

Trace Element Concentrations and Health Risk Assessment of Veined Rapa Whelk (*Rapana venosa*) from the Southern Black Sea (Sinop, Türkiye)

Levent Bat^{1*}, Ayşah Öztekin¹, Dilara Kaya Öztürk², Zeynep Hasançavuşoğlu¹

¹Sinop University, Faculty of Fisheries, Department of Hydrobiology, 57500, Sinop, Türkiye.

²Sinop University, Faculty of Fisheries, Department of Aquaculture, 57500, Sinop, Türkiye.

Abstract

(1) Background: The veined rapa whelk (*Rapana venosa*), an invasive alien species introduced to the Black Sea in the 1940s, has evolved from a significant marine pest threatening native bivalves into a highly valuable, globally exported commercial commodity. However, because mollusks possess a high capacity for bioaccumulating trace elements, monitoring their chemical profile is essential to ensure food safety for human consumers. (2) Methods: This study evaluates the concentrations of key trace elements, specifically Zn, Cu, Pb, As, Hg, and Cd, in the edible soft tissues of *R. venosa* collected from the Akliman coasts of Sinop in the southern Black Sea. Sampling was conducted from depths of 1–2 meters during May and June, utilizing specimens with shell lengths ranging between 6 and 8 cm. The element concentrations within the soft tissues were quantified using an Inductively Coupled Plasma Mass Spectrometry (ICP-MS) system. (3) Results: The results demonstrated that absolute mass concentrations followed a consistent abundance pattern, with Zn exhibiting the highest levels and Cd showing the lowest. Crucially, to prevent overestimating toxicological hazards, As risk characterization was refined by focusing on its hazardous inorganic fraction (iAs) based on established literature consensus. The human health risk assessment via target hazard quotient (THQ) and carcinogenic risk index (RI) analyses revealed that all values fell significantly below international safety thresholds. (4) Conclusions: Consequently, the commercial consumption of these mollusks poses no systemic or oncological health risks to consumers, though continuous monitoring of trace element dynamics remains crucial for long-term food safety management.

Keywords: Veined rapa whelk, Trace element bioaccumulation, Target Hazard Quotient, Invasive alien species, Marine gastropods, Consumer safety.

Introduction

The global landscape of fisheries and aquaculture has experienced unparalleled expansion over the last decade (FAO 2024). In Türkiye, which is surrounded by four seas on three sides, the Black Sea has historically been the most productive marine environment with the highest capture fisheries potential, owing to its unique biological dynamics and massive nutrient inputs (Bat et al. 2011). However, in recent years, due to overfishing, climate change (Bat et al. 2024a), and various anthropogenic pressures (Bat et al. 2018a), the volume of seafood obtained through capture fisheries in the Black Sea has steadily declined, falling below the production levels generated by modern aquaculture activities (Bat et al. 2024b). Amidst this structural transformation, the historical fishing city of Sinop (Bat et al. 2013 and 2018b)-with its hydrobiological advantages such as sheltered bays, optimal water temperatures, and favorable current patterns-has emerged as the primary hub where marine aquaculture is most intensively and efficiently practiced across the entire Black Sea region (Bat et al. 2024b). By dominating the decline in traditional fisheries with sustainable aquaculture investments, the coastal waters of Sinop not only contribute millions of dollars in export revenues to the regional economy but also serve as a critical stronghold for the seafood supply security of the Black Sea (Bat et al. 2024b).

As a rich source of high-quality animal protein, the safe consumption of seafood is essential for sustaining global food security. Among marine seafood commodities, mollusks are one of the most widely produced and consumed groups. The veined rapa whelk (*Rapana venosa*) is a commercially valuable gastropod (Sağlam et al. 2015a, 2015b; Gönener and Özsandıkçı 2017) characterized by its high productivity and rich nutritional profile, being high in protein, low in fat, and rich in essential elements (Bayraklı et al. 2016; Panayotova et al. 2019; Bayraklı 2024). However, the carnivorous feeding habits and benthic nature of certain mollusks facilitate the bioaccumulation of environmental contaminants from both their prey and the surrounding aquatic medium (Bat et al. 2023). Humans' dietary exposure to these pollutants through mollusk consumption has historically led to poisoning incidents, indicating that the food safety of these species deserves critical attention since few decades (Bat et al. 2000; Bat and Öztekin 2016). The Black Sea, a semi-enclosed basin receiving massive river discharges, is highly susceptible to anthropogenic pollution (Bat et al. 2018a). Within marine environments, trace elements constitute one of the most serious pollutant categories due to their toxicity, persistence, and pronounced tendency to bioaccumulate in aquatic organisms. This issue is compounded by the dynamics of invasive alien species within the basin. First introduced to the Black Sea in the 1940s (Dapkin 1953), *R. venosa* has successfully colonized



benthic habitats. Its success as an invasive species is primarily attributed to its rapid growth rates, early reproductive maturity, high fecundity, and remarkable adaptability to diverse habitats (Mutlu et al. 2022; Baştusta et al. 2025). Owing to its high fertility, versatile nature, and tolerance to hypoxia and pollution, *R. venosa* has exerted significant predatory pressure on native bivalves, such as the Mediterranean mussel (*Mytilus galloprovincialis*) (Janssen et al. 2014). Although initially classified strictly as a marine pest, *R. venosa* has transformed into a high-value commercial commodity, representing million-dollars export market for the Black Sea littoral states. Nevertheless, because they are selective predatory gastropods positioned high in the benthic food web, rapa whelks can bioaccumulate trace elements to levels that may exceed food safety thresholds (Bat and Arici 2018). Consequently, continuous assessment of the chemical body burden of this species is crucial for ensuring consumer safety and evaluating the ecological status of the region. To address this need, the objective of the present study was to determine the concentrations of key trace elements (Zn, Cu, Pb, As, Hg, and Cd) in the soft tissues of sized (6-8 cm) wild *R. venosa* collected from the Akliman coasts of Sinop (Southern Black Sea, Türkiye) in May and June of year 2024. Furthermore, a comprehensive health risk assessment was performed using the Target Hazard Quotient (THQ), Hazard Index (HI), and Carcinogenic Risk Index (RI) to evaluate (USEPA 2024; RAIS 2024) whether the consumption of these wild gastropods poses any potential threat to human health.

Materials and Methods

Sampling and Sample Preparation

Wild specimens of the veined rapa whelk were collected from the Akliman coasts of the Sinop Peninsula (Southern Black Sea, Türkiye) during May and June 2024 (Figure 1). Sampling was restricted to individuals with a shell length ranging between 6 and 8 cm to maintain size uniformity. A total of 30 individuals were randomly divided into three replicate groups, each containing 10 specimens.

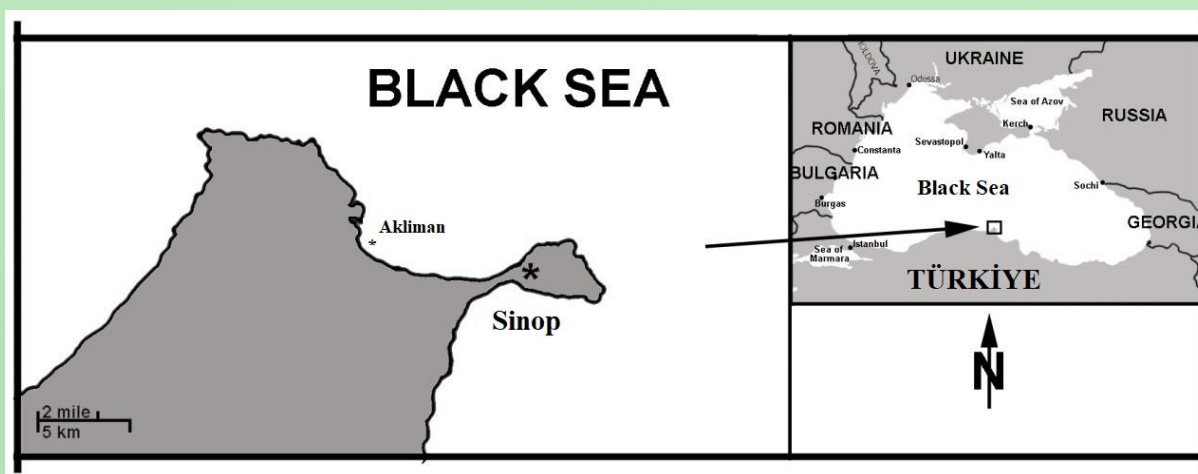


Figure 1. Sampling area

The samples collected were promptly transported to the laboratory under cold chain conditions. The shell surfaces were thoroughly cleaned using a synthetic brush to remove extraneous materials, labelled according to the sampling month, and stored in plastic bags at -21°C until further biometric measurements and chemical analyses. Prior to dissection, the whelks were thawed at room temperature. The soft tissues (including internal organs up to the furthest spiral fold) were carefully extracted from the shells, rinsed thoroughly with deionized water, and homogenized for trace element determination.

Analytical Procedures and Instrumentation

The concentrations of trace elements, specifically zinc (Zn), copper (Cu), lead (Pb), arsenic (As), mercury (Hg), and cadmium (Cd), in the soft tissues of *R. venosa* were determined using an Inductively Coupled Plasma Mass Spectrometry system (Agilent Technologies 7700X ICP-MS). Sample digestion and instrumentation was described as below (Bat et al. 2023, 2026):

The chemical analysis was conducted following the principles of EPA Method 200.3 for biological tissue preparation. Tissue samples of *R. venosa* (approximately 1.5 g) were placed into Teflon vessels and digested using a microwave digestion system (Milestone SK10). The digestion matrix consisted of an ultra-pure (suprapur) mixture of concentrated HNO₃ (65%) and H₂O₂ (30%) at a 7:1 (v/v) ratio, adhering to the HPR-FO-67 temperature and pressure operational program. The sealed vessels were brought to 200°C over 15 minutes and held at this thermal plateau for an additional 15 minutes. Once cooled, the digested extracts were transferred into 50 mL



polypropylene falcon tubes and diluted to volume with ultra-pure water. Analytical quality assurance and control protocols were verified by analyzing triplicate samples alongside a Certified Reference Material (CRM), specifically Lobster Hepatopancreas TORT-2. Multi-element calibration curves were established using Agilent standard solutions (27-element mix 2A, 8500-6940, and Hg, 8500-6940). The precision of the analytical method remained within $\pm 10\%$. For continuous instrumental drift monitoring, a 1 ppm internal standard (Agilent 5188-6525) was run systematically throughout the analysis. The Limit of Detection (LOD) and Limit of Quantitation (LOQ) values established for the validated analytical method are summarized in Table 1.

Table 1. Instrumental Limits of Detection (LOD) and Quantitation (LOQ) for the Analyzed Trace Elements.

Trace elements	LOD (ppb)	LOQ (ppb)
Zn	0.979	2.937
Cu	0.030	0.090
Pb	0.008	0.024
As	0.007	0.021
Hg	0.039	0.117
Cd	0.007	0.021

Consumer Health Risk Assessment

To evaluate the potential health risks associated with the dietary intake of trace elements through *R. venosa* consumption, the Estimated Daily Intake (EDI) and the Target Hazard Quotient (THQ) were calculated in accordance with the United States Environmental Protection Agency guidelines (USEPA, 2000, 2001).

Estimated Daily Intake (EDI)

The EDI ($\text{mg kg}^{-1}\text{day}^{-1}$) represents the theoretical daily exposure dose of a specific contaminant per unit of body weight and was calculated using the following equation guidelines (USEPA, 2000, 2001):

$$\text{EDI} = \frac{\text{FIR} \times \text{C}}{\text{BW}}$$

Where:

- **FIR:** Food intake rate for adult mollusks consumption (g day^{-1}), adapted as $<1 \text{ g day}^{-1}$ based on FAO (2023) criteria.
- **C:** Concentration of the target trace element in the soft tissue (mg kg^{-1} wet weight).
- **BW:** Average adult body weight, set at 70 kg (USEPA, 2000).

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

The THQ characterizes the ratio between the exposure dose and the reference dose (Rf. D.), serving as a metric for non-carcinogenic health risk assessment guidelines (USEPA, 2000, 2001):

$$\text{THQ} = \frac{\text{EF} \times \text{ED} \times \text{FIR} \times \text{C}}{\text{Rf. D.} \times \text{BW} \times \text{AT}}$$

Where:

- **EF:** Exposure frequency (365 days year⁻¹).
- **ED:** Exposure duration (70 years for adults).
- **Rf. D.:** Oral reference dose ($\text{mg kg}^{-1} \text{day}^{-1}$) for each element established by USEPA (2024).
- **AT:** Averaging time for non-carcinogenic effects, calculated as the product of EF x ED (365 days year⁻¹ x 70 years).

An HI value exceeding the safety threshold of 1.0 indicates potential non-carcinogenic health risks for the consuming population, whereas HI equal to or below this baseline implies that consumption is safe and devoid of significant health risks (USEPA, 2001, 2024).

Carcinogenic Risk Index (RI)

To estimate the potential lifetime carcinogenic risk associated with exposure to specific trace elements via *R. venosa* consumption, the Risk Index (RI) was calculated using the following equation (USEPA 2024; RAIS 2024):
 $\text{RI} = \text{EDI} \times \text{SF}$

- **SF:** Oral Slope Factor ($\text{mg kg}^{-1} \text{day}^{-1}$)⁻¹ established by the USEPA for carcinogenic contaminants

The calculated RI values were interpreted based on the regulatory safety thresholds defined by the USEPA (2024):

- $\text{RI} < 10^{-6}$ indicates a negligible or insignificant risk, meaning the probability of developing cancer from dietary exposure is exceptionally low.



- An RI value ranging between 10^{-6} and 10^{-4} ($10^{-6} < RI < 10^{-4}$) is classified as an acceptable or tolerable risk level.
- An $RI > 10^{-4}$ is considered a significant health concern, indicating an unacceptable carcinogenic risk that requires immediate attention.

Statistical Analysis

All experimental data were expressed as mean values $\pm$ standard deviation (SD). Prior to parametric hypothesis testing, the datasets were evaluated for normality using the Shapiro-Wilk test, and homogeneity of variances was verified via Levene's test. To determine whether the temporal variations in trace element concentrations, target hazard quotients (THQ), and carcinogenic risk indices (RI) between May and June were statistically significant, an independent-samples *t*-test (or Mann-Whitney U test for non-normally distributed data) was performed. Additionally, Pearson correlation analysis (or Spearman's rank correlation) was utilized to assess the strength and direction of the linear relationships among the verified trace elements in the soft tissues of *R. venosa*. All statistical evaluations were conducted using the SPSS software package (Version 27, IBM Corp., Armonk, NY, USA), and the threshold for statistical significance was strictly established at a *p*-value of less than 0.05 ($p < 0.05$).

Results

Trace Element Accumulation Profiles

The mean concentrations of six analyzed trace elements (Zn, Cu, Pb, As, Hg, and Cd) in the soft tissues of the veined rapa whelk collected from the Akliman coasts of Sinop were summarized in Table 2.

Table 2. Mean concentrations (mg. kg⁻¹ wet weight $\pm$ standard deviation, n=3) of trace elements in the soft tissues of *R. venosa* collected from Akliman coasts (Sinop, Southern Black Sea) during May and June 2024.

Months	Zn	Cu	Pb	As	Hg	Cd
May	7.80 $\pm$ 0.16	3.81 $\pm$ 0.28	0.040 $\pm$ 0.002	0.034 $\pm$ 0.004	0.022 $\pm$ 0.002	0.012 $\pm$ 0.001
June	7.34 $\pm$ 0.43	3.13 $\pm$ 0.15*	0.045 $\pm$ 0.009	0.028 $\pm$ 0.004*	0.020 $\pm$ 0.001	0.013 $\pm$ 0.001

* Indicates a statistically significant difference between May and June ($p < 0.05$).

Statistical analysis revealed distinct monthly variations for specific elements between the two sampling periods. The decrease in Cu and As concentrations from May to June was found to be statistically significant ($p < 0.05$), indicating a shifting bioaccumulation dynamic or a change in environmental availability as the season progressed into early summer. Conversely, no statistically significant temporal differences were observed for Zn, Pb, Hg, and Cd ($p > 0.05$), suggesting that the bioaccumulation of these elements remained stable throughout the studied months. While total As (tAs) concentrations stood at 0.034 (May) and 0.028 (June), the hazardous inorganic As (iAs) fraction-estimated at 10% of tAs (Marengo et al. 2018; Souza-Araujo et al. 2021; da Silva et al. 2025)-was remarkably lower (0.0034 mg/kg and 0.0028 mg/kg).

Dietary Exposure Risk Table

The estimated dietary exposure levels, expressed as EDI and EWI through the consumption of *R. venosa*, are presented in Table 3. The dietary exposure profile for both daily and weekly intake mirrors the established soft tissue bioaccumulation trend, with Zn and Cu values remaining noticeably higher than the rest of the analyzed elements. In contrast, the exposure rates calculated for non-essential toxic elements (Pb, As, Hg, and Cd) were considerably minimal across both sampling months. Temporal comparisons indicated a general slight reduction in the intake levels for most elements from May to June, except for Pb and Cd, which demonstrated stable or marginally higher values in the early summer period.

Table 3. Estimated Daily Intake (EDI, mg kg⁻¹ day⁻¹) and Estimated Weekly Intake (EWI, mg kg⁻¹ week⁻¹) of trace elements from the consumption of *R. venosa* collected in May and June 2024.

Risk Index	Month	Zn	Cu	Pb	As	Hg	Cd
EDI	May	1.11 x10 ⁻³	5.44 x10 ⁻⁴	5.8 x10 ⁻⁶	4.9 x10 ⁻⁶	3.2 x10 ⁻⁶	1.8 x10 ⁻⁶
	June	1.05 x10 ⁻³	4.47 x10 ⁻⁴	6.4 x10 ⁻⁶	4.0 x10 ⁻⁶	2.9 x10 ⁻⁶	1.8 x10 ⁻⁶
EWI	May	7.80 x10 ⁻³	3.81 x10 ⁻³	4.0 x10 ⁻⁵	3.4 x10 ⁻⁵	2.2 x10 ⁻⁵	1.2 x10 ⁻⁵
	June	734 x10 ⁻³	3.13 x10 ⁻³	4.5 x10 ⁻⁵	2.8 x10 ⁻⁵	2.0 x10 ⁻⁵	1.3 x10 ⁻⁵

Health Risk Assessment and Trace Elements Index Evaluation

The non-carcinogenic THQ and carcinogenic RI calculated for trace elements exposures during May and June are summarized in Table 4. To avoid the overestimation of health risks, As toxicity was specifically evaluated



based on its inorganic form (iAs), if iAs constitutes approximately 10% of the total As (tAs) concentration as widely established in the literature (Marengo et al. 2018; Souza-Araujo et al. 2021; da Silva et al. 2025).

The calculated THQ values for all elements, including iAs, ranged from 1.35×10^{-6} to 1.80×10^{-5} . In May, Cd exhibited the highest THQ (1.80×10^{-5}), followed by Cu (1.36×10^{-5}) and Hg (1.10×10^{-5}), while iAs showed a lower non-carcinogenic potential (1.62×10^{-6}). A similar trend was observed in June, where Cd remained the dominant contributor (1.80×10^{-5}) and iAs decreased slightly to 1.35×10^{-6} .

Carcinogenic RI was performed for Pb and iAs. The RI values for iAs were determined as 7.29×10^{-7} in May and 6.07×10^{-7} in June. For Pb, the RI values were 4.90×10^{-8} and 5.46×10^{-8} for May and June, respectively.

Table 4. Target Hazard Quotient (THQ) and Carcinogenic Risk Index (RI) values of trace elements across monitoring periods.

	Period	Zn	Cu	Pb	tAs	iAs	Hg	Cd
THQ	May	3.71×10^{-6}	1.36×10^{-5}	1.90×10^{-6}	1.62×10^{-5}	1.62×10^{-6}	1.10×10^{-5}	1.80×10^{-5}
	June	3.50×10^{-6}	1.12×10^{-5}	2.10×10^{-6}	1.35×10^{-5}	1.35×10^{-6}	9.70×10^{-6}	1.80×10^{-5}
RI	May	-	-	4.90×10^{-8}	7.29×10^{-6}	7.29×10^{-7}	-	-
	June	-	-	5.46×10^{-8}	6.07×10^{-6}	6.07×10^{-7}	-	-

tAs= As (Total); iAs= As (inorganic)

Discussion

Trace Element Accumulation Profiles

The concentrations of the analyzed trace elements in the soft tissues of *R. venosa* exhibited distinct variations depending on the specific element and the sampling month (Bat et al. 2023). In the present study, for both sampling periods, a consistent and robust bioaccumulation hierarchy was observed across the specimens, establishing a definitive decreasing profile. Zn was predominantly the most abundant element accumulated within the soft tissues, followed closely by Cu. This prominent dominance of Zn and Cu reflects their biological roles as essential physiological elements, which gastropods actively regulate for metabolic processes and enzymatic functions.

Conversely, the non-essential and highly toxic heavy metals, along with metalloids, displayed remarkably lower bioaccumulation levels throughout the study. Among these regulated contaminants, Pb and As occupied the intermediate segment of the accumulation spectrum, showing minor fluctuations between the late spring and early summer periods. Hg and Cd were sequestered in the least amounts, with Cd consistently remaining the least accumulated element in the soft tissues of the veined rapa whelk. The minimal accumulation of these hazardous trace metals suggests a low environmental exposure level at the studied habitat or a specific metabolic exclusion mechanism by the organism during the sampling months.

Comparison of Trace Element Concentrations with Food Safety Standards

To evaluate the commercial viability and food safety compliance of the analyzed matrix, the measured trace element concentrations during May and June were compared against established national and international regulatory thresholds for mollusks.

A critical observation from the regulatory framework is that no specific permissible limit or criterion has been established for As across any of the evaluated guidelines, including the Ministry of Agriculture, Forestry and Fisheries (MAFF 1995), Turkish Food Codex (Official Gazette of Republic of Türkiye 2002 and 2009), and European Commission Regulations (Council of Europe 2001; Commission Regulation 2006). This absence of an As standard highlights the complexity of metalloid regulation in marine organisms and underscores the importance of utilizing risk indices like THQ and RI to independently verify its safety. For the remaining regulated elements, the concentration levels in this study were found to be exceptionally low and well within all safe legal limits:

Zn and Cu: The maximum concentrations detected in this study (Zn: 7.80 mg/kg; Cu: 3.81 mg/kg in May) were profoundly below the most stringent guidance limits. Zn levels were safely lower than the 50 mg/kg threshold specified by both MAFF (1995) and the Turkish Food Codex (Official Gazette of Republic of Türkiye 2002). Similarly, Cu levels did not exceed the strict 20 mg/kg maximum permissible limit set by the same authorities.

Pb: The maximum measured Pb concentration (0.045 mg/kg in June) was significantly lower than the maximum allowable level of 1.5 mg/kg stipulated for mollusks by the Commission Regulations (Council of Europe 2001; Commission Regulation 2006) and the Turkish Food Codex (Official Gazette of Republic of Türkiye 2002 and 2009), as well as the 10 mg/kg screening limit of MAFF (1995).

Hg: The recorded Hg concentrations (0.022 mg/kg in May and 0.020 mg/kg in June) were substantially below the uniform European and Turkish regulatory limit of 0.5 mg/kg (Council of Europe, 2001; Official Gazette of Republic of Türkiye 2002 and 2009; Commission Regulation 2006).

Cd: Despite having the lowest physiological tolerance ceiling among the metals, the measured Cd values (0.012 - 0.013 mg/kg) exhibited a vast safety margin when compared to the legal threshold of 1.0 mg/kg strictly enforced for molluscan products by European and Turkish food codices, and the 0.2 mg/kg limit of MAFF (1995).



In conclusion, the comparative assessment demonstrates that the concentrations of all regulated heavy metals in the sampled mollusks are safely below the maximum permissible limits set by both Turkish (Official Gazette of Republic of Türkiye 2002 and 2009) and international food safety authorities (Council of Europe, 2001; Commission Regulation 2006). These results confirm that the monitored matrix poses no toxicological threat regarding commercial food safety regulations.

Health Risk Assessment and Trace Elements Index Evaluation

The non-carcinogenic health risk coefficients (THQ) for all investigated heavy metals were significantly below the US EPA threshold of 1 (THQ<1), indicating no substantial non-carcinogenic health hazard to the consumer population during the monitoring periods.

A critical refinement was applied to the carcinogenic risk evaluation of As. Raw risk estimates based on total As (tAs) often overemphasize the actual threat, as organic As compounds possess minimal toxicity. By adopting the conservative literature consensus (Marengo et al. 2018; Souza-Araujo et al. 2021; da Silva et al. 2025) that inorganic As (iAs) represents roughly 10% of tAs, the realistic carcinogenic RI for iAs were calculated as 7.29×10^{-7} (May) and 6.07×10^{-7} (June).

According to the US EPA risk characterization guidelines, an RI value below 10^{-6} indicates a negligible or insignificant carcinogenic risk. Prior to speciation correction, tAs values marginally fell into the 10^{-6} - 10^{-4} acceptable/tolerable risk range. However, focusing precisely on the toxicologically relevant iAs fraction revealed that the true carcinogenic risk of As in this study is entirely negligible (RI < 10^{-6}). Similarly, the RI values for Pb (approx. 5×10^{-8}) were well below the critical baseline. Consequently, it can be concluded that the long-term consumption or exposure to the investigated matrix does not pose any alarming oncological or systemic health risks regarding Pb and As dynamics.

The minor temporal fluctuations observed between May and June can be attributed to environmental factors such as variation in hydrodynamic conditions, seasonal precipitation changes altering dilution effects, or localized shifts in anthropogenic discharges. The subtle increment in Pb indices during June underscores the possibility of minor seasonal traffic / tourism activity or agricultural run-off impacts, which should be verified with extended longitudinal data.

Conclusion

This study provided a comprehensive temporal evaluation of trace element concentrations (Zn, Cu, Pb, As, Hg, and Cd) and associated human health risks in the investigated molluscan matrix during May and June. The concentration hierarchy consistently followed the pattern of Zn > Cu > Pb > As > Hg > Cd across both monitoring periods. Comparative assessments against national and international food safety standards (including Turkish Food Codex, European Commission Regulations, and MAFF guidelines) demonstrated that all regulated heavy metals were exceptionally low and remained safely below the maximum permissible thresholds. Notably, while global food safety guidelines lack specific criteria for As, target health risk indexes effectively bridged this regulatory gap.

By implementing a toxicologically refined speciation approach-evaluating As risks based on the toxic inorganic fraction (iAs= 10% of tAs)-the study demonstrated that the realistic non-carcinogenic THQ and carcinogenic RI (< 10^{-6}) for all elements were well within safe physiological limits. Minor temporal fluctuations between May and June, particularly the subtle elevation of Pb in June, highlight the seasonal dynamics of environmental factors and potential localized anthropogenic inputs. In conclusion, the analyzed mollusks are commercially viable and completely safe for human consumption, presenting no systemic or oncological health risks. Nonetheless, establishing localized longitudinal monitoring programs is recommended to maintain comprehensive oversight of trace elements dynamics and long-term food safety security in the region.

Declarations

Ethical Approval Certificate

Ethical approval was not required for this study. This article does not contain any studies involving human subjects. We confirm that this manuscript complies with all Ethical Rules applicable to the journal.

Author Contribution Statement

Levent Bat: Conceptualization, validation, data curation, writing-original draft preparation, supervision, writing-review and editing.

Ayşah Öztekin: Investigation, resources, visualization, software, methodology, formal analysis.

Dilara Kaya Öztürk: Data collection, investigation, methodology, formal analysis.

Zeynep Hasançavuşoğlu: Data collection, investigation, methodology, formal analysis.

All authors have read and agreed to the published version of the manuscript.



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Conflict of Interest

The authors declare no conflict of interest.

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