10
As	0.011 ± 0.001	<1.0

Microbiological analyses demonstrated compliance with Algerian regulatory standards (Table 4).

Table 4 Microbiological quality of mussel flesh

Parameter	Result
Aerobic mesophilic bacteria (30°C)	5.0×10^2 CFU/g
Thermotolerant coliforms	Absent
Coagulase-positive Staphylococcus	Absent
Salmonella spp./25 g	Absent

3.3 Contamination indices and human health risk assessment

The calculated bioconcentration factors are presented in Table 5.

Table 5 Bioconcentration factors (BCF)

Metal	BCF (L/kg)
Cu	≥31,500
Pb	≥3,800

Metal	BCF (L/kg)
Hg	≥39

Because dissolved metal concentrations in seawater were below the analytical detection limits, the reported BCF values represent minimum estimates of the actual bioaccumulation capacity.
The Heavy Metal Pollution Index (HPI) was estimated at 10.6, well below the critical threshold of 100, indicating the absence of significant heavy metal pollution in the farming water.
The individual contamination factors (CF) calculated for each metal, together with the resulting cumulative contamination degree (CD), are presented in Table 6.

Table 6 Individual contamination factors (CF) and cumulative contamination degree (CD)

Metal	Measured concentration (µg/g DW)	EU limit (µg/g)	CF
Ni	0.025	2.0	0.013
Pb	0.19	0.30	0.63
Hg	0.039	0.10	0.39
Cd	0.29	0.50	0.58
Cr	0.075	1.0	0.075
Cu	0.63	2.0	0.315
Zn	0.019	0.10	0.19
As	0.011	1.0	0.011

[a] $CD = \Sigma CF_i = 2.21$.
All individual contamination factors were below 1, indicating that none of the analyzed metals exceeded the corresponding European maximum level. The cumulative contamination degree (CD = 2.21) confirms an overall low contamination level and a comfortable safety margin with respect to regulatory limits.
The Metal Pollution Index (MPI) was 0.069 µg/g DW.

The estimated daily intake (EDI) and the corresponding target hazard quotient (THQ) calculated for each metal are presented in Table 7.

Table 7 Estimated daily intake (EDI) and Target Hazard Quotient (THQ)

Metal	EDI (mg/kg bw/day)	THQ
Cd	1.66E-5	0.017
Pb	1.09E-5	0.003
Hg	2.23E-6	0.022
Cr	4.29E-6	0.001
Cu	3.60E-5	0.001
Ni	1.43E-6	<0.001
Zn	1.09E-6	<0.001
As	6.29E-7	0.002

All individual THQ values were below 1, and the cumulative Hazard Index (HI = 0.046) remained well below the threshold for non-carcinogenic risk. The absence of Escherichia coli in mussel flesh indicates that the production area met the microbiological criteria corresponding to a Class A harvesting area according to Regulation (EC) No. 854/2004, subject to confirmation through routine monitoring.

4. Discussion

The physicochemical characteristics of the farming water indicated good environmental quality. The alkaline pH, low turbidity, low hydrocarbon concentration, and the absence of detectable nitrites, nitrates, phosphates, and residual chlorine suggest that the site was not affected by significant nutrient enrichment or anthropogenic pollution during the sampling period, consistent with the quality requirements established for shellfish-growing waters under Directive 2006/113/EC (Directive 2006/113/EC 2006). Moreover, the Heavy Metal Pollution Index (HPI = 10.6) remained well below the critical threshold of 100, indicating negligible metal contamination (Mohan et al. 1996; Edet and Offiong 2002).
Trace metal concentrations in Mytilus galloprovincialis from the Kristel farming site were all below the maximum limits established by Commission Regulation (EU) 2023/915, confirming the sanitary quality of the mussels. Similar findings have been reported in cultivated mussels from the Calich Lagoon (Sardinia, Italy), where trace metal concentrations remained within the European regulatory limits despite the semi-enclosed nature of the farming area (Meloni et al. 2022). Conversely, higher concentrations of several metals have been reported in wild populations from Lake Faro (Sicily), although the calculated THQ values generally remained below the critical threshold for non-carcinogenic risk (Younis et al. 2024; Bruno et al. 2024). Likewise, mussels collected along the Sea of Marmara showed greater spatial variability in Cd, Pb, Hg, Cu, and Zn concentrations, with cumulative Hazard Index values approaching 0.7 in the most impacted sites but remaining below the critical value of 1 (Hacısalihoglu 2025). Similar conclusions were reported for the Turkish Black Sea coast (Bat et al. 2023).
Comparable observations have also been reported along the Moroccan coastline. Although active bioaccumulation of Cu, Zn, Cd, and Pb has been described in mussels collected near wastewater discharge areas, trace metal

concentrations generally remained below the European regulatory limits (El Mourabit et al. 2024). In Algeria, seasonal investigations performed on the western coast, including the Kristel area, demonstrated moderate spatial and temporal variations in Pb, Cu, and Zn accumulation without systematic exceedance of regulatory standards (Rouane-Hacène et al. 2015; Guendouzi et al. 2024). Overall, these comparisons indicate that the Kristel mussel farming site belongs to the least contaminated areas reported for M. galloprovincialis in the Mediterranean basin.

The calculated bioconcentration factors (BCF) confirmed the well-known ability of M. galloprovincialis to accumulate trace metals, particularly copper and lead, even when dissolved concentrations in seawater remain extremely low. This finding is consistent with the role of mussels as efficient bioindicators of coastal metal contamination previously described by Rainbow (1995, 2002) and confirmed in Mediterranean monitoring studies (Andral et al. 2011). Nevertheless, because dissolved metal concentrations were below the analytical detection limits, the calculated BCF values should be regarded as conservative minimum estimates.

Human health risk assessment further confirmed the safety of mussel consumption. All individual Target Hazard Quotient (THQ) values were below 1, and the cumulative Hazard Index (HI = 0.046) remained far below the threshold of concern, indicating no appreciable non-carcinogenic risk. Similar conclusions have been reported for Mediterranean mussels from Italy, Türkiye, Morocco, and Algeria despite higher trace metal concentrations than those observed in the present study (Bat et al. 2023; Younis et al. 2024; El Mourabit et al. 2024; Guendouzi et al. 2024).

The absence of thermotolerant coliforms, coagulase-positive Staphylococcus, Salmonella, and Escherichia coli demonstrates the excellent microbiological quality of both seawater and mussel flesh. These findings are consistent with the microbiological criteria established for Class A shellfish harvesting areas under Regulation (EC) No. 854/2004 and with the recommendations of the Codex Alimentarius (CXS 292-2008) and FAO/WHO guidelines for the sanitary quality of bivalve molluscs (FAO/WHO 2022).

This study has several limitations. First, it was based on a single sampling campaign at one aquaculture site, preventing the assessment of seasonal variability previously reported for Mediterranean mussels (Rouane-Hacène et al. 2015). Second, only three metals were measured in seawater, limiting the calculation of BCF and HPI. Third, viral pathogens such as norovirus and hepatitis A virus were not investigated, although they are recognized as important foodborne hazards associated with shellfish consumption (Lees 2000). Finally, human dietary exposure was estimated using default consumption assumptions recommended by the USEPA (USEPA 2011). Future investigations should therefore include seasonal monitoring, a broader range of contaminants, viral analyses, and local dietary surveys to provide a more comprehensive assessment of the sanitary quality of Algerian mussel farming areas.

5. Conclusion

The present study provides the first integrated assessment of the physicochemical and microbiological quality of the farming water, trace metal contamination, and sanitary safety of Mytilus galloprovincialis cultivated at the Kristel aquaculture site (Oran, Algeria). The results demonstrated that the farming water was free from detectable microbiological and metal contamination for the investigated parameters, while mussel tissues complied with both the maximum trace metal levels established by Commission Regulation (EU) 2023/915 and the Algerian microbiological standards.

Comparison with recent studies conducted across the Mediterranean basin, including Spain, Italy, Türkiye, Morocco, Tunisia, and Algeria, indicated that the Kristel site belongs to the lower range of trace metal contamination reported for M. galloprovincialis. Moreover, the calculated health risk indices (THQ < 1 for all metals; HI = 0.046) confirmed that mussel consumption is not associated with appreciable non-carcinogenic health risks under the exposure scenario considered. The absence of Escherichia coli and other microbiological indicators further supports the excellent sanitary quality of the mussels and suggests that the farming area is consistent with the microbiological criteria for a Class A shellfish harvesting area according to European regulations.

Although these findings demonstrate the high sanitary quality of mussels produced at the Kristel site, the study was limited to a single sampling campaign. Therefore, seasonal and multi-year monitoring, together with the determination of a broader range of trace metals and emerging contaminants in seawater, is recommended to confirm the long-term environmental status of the farming area and support its official sanitary classification. Such investigations would also strengthen the sustainable development of mussel aquaculture and contribute to the production of safe, high-quality seafood for human consumption.

Statements and Declarations

Funding

This research received no external funding. The authors did not receive support from any organization for the submitted work.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships, and no non-financial competing interests, that could have appeared to influence the work reported in this paper.

Author Contributions

Hichem Benhamou: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Validation, Visualization, Writing — original draft, Writing — review & editing.
Sabrine Louala: Conceptualization, Supervision, Methodology, Validation, Project administration, Writing — review & editing.

Ethics Approval
Not applicable.

Consent to Participate
Not applicable. This study did not involve human participants.

Consent for Publication
Not applicable.

Data Availability
The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code Availability
Not applicable.

Declaration on the Use of Artificial Intelligence
The authors used generative artificial intelligence solely to improve the English language and readability of the manuscript. The authors take full responsibility for the content of the manuscript, including the accuracy of the data, analyses, and conclusions.

References

1. Ali H, Khan E, Ilahi I (2019) Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. J Chem 2019:6730305. https://doi.org/10.1155/2019/6730305
2. Andral B, Galgani F, Tomasino C, Bouchoucha M, Blottiere C, Scarpato A, Deudero S, Guarniero I, Marras P, Franco T, Mikhailov V (2011) Chemical contamination baseline in the Western Basin of the Mediterranean Sea based on transplanted mussels. Arch Environ Contam Toxicol 61:261–271. https://doi.org/10.1007/s00244-010-9599-x
3. Bat L, Yardım Ö, Öztekin A, Arıcı E (2023) Assessment of trace metal concentrations in Scophthalmus maximus (Linnaeus, 1758) from the Black Sea coast: implications for food safety and human health. J Hazard Mater Adv 12:100384. https://doi.org/10.1016/j.hazadv.2023.100384
4. Bruno F, Nava V, Zappalà S, Costa GL, Fazio F, Parrino V, Licata P (2024) Mineral composition in mussel Mytilus galloprovincialis and clam Tapes decussatus from Faro Lake (Messina, Italy): risk assessment for human health. Front Toxicol 6:1494977. https://doi.org/10.3389/ftox.2024.1494977
5. Codex Alimentarius Commission (2022) Standard for Live and Raw Bivalve Molluscs (CXS 292-2008). Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO), Rome, Italy
6. Commission Regulation (EU) 2023/915 (2023) Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No. 1881/2006. Off J Eur Union L119:103–157
7. Directive 2006/113/EC (2006) Directive 2006/113/EC of the European Parliament and of the Council of 12 December 2006 on the quality required of shellfish waters. Off J Eur Union L376:14–20
8. Edet AE, Offiong OE (2002) Evaluation of water quality pollution indices for heavy metal contamination monitoring. GeoJournal 57:295–309. https://doi.org/10.1023/B:GEJO.0000007250.92458.DE
9. El Mourabit Y, Hasni M, Agnaou M, Nadir M, Abou Oualid J, Moukrim A, Ait Alla A (2024) Assessment of trace metal bioaccumulation in Mytilus galloprovincialis from the central Atlantic Ocean after the installation of wastewater treatment facilities. Chemosphere 348:140730. https://doi.org/10.1016/j.chemosphere.2023.140730
10. Food and Agriculture Organization of the United Nations (FAO), World Health Organization (WHO) (2022) Technical Guidance for the Safe Production and Processing of Bivalve Molluscs. FAO, Rome, Italy
11. Goldberg ED (1975) The Mussel Watch—a first step in global marine monitoring. Mar Pollut Bull 6:111–114. https://doi.org/10.1016/0025-326X(75)90271-4
12. Guendouzi Y, Benhalima M, Serbah I, Fara M, Fowler SW, Boulahdid M, Soualili DL (2024) A novel approach to assess temporal baseline levels of trace metal contamination in Mytilus galloprovincialis from the Mediterranean, Marmara and Black Seas. Mar Pollut Bull 202:116367. https://doi.org/10.1016/j.marpolbul.2024.116367
13. Hacısalihoglu S (2025) Heavy metal accumulation and human health risk in Mediterranean mussels from the southern Marmara Sea, Türkiye. Toxics 13(12):1084. https://doi.org/10.3390/toxics13121084
14. Håkanson L (1980) An ecological risk index for aquatic pollution control: a sedimentological approach. Water Res 14:975–1001. https://doi.org/10.1016/0043-1354(80)90143-8

15. Joint FAO/WHO Expert Committee on Food Additives (JECFA) (1986) Evaluation of Certain Food Additives and Contaminants. WHO Technical Report Series No. 776. World Health Organization, Geneva, Switzerland
16. Joint FAO/WHO Expert Committee on Food Additives (JECFA) (2003) Summary and Conclusions of the Sixty-first Meeting of the Joint FAO/WHO Expert Committee on Food Additives. FAO/WHO, Rome, Italy
17. Joint FAO/WHO Expert Committee on Food Additives (JECFA) (2011) Safety Evaluation of Certain Food Additives and Contaminants. WHO Food Additives Series No. 64. World Health Organization, Geneva, Switzerland
18. Lees D (2000) Viruses and bivalve shellfish. Int J Food Microbiol 59:81–116. https://doi.org/10.1016/S0168-1605(00)00248-8
19. Meloni D, Mudadu AG, Abete MC, Bazzoni AM, Griglione A, Pederiva S, Stella C, Serra S, Fois N, Esposito G, Squadrone S (2022) Occurrence of trace elements in Mediterranean mussels (Mytilus galloprovincialis Lamarck, 1819) from an experimental pilot farm in the Calich Lagoon (Sardinia, Italy). Ital J Food Saf 11(1):9970. https://doi.org/10.4081/ijfs.2022.9970
20. Mohan SV, Nithila P, Reddy SJ (1996) Estimation of heavy metal pollution index for drinking water. J Environ Sci Health A 31:283–289. https://doi.org/10.1080/10934529609376357
21. Rainbow PS (1995) Biomonitoring of heavy metal availability in the marine environment. Mar Pollut Bull 31:183–192. https://doi.org/10.1016/0025-326X(95)00116-5
22. Rainbow PS (2002) Trace metal concentrations in aquatic invertebrates: why and so what? Environ Pollut 120:497–507. https://doi.org/10.1016/S0269-7491(02)00238-5
23. Rodier J, Legube B, Merlet N, Brunet R (Eds) (2009) L'analyse de l'eau: eaux naturelles, eaux résiduaires, eau de mer: chimie, physico-chimie, microbiologie, biologie, interprétation des résultats, 9th edn. Dunod, Paris
24. Rouane-Hacène O, Boutiba Z, Belhaouari B, Guibbolini-Sabatier ME, Francour P, Risso-de Faverney C (2015) Seasonal assessment of biological indices, bioaccumulation and bioavailability of heavy metals in mussels Mytilus galloprovincialis from the Algerian west coast applied to environmental monitoring. Oceanologia 57:362–374. https://doi.org/10.1016/j.oceano.2015.07.004
25. United States Environmental Protection Agency (USEPA) (1989) Risk Assessment Guidance for Superfund. Volume I: Human Health Evaluation Manual (Part A). EPA/540/1-89/002. Washington, DC, USA
26. United States Environmental Protection Agency (USEPA) (2000) Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites. Washington, DC, USA
27. United States Environmental Protection Agency (USEPA) (2011) Exposure Factors Handbook: 2011 Edition. EPA/600/R-09/052F. Washington, DC, USA
28. United States Environmental Protection Agency (USEPA) (2013) Regional Screening Levels (RSLs): User's Guide. Washington, DC, USA
29. Usero J, González-Regalado E, Gracia I (1996) Trace metals in the bivalve mollusc Chamelea gallina from the Atlantic coast of southern Spain. Mar Pollut Bull 32:305–310. https://doi.org/10.1016/0025-326X(95)00209-6
30. World Health Organization (WHO) (2017) Guidelines for Drinking-water Quality, 4th edn incorporating the first addendum. World Health Organization, Geneva, Switzerland
31. Younis AM, Hanafy S, Elkady EM, Alluhayb AH, Alminderej FM (2024) Heavy metals bioaccumulation in Mytilus galloprovincialis and Tapes decussatus from Faro Lake (Messina, Italy). Sci Rep 14:18706. https://doi.org/10.1038/s41598-024-69561-7