

Article

Accumulation of Metals and Metalloids in Marine Invertebrates and Macroalgae in False Bay (Cape Town, South Africa)

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Abstract

The concentrations of 18 metal(loid)s were measured in five marine invertebrate species (*Oxystele tigrine* and *sinensis*, *Marthasterias glacialis*, *Cymbula oculus* and *granatina*, *Parechinus angulosus*, and *Mytilus galloprovincialis*) and five macroalgae/seaweed species (*Aeodes orbitosa*, *Gelidium pristoides*, *Caulerpa filiformis*, *Ulva* sp., and *Bifurcaria brassicae formis*) collected from eight sites within the marine environment of False Bay, Cape Town, South Africa. To assess the potential human health hazards associated with consumption, samples were acid digestion and analysed using inductively coupled plasma optical emission spectrometry (ICP-OES). The analysed elements included trace metals (Fe, Mn, Zn) toxic metals (Pb, Cd, As), transition metals (Ta, Ti), alkali metals (Li), and metalloid (Se, As). Metal concentration varied widely among species and locations, with values ranging from Zn: not detected (nd)—3836.04 mg/kg dry weight (dw); As: nd—77.98 mg/kg dw; Pb: nd—301.15 mg/kg dw; Li: nd—97.28 mg/kg dw, indicating diverse metal accumulation patterns. Human health risk was evaluated using the target hazard quotient (THQ) and hazard index (HI). Arsenic consistently exceeded the THQ threshold of one across all sites, and all the HI values were greater than one for all edible species, suggesting potential non-carcinogenic health risks associated with the consumption, except for *M. glacialis*, which is not commonly consumed. The HI metrics demonstrate the adverse impacts of metal concentration in marine biota. The observed spatial and biological variability in metal accumulation highlights the limitations of relying solely on metal concentrations for assessing health risks, food safety or anthropogenic contamination, and therefore more frequent and comprehensive monitoring is recommended.



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Keywords: False Bay; health risk assessment; marine organisms; contamination; marine environment

1. Introduction

Marine and coastal environments are vital ecosystems that provide ecological, economic and cultural services [1]. However, they are increasingly threatened by pollution from both natural and anthropogenic sources [2]. Among the various contaminants, metals

have raised particular concern due to their non-biodegradable, persistent nature as well as their ability to enter and build up within food web networks [3], ultimately posing significant risks to both wildlife and human health [4].

In numerous regions, major sources of metal pollution include urban runoff, wastewater discharge, industrial effluents, and agricultural activities [2,5]. While some metals such as iron, zinc, and copper are essential for biological processes in trace amounts [6], others such as cadmium, lead, mercury and arsenic are toxic even at low concentrations [7]. Prolonged exposure to elevated levels of these metals has been linked to detrimental effects in marine biota, including reduced reproduction, impaired growth, oxidative stress, and mortality [4,8,9]. Marine invertebrates, particularly filter-feeding bivalves and gastropods such as clams and mussels, are widely used as bioindicators of coastal metal contamination. Their sessile nature, feeding mechanisms and ability to accumulate metals from water and food particles allow their use as sentinels for monitoring environmental health. Similarly, macroalgae are effective in tracing metal contamination patterns due to their high surface area-to-volume ratio and direct metal uptake from seawater [10,11].

South Africa's oceans face significant pollution challenges, with chemical pollutants, microbes and plastic waste being major concerns, with the main source of pollution originating from wastewater treatment plants, sewer blockages, poor operations, and lack of maintenance, as well as land-based sources of metal pollution [12]. False Bay, located on the southern coast of Cape Town, South Africa, is a semi-enclosed coastal embayment of high ecological and socio-economic importance [13]. The bay receives many million litres of poorly treated sewage effluents from seven wastewater treatment plants (WWTPs) daily and is influenced by urban development, informal settlements, stormwater runoff, and maritime activities. Rapid population growth and insufficient wastewater infrastructure have exacerbated pollution pressure, raising concerns about metal contamination in its marine ecosystems [14]. While international studies have documented metal uptake in marine organisms and the associated ecological and health risks [15,16], there remains a significant gap in region-specific data for South Africa coastlines, particularly False Bay, which is influenced by both urban runoff and wastewater discharges. Despite being ecologically and economically important, False Bay has received limited attention in terms of trace metal monitoring, especially with respect to commonly consumed invertebrates and macroalgae.

The aim of this research was to conduct a comprehensive field investigation of selected metals within the marine environment of False Bay, South Africa. This research represents the first attempt to assess the occurrence and relative accumulation of metals in the various species of invertebrates and macroalgae in this region. By quantifying the levels of these metals in these different species, the study seeks to enhance understanding of how metal(loid) laden effluent discharges from various WWTPs impact the nearshore ecosystem. Furthermore, the findings will support global assessments of metal accumulation in marine biota and contribute to determining the potential health risk associated with metal exposure, ultimately informing evaluations of seafood safety and environmental health in False Bay.

2. Materials and Methods

2.1. Description of Sampling Sites

False Bay, situated at 34°13.19' S 18°38.4' E of Cape Town, stretches approximately 30 km at its widest point. It is bordered by the Cape Peninsula and Cape Hangklip in the southwestern corner of South Africa. The sandy northern edge of the bay defines the southern limit of the region (Cape Flats). The bay also hosts key infrastructure, including South Africa's largest naval base in Simon's Town and smaller fishing harbours at Kalk

Bay and Gordon's Bay. Samples were gathered from eight different locations along the bay (Figure 1) that are described in Table 1. There was a severe drought during 2015–2018 in Cape Town with little runoff from stormwater during this whole period.

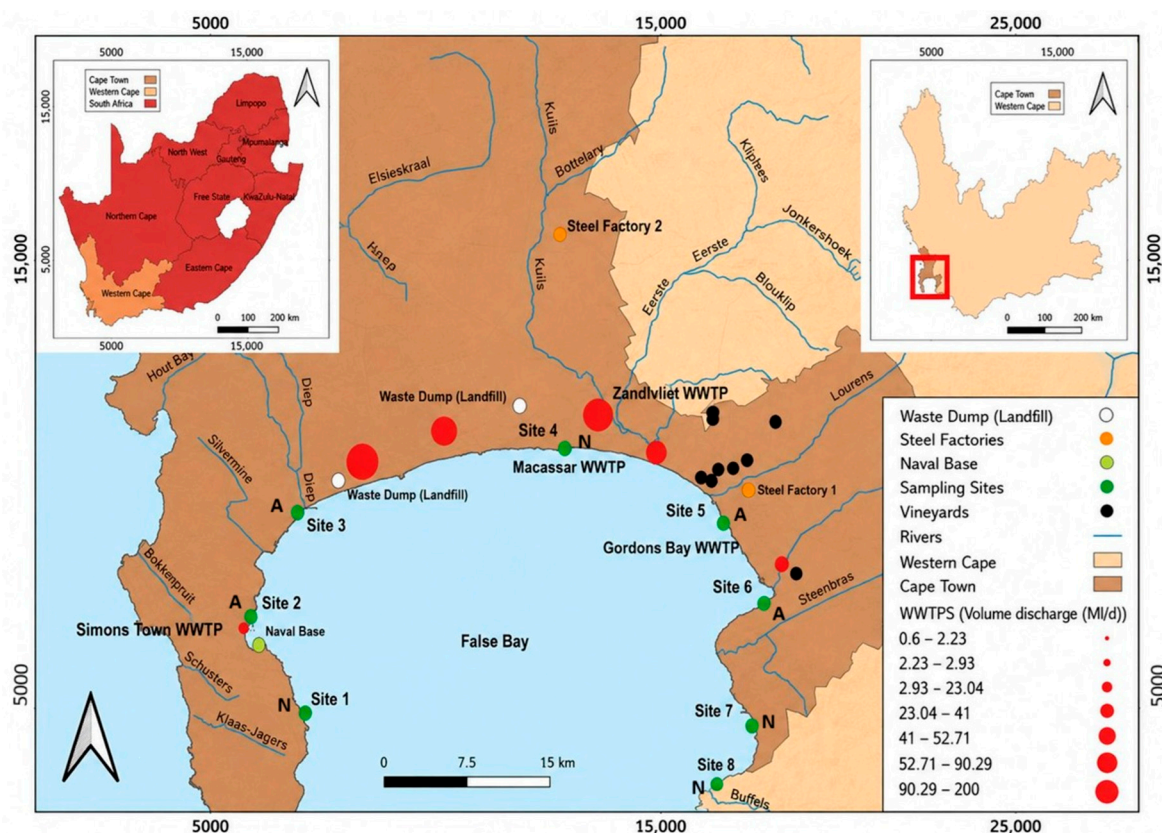


Figure 1. False Bay map depicting the sampling area, including the locations of WWTPs and their daily discharge volumes (million litres per day (mL/d)), the city's legal landfill; A = anthropogenic stress; N = natural without anthropogenic stress.

Table 1. Description of the sampling sites.

Site Point	Site Name	Coordinates of the Sampling Site
1	Miller's Point	34°13'57.9" S, 18°28'36.5" E
2	Simon's Town	34°10'22.87" S, 18°25'42.73" E
3	Muizenberg	34°6'38.12" S, 18°28'5.09" E
4	Monwabisi beach	34°04'26.8" S, 18°41'21.5" E
5	Strand	34°7'3.71" S, 18°49'29.38" E
6	Gordon bay/Bikini beach	34°9'57.55" S, 18°51'30.39" E
7	Klippies Baai camp site	34°14'39.21" S, 18°51'6.77" E
8	Rooi Els	34°17'50.65" S, 18°48'49.16" E

Circulation patterns within the bay vary seasonally. During winter, when northeasterly winds dominate, water movement tends to weaken, with surface currents rotating counter-clockwise and deeper waters exhibiting cyclonic circulation. In contrast, Gordon's Bay is located in the northeast corner and often forms a closed, cyclonic loop under north-westerly wind influence. In summer, southeasterly winds induce a predominantly clockwise rotation in both surface and deeper layers, creating a strong, narrow current along the eastern coast. However, Gordon's Bay experiences a reversal, forming an anticlockwise gyre [17]. These wind-driven circulation dynamics influence sediment and particulate transport. Typically, materials move northward along the western shores and then turn east along the bay's

northern edge, while transport on the eastern shoreline continues northward. False Bay receives discharge from seven different wastewater treatment facilities, which variously release about 0.6–200 million litres from each plant per day [14]. Site 1 is a relatively remote area with the coastline characterised by surrounding vegetation, boulders of various sizes, and fine-to-medium-grained sandy sediments. Despite its seclusion, the presence of stormwater outlets, a nearby WWTP discharging into the ocean, and local human activity including a nearby slipway and restaurant pose potential pollution risks. Site 2 is a rocky shoreline with similar sediment texture and is located close to the town's main sewer pump station, whose overflow pipe releases directly into the surf zone. As a semi-enclosed embayment on the northwestern edge of the bay, this location often exhibits poor water circulation. Site 3 has large coastal boulders, fine-to-medium sand, and a major effluent discharge pipe directed into the ocean. Site 4 is a more open coastal area with protective limestone cliffs nearby. It features a large tidal pool and recreational facilities, including picnic and camping areas, making it a frequently visited public site, but is in close proximity to significant volumes of surf zone effluent discharge. Site 5 is on the eastern shoreline of False Bay, near the base of the Hottentots Holland Mountains, between Macassar and Gordon's Bay. It is known for its long stretch (~5 km) of white sandy beach and is situated around 50 km southeast of Cape Town, but it is also heavily impacted by surf zone sewage effluent discharges. Site 6 is a harbour town positioned in the northeastern corner of the bay. The local WWTP releases effluent along this coast, with discharge volumes reported to have increased significantly in recent years. Site 7 is a remote but popular recreational area used for picnicking, camping, and braais, attracting regular public use. Site 8 is located on the eastern coastline of False Bay, approximately 5 km north of Pringle Bay. This small coastal town features a narrow beach and is where the Rooi Els River meets the sea [17]. The coastal environment of False Bay consists of a heterogeneous mixture of rocky shores, intertidal rock pools, and fine-to-medium-grained sandy sediments. Coastal sediments act as important sinks and potential secondary sources of metal(loid)s, influencing their transport, redistribution, and bioavailability to benthic organisms such as marine invertebrates and macroalgae. Consequently, the characteristics of the coastal substrate are an important component of the environmental setting, although sediment samples were not included in the present study. The sampling sites were selected based not only on their proximity to wastewater discharge points in some cases, but also on their relative isolation from such effluent sources in other cases as well as from anthropogenic influences (marked as 'A' on the study map). This dual rationale allowed for a broader assessment. Additionally, the sites were strategically distributed across the entire False Bay coastal zone from east to west to evaluate whether ocean circulation patterns were effectively dispersing pollutants throughout the bay. Information regarding the sampling sites and WWTP has been previously reported [18].

2.2. Sample Collection and Handling

Samples (Table 2) were collected from rock pools located along the shoreline at eight sites representing gradients of anthropogenic impact, including areas adjacent to wastewater treatment plant (WWTP) effluents and relatively pristine reference sites, as shown in Figure 1, along the coastline of False Bay, South Africa. Sampling was conducted in May 2018 during the late autumn and coincided with the Cape Town drought period. All samples were collected during a single sampling campaign using hand collection and a polypropylene knife. The sampling period was selected to provide a representative assessment of metal(loid) accumulation in marine biota under the prevailing environmental conditions at the time of collection. Species were selected based on their availability, ecological relevance and human consumption patterns, with bivalves and gastropods acting

as established bioindicators of metal contamination. The number of individuals collected for each species at each sampling site is provided in Table 2. For each species at a given site, all individuals of comparable size were pooled to produce a single composite sample for analysis. The same sample preparation procedure was applied consistently to all species and sites to ensure methodological uniformity and to minimise variability arising from individual differences. The collected invertebrates and seaweeds were carefully placed in polyethylene bags, transported in cool bags containing ice, and then taken to the laboratory. Upon arrival, the fresh weight of each sample was recorded. Marine invertebrates were dissected to remove the soft tissue from their shells. The soft tissues of each of the invertebrates and seaweed samples were rinsed thoroughly with Milli-Q water to remove adhering sediment and debris before being homogenised (E2355, Eberbach Corp., Belleville, MI, USA). Homogenisation was performed on the composite sample for each species at each site to obtain a representative sample and reduce individual biological variability. All homogenised samples were stored at $-20\text{ }^{\circ}\text{C}$ before freeze-drying (LyoAlfa, Telstar, Barcelona, Spain). The freeze-dried samples were then ground into a fine powder using an agate mortar and pestle prior to digestion and metal(loid) analysis.

Table 2. Species of samples collected, sample size and individual unit no at each sampling location.

Species				Sample Size	
Scientific Name	Popular Name	Phylum	Class	Sample Weight (g)	Unit No
<i>Aeodes orbitosa</i>	Slippery orbit	Rhodophyta	Florideaphyceae	250	-
<i>Gelidium pristoides</i>	Red algae	Rhodophyta	Florideaphyceae	250	-
<i>Caulerpa filiformis</i>	Strap Caulerpa	Chlorophyta	Ulvophyceae	250	-
<i>Ulva</i> sp	Sea lettuce	Chlorophyta	Ulvophyceae	250	-
<i>Bifurcaria brassicac formis</i>	Hanging wrack	Ochrophyta or Heterokontophyte	Phaeophyceae	250	-
<i>Oxystele tigrine and sinensis</i>	Sea snail	Mollusca	Gastropoda	-	30
<i>Marthasterias glacialis</i>	Starfish	Echinodermata	Asteroidea	-	15
<i>Cymbula oculus and granatina</i>	Limpet	Mollusca	Gastropoda	-	30
<i>Parechinus angulosus</i>	Sea urchin	Echinodermata	Echinoidea	-	20
<i>Mytilus galloprovincialis</i>	Mussels	Mollusca	Bivalvia	-	35

2.3. Reagents and Standards

Standard solutions were prepared, and samples were diluted using Milli-Q water from the Milli-Q Element system (Merck, Darmstadt, Germany). Analytical-grade chemicals nitric acid (HNO_3 , 65%) and hydrogen peroxide (H_2O_2 , 30%) (Merck, Darmstadt, Germany) were used for the sample digestion preparation. Eighteen distinct metals standards, namely aluminium (Al), arsenic (As), cadmium (Cd), lithium (Li), chromium (Cr), titanium (Ti), cobalt (Co), copper (Cu), beryllium (Be), iron (Fe), nickel (Ni), lead (Pb), manganese (Mn), molybdenum (Mo), selenium (Se), strontium (Sr), tantalum (Ta), and zinc (Zn), as well as certified reference material (CRMs) ERM-CE278K mussel tissue were obtained from the LGC standards (Cape Town, South Africa).

2.4. Biota Sample Preparation

All analyses were conducted in triplicate to ensure reproducibility. For digestion, high-pressure decomposition vessels (digestion bombs) were used. Dried soft tissue of each homogenised invertebrate and seaweed samples (0.65 g, $n = 3$) from the different sites were placed separately in a Teflon container and then mixed with 8 mL of HNO_3 and 4 mL of H_2O_2 . The mixture was then heated to $140\text{ }^{\circ}\text{C}$ for 130 min. Samples were allowed to cool to room temperature, and each solution was then filtered using a $0.45\text{ }\mu\text{m}$ nitrocellulose

membrane filter into an acid-washed polypropylene volumetric flask and then diluted to a final volume of 25 mL with Milli-Q water. A blank digestion and CRMs ERM-CE278K mussel tissue was also analysed using the same procedure [19].

2.5. Instrumentation

Metal analysis was performed using an inductively coupled plasma optical spectrometer (ICP-OES) (Varian 710 ES, Chemetrix, Cape Town, South Africa). The instrument operated at 1.2 kW radiofrequency and a frequency of 40 MHz. High-purity argon gas (99.996%) served multiple roles: for plasma generation (15.5 L/min), nebulization (200 kPa), and optical system support (1.5 L/min), with a pressure of 100 PSI and system power maintained at 600 W during operation. A glass double-pass cyclonic spray chamber was used for sample introduction. The sample uptake delay was set to 30 s, with a 15 s stabilisation period prior to measurement. Each sample was analysed in triplicate to ensure precision, with a run duration of 13 min. The specific wavelength lines in nanometres employed for the ICP-OES analysis were as follows: Cd (214.439), Ti (336.122), As (193.696), Pb (217.000), Cr (267.716), Zn (213.857), Fe (238.204), Li (670.783), Al (394.401), Mn (259.373), Co (238.892), Ta (268.517), Ni (221.648), Se (203.985), Sr (407.771), Cu (327.395), Be (313.042), and Mo (202.032).

2.6. Quality Assurance

The analysis was conducted in triplicate to ensure accuracy and reproducibility. At regular intervals of every ten measurements, blank samples were analysed. To quantify the element of interest, daily calibration was carried out using NIST traceable standards. Prior to analysing the samples, a quality control standard was tested to confirm the accuracy of the calibration standards. Throughout the analysis, control standards were employed to monitor accuracy and drift in the instrument. Data collection and processing were controlled by software, and the results were then exported in Excel format. The precision of the determination process was evaluated through the examination of CRMs for mussel tissue. For analytes not included in the reference material, the matrix was spiked with known quantities, and recoveries were calculated accordingly. The recovery values obtained for all elements ranged between 97.02 and 100.89% with a percentage deviation of less than 10% (Table 3).

Table 3. Analytical parameters of ERM-CE278k mussel tissue.

Metals	CRMs for Mussel Tissue				
	Observed Value (mg/kg)	Certified Value (mg/kg)	Recovery (%)	LOD (mg/kg)	LOQ (mg/kg)
As	6.5	6.7	97.02	0.001	0.003
Sr	18.8	19	98.95	0.016	0.053
Be	1.95	* 2.0	97.5	0.001	0.003
Fe	158.3	161	98.32	0.011	0.036
Co	0.207	0.21	98.57	1.140	3.762
Cr	0.72	0.73	98.63	0.001	0.003
Al	1.481	* 1.510	98.29	0.028	0.092
Pb	2.20	2.18	100.92	0.001	0.003
Ta	3.5	* 3.90	97.12	0.014	0.046
Se	1.58	1.62	97.53	0.001	0.003
Cu	5.95	5.98	99.50	0.013	0.043
Ti	2.47	* 2.46	100.40	0.001	0.003
Cd	0.339	0.336	100.89	0.001	0.003
Mn	4.82	4.88	98.77	0.011	0.036

Table 3. Cont.

Metals	CRMs for Mussel Tissue				
	Observed Value (mg/kg)	Certified Value (mg/kg)	Recovery (%)	LOD (mg/kg)	LOQ (mg/kg)
Zn	68.95	71.0	97.11	0.033	0.109
Ni	0.688	0.69	99.71	0.004	0.013
Mo	0.49	* 0.5	98.0	0.020	0.066

* Metals not present in ERM-CE278k mussel tissue.

2.7. Statistical Analysis

A multivariate analysis of variance (MANOVA) was performed to evaluate the differences in metal concentrations across various environmental organisms and sites. None of the metals had a statistically significant multivariate effect on the response variables. All the *p*-values were greater than 0.05. The data were further subjected to the Shapiro test, which showed that the assumption of normality was not met, with a *p*-value of 0.0009. It was further subjected to the Kruskal–Wallis rank sum test, followed by Dunn’s post hoc test (with Bonferroni correction), which then confirmed no statistical difference between metals, organisms and sites with *p*-values much greater than 0.05. Both the MANOVA results and the Kruskal–Wallis test indicated that none of the individual metals analysed showed statistically significant differences across the groups (organisms and sites). All analyses were carried out using RStudio version 4.5.2.

2.8. Calculation of Metal Pollution Index

The metal pollution index (MPI) was calculated to assess the collective concentration of metals identified in each invertebrate sampled from different sites. The MPI was evaluated according to [20] using Equation (1).

$$MPI = (M_{C1} \times M_{C2} \times M_{C3} \dots M_{Cn})^{1/n} \quad (1)$$

where M_{C1} , M_{C2} , M_{C3} , M_{Cn} is the concentrations (mg/kg dry weight (dw)) of 1st metal, 2nd metal, 3rd metal and “*n*” metal respectively in a certain tissue. The MPI does not rely on predefined reference values such as safety thresholds, baseline concentrations, or uncontaminated reference sites. Additionally, MPI lacks a standardised scale or categorical framework to classify pollution severity [21]. Nevertheless, it serves as a practical tool for identifying sites with elevated metal concentrations, enabling spatial comparisons across study locations or temporal tracking of contamination at a single site.

2.9. Health Risk Assessment

2.9.1. The Target Hazard Quotient (THQ)

The THQ was employed to evaluate potential risks to human health regarding non-carcinogenic effects of metals through seafood consumption and is expressed using Equation (2) [22]:

$$THQ = \frac{EF \times ED \times IR \times C}{BW \times AT \times RfD} \quad (2)$$

In this assessment, THQ was calculated using the following parameters: EF (exposure frequency) is based on 365 days per year, ED (exposure duration) spans over 30 years, IR (ingestion rate) is set at 0.02 kg/day, C indicates metal concentration in mg/kg wet weight (ww) (since seafood is consumed in its fresh form, the measured concentrations in dw were converted to ww concentration using moisture content of each sample (Supplementary Material, Table S1)), and BW stands for body weight (70 kg). The estimate

was derived using average height and body mass index data for men and women, based on findings from a national survey carried out in 2016 [23]. According to the survey, women aged 25 and older had an average weight of 75.6 kg, while men in the same age group averaged 71.8 kg. To represent the general adult population, including individuals aged 18 to 25, a standard reference weight of 70 kg was adopted. AT is the averaging time derived from multiplying 365 (days/year) by ED. The RfD (oral reference dose), utilised in this analysis, is sourced from EPA's Integrated Risk Information System (IRIS) online database [24] and the literature as given in Table 4. An RfD is the estimated daily oral exposure of the human population which is expected to pose minimal risk of harmful effects throughout an individual's lifetime [25].

Table 4. Oral reference dose of metals.

Metals	RfD (mg/kg/day)	Metals	RfD (mg/kg/day)
Ni	0.02	Sr	0.6
Cd	0.001	Mo	0.005
Pb	0.002 ^a	As	0.00006 ^c
Cr	0.0009	Se	0.005
Mn	0.14	Be	0.002
Cu	0.04 ^b	Co	0.003
Fe	0.7	Ti	na
Zn	0.3	Li	0.002 ^b
Al	1 ^b	Ta	na

^a: [26]; ^b: [27]; ^c: [28]; na: not available.

2.9.2. The Hazard Index (HI)

The hazard index is the cumulative hazard quotients (HQs) for all metals present in each sample and was computed to evaluate the combined health risks associated with exposure to multiple metals; HI was calculated using Equation (3):

$$HI = \sum THQ_i \quad (3)$$

THQ_i refers to the targeted hazard quotient assigned to an individual metal. Ti and Ta were excluded from the evaluation as their oral reference dose (RfD) information was unavailable. A HI value below 1 indicates a safe assumption for the exposed population. However, when the HI falls between 1 and 5, there exists a potential risk associated with a specific metal in the exposed population [29].

3. Results

3.1. Concentration of Metals in Marine Invertebrates

The species selection was determined based on their abundance at various sites, considering the type of samples found at each location. Five different species of organisms were collected from all eight sites. The results are summarised in Figure 2a,b. All invertebrate metal concentrations were reported in mg/kg dry weight (dw).

While the MANOVA and Kruskal–Wallis tests did not identify statistically significant differences among sites or species ($p > 0.05$) (Supplementary Material, Tables S2–S6), the lack of significance may reflect high within-group variability and limited temporal replication rather than an absence of ecological differences. Effect size analysis indicated moderate differences in Pb concentrations between sites, suggesting localised hotspots of contamination that may not have been captured statistically due to sample size constraints. This highlights the importance of complementing statistical testing with ecological risk

indices (e.g., THQ, HI, MPI), which revealed consistent exceedances of safety thresholds despite the absence of significant group-level variance.

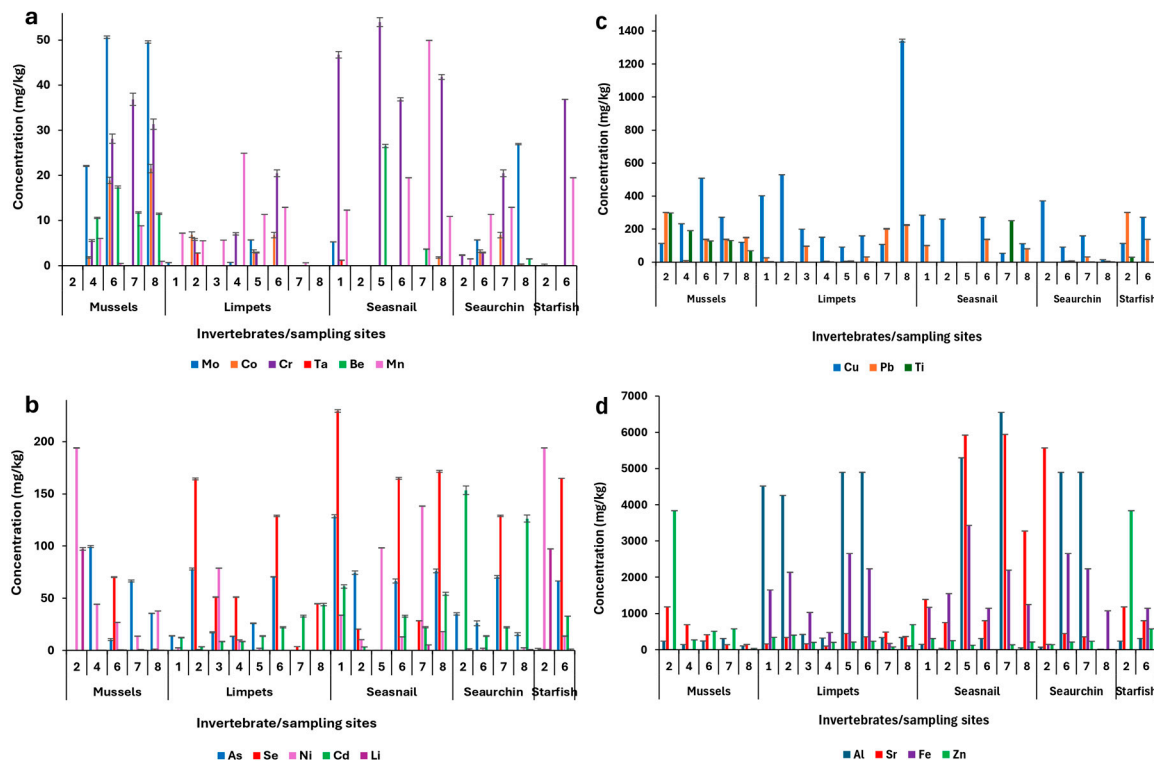


Figure 2. (a–d) Concentrations of metal(loid)s (mg/kg dry weight; $n = 3$) detected in marine invertebrate samples collected from eight coastal sites (sites 1–8) around False Bay, South Africa. Values represent mean concentrations with associated variability across sites.

3.1.1. *Mytilus galloprovincialis* (Mussels)

M. galloprovincialis was collected from sites 2, 4, 6, 7, and 8. Metal(loid) accumulation patterns showed considerable variability among sites, with no consistent trend across sampling locations. Ta and Fe were not detected in any mussel samples, while Se was detected only at sites 6 and 8. Arsenic (As), Mo, Co, Cr, Cd, Be, and Mn showed site-specific variations, with some elements absent at certain locations but detected at measurable concentrations in others. Aluminium (Al) was detected in all samples, with the highest concentration observed at site 7 and the lowest at site 8.

Several elements exhibited notably elevated concentrations at specific sites. Pb showed the highest concentration at site 2, whereas Cu, Zn, Ni, Li, Ti, and Sr were also elevated in mussels from site 2 compared with other locations. In contrast, some elements, including Cr and Al, showed maximum concentrations at other sites. Overall, the accumulation of metals in *M. galloprovincialis* demonstrated substantial spatial variability, highlighting differences in metal exposure and accumulation among sampling sites. Notably, certain metals were absent in samples from site 2, while others displayed the highest concentration at this site compared to the other sampling locations.

3.1.2. *Cymbula oculus* and *granatina* (Limpet)

C. oculus and *C. granatina* samples were collected from all eight sites. Li and Be were not detected in any samples, while Ta was detected only at site 2. Mo was observed exclusively at sites 1, 4, and 5, whereas Co and Cr showed site-specific detection patterns. Ni was not detected at sites 6–8 but showed a maximum concentration at site 3. Se was

absent from sites 1 and 5 but was detected at other locations, with the highest concentration recorded at site 2.

Sr, Fe, Al, and Zn were consistently detected across sites with relatively high concentrations, whereas Ti occurred at comparatively lower levels. Cd and Cu were detected in all samples, with the highest concentrations observed at site 8. Mn and As were not detected at site 8 but were present at other sites, while Pb showed substantial spatial variability, with the highest concentration recorded at site 8 and the lowest at site 5. Overall, metal(loid) accumulation in *C. oculus* and *C. granatina* exhibited considerable spatial variability across False Bay, reflecting differences in metal availability and site-specific environmental conditions.

3.1.3. *Parechinus angulosus* (Sea Urchins)

P. angulosus was collected from sites 2, 6, 7, and 8. Ta was not detected in any samples, while Pb, Co, and Ti were only detected at sites 6–8. Li, Mo, and Ni showed limited site-specific detection, whereas Se was detected only at site 7. Cu, As, Zn, Cd, and Fe were present in all samples, with Cu and Fe showing relatively high concentrations. Sr exhibited substantial variability, with the highest concentration recorded at site 2, while it was not detected at site 8. Overall, metal(loid) accumulation in *P. angulosus* varied considerably among sampling sites.

3.1.4. *Oxystele tigrine* and *sinensis* (Sea-Snail)

O. tigrine and *sinensis* were collected from all sites except sites 3 and 4. All investigated metal(loid)s were detected in at least one sample, but their distribution varied markedly among sites. Several elements, including Mo, Ta, Co, Li, Ti, and Be, showed restricted occurrence, whereas Fe and Sr were consistently detected at high concentrations across all sites. Cu, Se, Cd, Pb, As, Cr, Mn, and Zn exhibited considerable spatial variation, with site-specific differences in maximum concentrations. Overall, the two sea snail species showed heterogeneous metal(loid) accumulation patterns, reflecting differences in environmental exposure among locations.

3.1.5. *Marthasterias glacialis* (Starfish)

M. glacialis were found and collected only from sites 2 and 6. Co, Ta, Be, and Mo were not detected at either site, while several metals showed site-specific occurrence. Li and Ti were detected only at site 2, whereas As, Cr, Se, Cd, Mn, and Fe were detected only at site 6. Pb, Cu, Zn, Ni, and Sr were present at both sites, with Fe, Sr, Ti, and Zn showing relatively high accumulation compared with other elements. The overall metal profiles differed between sites, indicating spatial variability in metal exposure and accumulation in this species.

3.2. Concentration of Metals in Macroalgae (Seaweeds)

Five distinct seaweed species (*Ulva* sp., *Gelidium pristoides*, *Bifurcaria brassicaeformis*, *Caulerpa filiformis*, *Aeodes orbitosa*) were collected from eight different sites within False Bay (Figure 3a–d). Notably, the distribution of each seaweed species differed across the various sites in False Bay. All concentrations of metals in seaweed were reported in mg/kg dw.

3.2.1. *Ulva* sp. (Sea Lettuce)

The presence of this seaweed species was exclusively observed and gathered from sites 2, 4, and 7. No traces of Cd and Be were found in any of the samples collected from these sites. Notably, samples from site 7 exhibited the highest concentrations of Al (402.06 mg/kg), Pb (9474.43 mg/kg), and Cu (175.71 mg/kg) compared to samples from sites 2 and 4. As, Ta, Mo and Mn were only detected in samples from site 4 (74.35 mg/kg,

778.39 mg/kg, 66.05 mg/kg and 244.49 mg/kg, respectively). Sr, Zn and Ni were exclusively detected in samples collected from sites 2 and 4, whereas S, Co, and Fe were only found in samples from sites 4 and 7. Li was detected only in samples from sites 2 and 7, while Cr was found in samples from all three sites, with samples from site 4 displaying the highest concentration at 364.75 mg/kg.

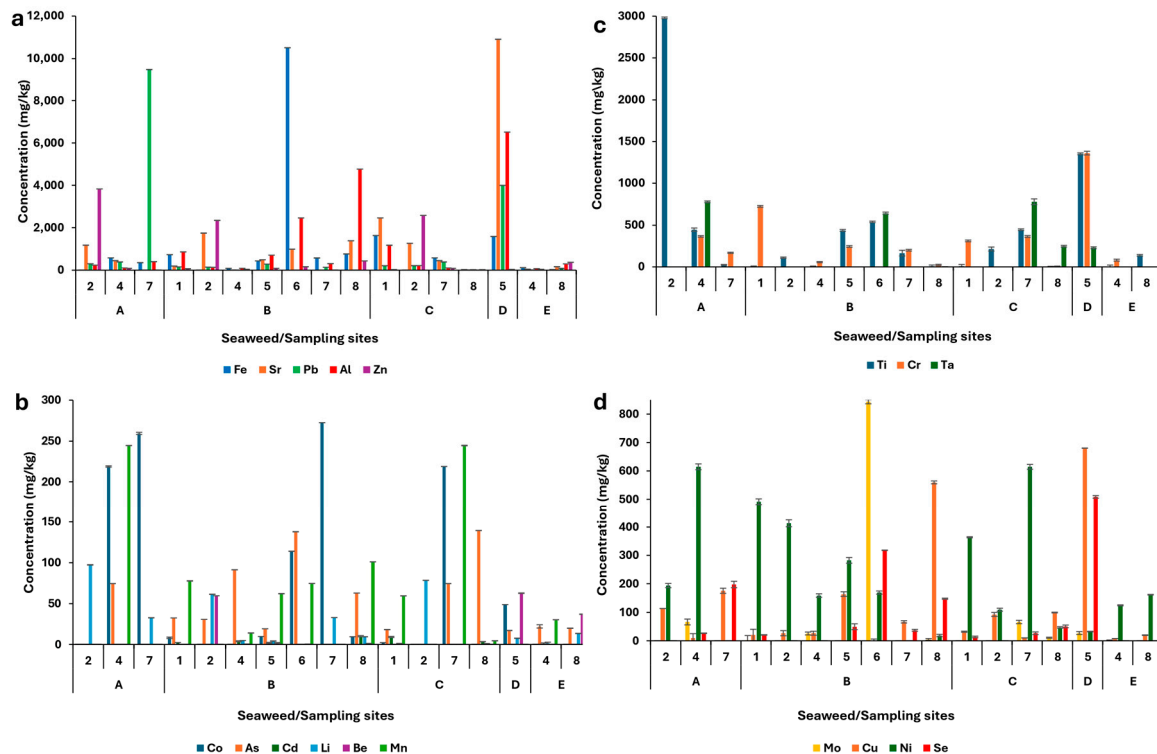


Figure 3. (a–d) Metal(loid) concentrations (mg/kg dry weight; $n = 3$) in seaweed samples collected from Sites 1 to 8 in False Bay. Results reflect average concentrations across all sites for each species. A—*Ulva* sp. (sea lettuce); B—*Gelidium pristoides* (red algae); C—*Bifurcaria brassicaeformis* (hanging wrack); D—*Caulerpa filiformis* (strap caulerpa); E—*Aeodes orbitosa* (slippery orbit).

3.2.2. *Gelidium pristoides* (Red algae)

G. pristoides was collected from all sites except site 3 and exhibited marked spatial variation in metal(loid) accumulation. Al and Ti were detected in all samples, while Fe showed exceptionally high concentrations, particularly at site 6. As, Ni, Zn, and Sr were absent from site 7 but were detected at the remaining sites. Mn was not detected at sites 2 and 7, whereas Ta was detected only at sites 6 and 8. Cu was present at all sites except site 6, while Pb and Cd showed restricted occurrence across the sampling sites. Co and Se were absent from sites 2 and 4, whereas Be, Li, and Cr displayed site-specific detection patterns. Mo was detected only at sites 1, 4, 6, and 8. Overall, *G. pristoides* exhibited considerable variability in metal(loid) accumulation, with Fe, Al, Ti, Zn, and Sr generally occurring at relatively high concentrations.

3.2.3. *Bifurcaria brassicaeformis* (Hanging Wrack)

B. brassicaeformis was collected from sites 1, 2, 7, and 8 and similarly displayed spatial differences in metal(loid) accumulation. Pb, Sr, Cu, Ti, Zn, and Ni were detected in samples from all sampling sites, whereas Be was detected only at site 1. Fe occurred in samples at sites 1, 7, and 8, while Li was detected only at sites 2 and 8. Mo and Ta were restricted to sites 7 and 8, Co to sites 1 and 7, and Cd to sites 1 and 8. Se and Mn were detected at sites 1, 7, and 8, while As and Cr were present at all sites. Al was detected at all sites except site

8. These findings demonstrate substantial spatial variability in metal(loid) accumulation among seaweed species across False Bay.

3.2.4. *Caulerpa filiformis* (Strap Caulerpa)

C. filiformis was only found at site 5. No traces of Be and Cd were found in this seaweed sample. Sr had an extremely high concentration (10,906.48 mg/kg) in this seaweed, while Li was the metal with the lowest concentration (7.57 mg/kg). The metal(loid) distribution within this particular seaweed species follows: Sr > Al > Pb > Fe > Cr > Ti > Cu > Se > Ta > Be > Co > Ni > Zn > Mo > As > Li.

3.2.5. *Aeodes orbitosa* (Slippery Orbit)

The seaweed species was peculiar to only sites 4 and 8. Co, Ta and Se were not found in samples from either of the sites. However, Mo, Cr, Cd, and Mn were only present in samples from site 4 (0.6, 80.99, 1.07, 30.18 mg/kg, respectively), while Be was only detected in samples from site 8 (36.91 mg/kg). The distribution of detected metals in seaweed samples from site 4 follows: Ni > Fe > Cr > Al > Sr > Zn > Mn > As > Cu > Pb > Li > Cd > Ti > Mo, while the distribution of detected metals in seaweed samples from site 8 follows: Zn > Al > Sr > Ni > Ti > Pb > Be > Fe > As > Cu > Li.

3.3. Metal Pollution Index

As MPI is calculated as the geometric mean of metal concentrations within a given aquatic system, it can serve as a broad indicator of metal pollution. This approach is particularly useful because it mitigates the influence of extreme outliers common in environmental datasets by reducing skewness. While some metals naturally occur in trace amounts, others may be present in much higher concentrations due to anthropogenic sources, and the geometric mean helps balance such variability. However, it is important to note that while MPI offers a generalised overview of contamination levels, it does not account for the dynamic behaviour of metals in the environment. Specifically, it does not distinguish between the solid and liquid phases of aquatic systems, which are critical to understanding metal mobility, bioavailability, and potential ecological impacts. The metal pollution index (MPI) (expressed in terms of dry weight) indicates extreme contamination when it is greater than 100, very high contamination when it is between $50 < \text{MPI} < 100$, high contamination when it is $20 < \text{MPI} < 50$, medium contamination when $10 < \text{MPI} < 20$ and low contamination when it falls within the range of 5 to 10 in invertebrate tissues. Values of the MPI ranging from 2 to 5 suggest very low contamination, and an $\text{MPI} < 2$ indicates no impact. An elevated MPI value indicates a more substantial accumulation of metals in the sample [30]. Figure 4 illustrates the MPI values in invertebrate samples from each sampling location in False Bay. These findings indicate extremely high to very high contamination of metals and confirm the dynamic behaviour of metals in different species, as well as within the same species, where extreme outliers were found. However, the bioavailability cannot be gleaned from the applied methods.

3.4. Overview of Human Health Risk Assessment

The calculated target hazard quotients (THQs) for metals resulting from the ingestion of various seafood items are shown in Figure 5a,b. The health risk assessment was conducted using assumptions in line with the USEPA guidelines, with the threshold value for an acceptable THQ set at 1. In this study, the THQ estimated for mussels is as follows: in site 2 only Li and Pb were greater than 1; in site 4, with the exception of As, all THQ values were less than 1; in site 6, As, Co, Cr and Pb were greater than 1; in site 7 the THQ values remained below 1 for all metals except As, Cr and Pb; and in site 8 As, Co, Cr and Pb had a THQ value greater than 1. These findings indicate that continuous consumption

of mussels from these sites over a 30-year period may potentially pose a significant health risk due to non-carcinogenic effects, particularly related to As and Pb exposure. Similarly, for limpets, THQ values exceeding the threshold were observed for As and Pb in samples collected from all eight sites, except for those metals that were not detected. There is a significant health risk associated with Cd, As, Cr, Se, and Pb from the consumption of sea snails, i.e., $THQ > 1$. The estimated THQ values for metals in sea urchins showed a high risk associated with As and Cd, while a non-carcinogenic effect are associated with As, Cr and Pb by the consumption of starfish from site 6 and Li and Pb in site 2, although the species of starfish are not edible.

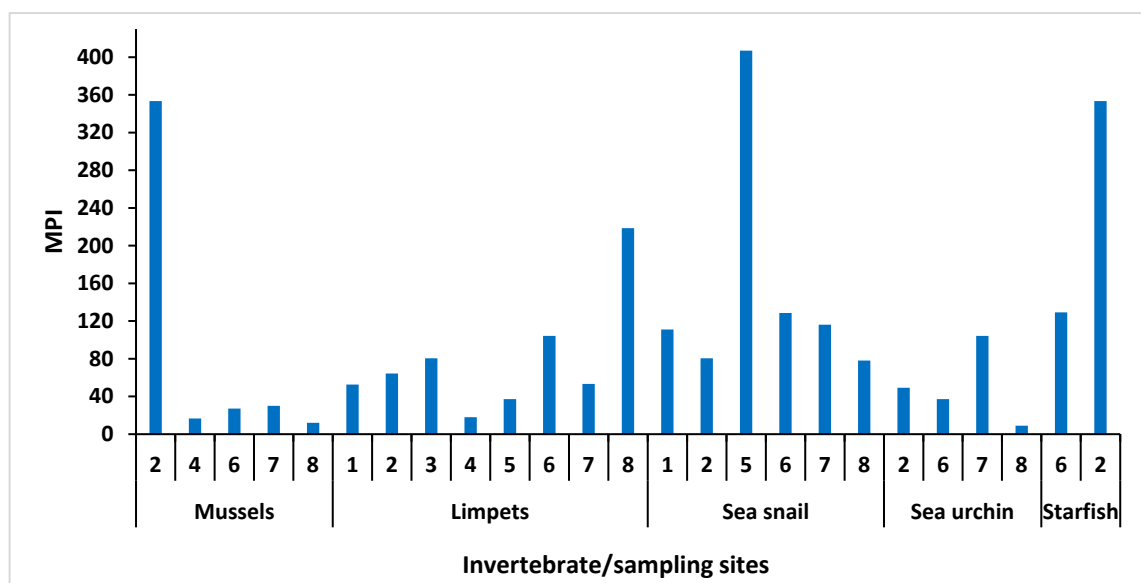


Figure 4. MPI values of various invertebrates across the sites.

The hazard index, which combines the risks of all metals, provides a cumulative estimate of the potential health risks. A HI value between 1 and 5 suggests moderate risk, while values exceeding 5 indicate a high risk of adverse effects [31], especially when these metals accumulate in the body over time. In this study, HI values ranged from 3.35 to 36.9 (Table 5) for invertebrates from all the sampling sites, with sea snails showing the highest values.

Table 5. Hazard index (HI) of metal(loid) in marine invertebrate species.

Marine Organisms	Sampling Sites	HI	Marine Organisms	Sampling Sites	HI
Mussels	2	13.62	Sea snail	1	36.90
	4	9.94		2	16.06
	6	13.69		5	3.25
	7	19.88		6	22.71
	8	18.44		7	3.67
Limpets	1	5.69	Sea urchin	8	24.78
	2	21.50		2	22.25
	3	8.55		6	9.81
	4	4.57		7	25.58
	5	7.79		8	14.32
	6	20.67	Starfish	6	34.24
	7	8.43		2	20.43
	8	12.43			

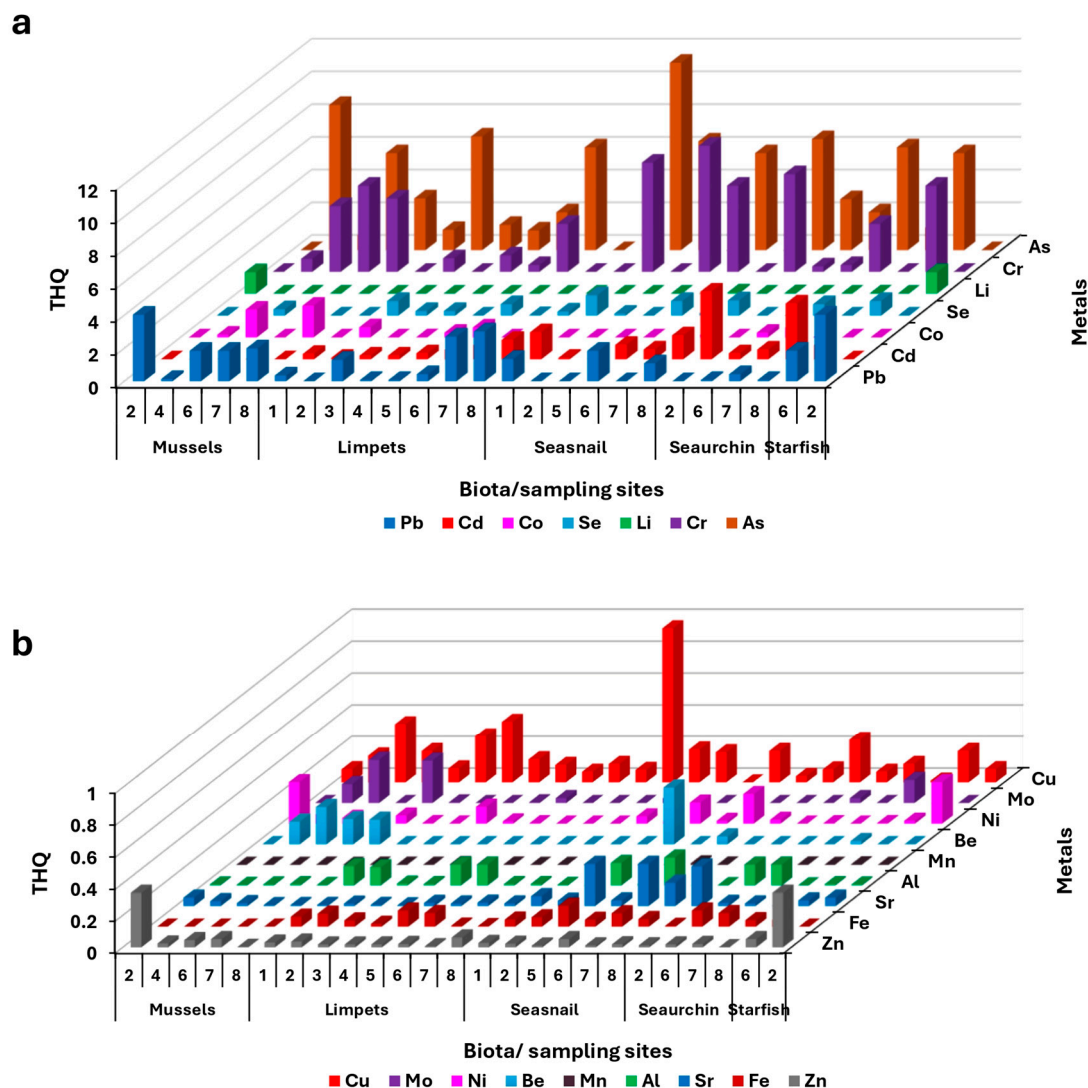


Figure 5. (a,b) Various target hazard quotients (THQs) calculated through seafood consumption (biota) in relation to metal(loid) exposure.

4. Discussion

The concentration of 18 metals was evaluated in selected marine invertebrates and macroalgae (seaweed) from False Bay (Figures 2 and 3a–d). Species-specific accumulation patterns were analysed across eight coastal sites to assess both ecological exposure and potential human health risks associated with seafood consumption. These findings are particularly relevant in light of Taljaard (2006) [32], which revealed that sewage outfalls and WWTPs in urban industrial areas discharge a range of pollutants such as endocrine-disrupting chemicals and metals into False Bay. The presence of such discharges highlights the importance of monitoring metal levels in local marine biota, especially species commonly consumed by humans or used as ecological indicators.

Different organisms possess varying capabilities to accumulate metals from their surroundings. Several factors, including the age of the organism, level of metal in their food and habitats, metabolic abilities, various dietary pathways, and physiological processes, can lead to variations in metal bioaccumulation among species [1]. As expected, interspecies diversity in metal accumulation was observed not only among the organisms investigated but also within the same species. Although subjected to the same environment, the studied species did not exhibit uniform levels of metal accumulation. Overall, *Oxystele* spp. (sea snails) demonstrated a greater propensity to accumulate most metals, such as Cr, Al, Fe and

Sr, compared to other marine organism species, suggesting their higher tolerance towards metal contamination. These gastropods possess slower metabolic and filtration rates [33] compared to bivalves and limpets; however, their dietary habits of feeding on epiphytes and microalgae can lead to episodic accumulation, especially in microhabitats subject to high anthropogenic loading, which may explain general variability in the metal accumulation patterns. In contrast, limpets (*C. oculus/granatina*) showed a moderate accumulation except for Cu, Al and Fe, which had very high values. As intertidal grazers, limpets feed by scraping algae and biofilms off rock substrates that tend to accumulate heavy metals through adsorption and sedimentation processes [34]. Their continuous contact with contaminated rock surfaces and their semi-mobile behaviour enhance their exposure to metal-enriched particulates, especially in environments with limited flushing, such as Monwabisi and Rooi Els. The significant presence of Pb in limpets at site 8 may reflect legacy contamination or ongoing deposition in low-energy zones. While *M. galloprovincialis* (mussels) showed higher accumulation of Zn and Ni compared to *C. oculus/granatina*, this could be as a result of their role as a suspension feeder, filtering large volumes of seawater to extract phytoplankton and organic particulates [35]. Through this process, they also ingest dissolved and particulate-bound metals suspended in the water column. Their sessile nature further exposes them to pollutants in proximity to wastewater treatment plant (WWTP) effluent plumes and resuspended sediments.

With the global population growing and concerns about food scarcity rising, there is a need to explore alternative protein sources beyond animal proteins. Seaweed emerges as a promising contender, being a valuable protein source. Throughout history, different seaweeds have been used as food and in animal feed by diverse cultures around the globe. In recent times, its versatile applications in industries such as pharmaceuticals, cosmetics and food have garnered attention, leading to an anticipated increase in their exploration and utilisation. [36,37]. While substantial evidence supports the nutritional and health benefits of seaweed consumption, unresolved questions remain regarding the safety of regular intake, particularly given their capacity to bioaccumulate metals from the marine environment. Such contamination could undermine the benefits of seaweed as a sustainable food source.

Our findings (Figure 3a–d) reveal that metal concentrations in seaweeds were often comparable to those detected in invertebrates, raising concern about their safety as alternative proteins. Specifically, *G. pristoides* accumulated elevated levels of Fe and Mo, which, although essential in trace amounts, may pose toxicity risks when present in excess. *C. filiformis* contained high concentrations of Sr, Al, Be, Se, Cu, and Cr, several of which (e.g., Be, Cr) are toxic even at relatively low exposures. *B. brassicaeformis* showed notable As accumulation, a well-documented human carcinogen, while *Ulva* sp. presented elevated Pb, Li, Ti, and Zn levels, with Pb being particularly concerning due to its neurotoxic effects. Both *Ulva* sp. and *B. brassicaeformis* also contained Ni, Ta, and Mn, elements that can be hazardous when bioaccumulated over time. Taken together, these results suggest that although seaweeds offer significant nutritional promise, their role as safe alternative protein sources is constrained by the potential for metal contamination. Without effective monitoring and regulation, the consumption of contaminated seaweeds could expose populations to chronic health risks, negating their intended benefits.

Worthy of note, among the metals analysed in this study, the heavy metals (Fe, Ti, Cd, Sr, Ni, Zn, Pb, Cu, Co, Cr and Mn) were observed to be present in high levels across the marine invertebrates and seaweed. The observed metal trends serve as evidence of metal pollution in this marine environment, likely originating from anthropogenic sources, possibly stemming from effluent discharge from WWTPs surrounding this bay, as well as harbouring activities, agriculture, metallurgical processes, and industrial effluent that may

discharge into the marine milieu. Each of the sampling locations represents a different degree and type of anthropogenic influence that can contribute to metal loading in the marine environment. In general, the elevated metal concentration in site 2, which is Simon's Town, might be due to the various harbouring activities taking place at that specific location; it is the largest naval base of the South African Navy [38]. The base also includes a naval dockyard responsible for repairs and maintenance of ships, submarines, aircraft, and other equipment, which can introduce metals such as Cu and Pb into the marine environment. Sites 3 and 4 are close to dense urban areas and informal settlements, where stormwater runoff may carry metal from vehicle emissions, roofing materials, and street dust. However, due to the drought at that time with no/little runoff, the likely main source of this pollution would be sewage-related because sewage effluent discharges continued unabated. Sites 5 to 8, while relatively less urbanised, are not immune to diffuse pollution, especially from upstream river discharges and tourism-related waste. This geographic range thus provides a basis for associating localised metal pollution with specific anthropogenic stressors.

The increasing apprehension regarding the pollution of False Bay led to a multitude of research studies back in the 1980s and 1990s. These studies focused on specific pollution sources entering False Bay, including point sources [39], rivers [40], discharges from industrial effluent [41] and stormwater [42]. Presently, the problems highlighted previously are still of concern due to the continuous high level of metal pollution in the various marine species sampled from this bay. In 2016, Sparks and Mullins identified sewage effluent, commercial, agricultural and urban development as the main pollution sources in False Bay, significantly contributing to the deterioration of water quality and the decline in sensitive species [43]. The reasons attributed by Sparks and Mullins (2016) [43] could be the contributing factor resulting in the absence of certain species in specific sites along the bay in this study. Since marine organisms have a well-documented ability to accumulate metals and other contaminants present in water [18], this could explain the elevated levels of metals found in samples investigated in this study. Aside from the heavy metals, Li, Be, and Al were also found to be present at high levels in the samples investigated in this study.

While this research provides important baseline data for metal concentrations in marine invertebrates and seaweeds in this locality, two limitations of the current study are, firstly, that sampling was conducted during a single time point, which may not capture seasonal or interannual variability in metal concentrations, and, secondly, that the study focused solely on biota without a parallel analysis of sediment and seawater. Including these matrices in future studies would provide a more comprehensive understanding of metal sources, mobility and bioavailability in the coastal ecosystem.

From a health perspective, the levels of Cd and Pb in marine organisms exceeded international safety limits, including those set by the FAO/WHO, European Union and Australian National Health and Medical Research Council (ANHMRC), which are 0.05 mg/kg, 2.0 mg/kg, 0.50 and 1.0 µg/kg respectively for Cd and 1.5 mg/kg for Pb [44,45]. Chronic exposure to these toxic metals can lead to kidney, liver and neurological damage [46]. Mn occurs in many food sources naturally, and it is an essential micro element for humans. Adverse effects have been reported in epidemiological studies due to long exposure to very high levels of Mn [47]. Similarly, excessive intake of essential metals like Cu, Zn and Co can result in toxicity, even though they play important physiological roles (growth, enzymatic function and cellular processes) [48]. Adults require about 14–20 mg/day of Zn daily, which is sufficient for their nutritional needs [49]. The observed levels of Cu and Zn are higher in the marine invertebrates when they are consumed, relative to nutritional needs. The World Health Organisation (WHO) and other agencies have estimated that the daily intake of Co through food ranges from 5 to 45 µg/day [50]. Nickel is also toxic at very high concentrations and can be carcinogenic when ingested in high amounts [51], even

though it plays a vital role as an essential nutrient in certain chemical processes within the body; symptoms of deficiency occur when the intake of Ni is insufficient. Some elements (Ti, Sr, Ta) are considered non-essential but are being studied for accumulation and possible sublethal effects in aquatic systems [52].

Table 5 shows the concentration of metals in other regions of the world in comparison to the results obtained from this study. The variations in metal concentrations between this study and previously published research are likely attributable to specific local differences in patterns of metal release from main sources, resulting concentrations in water, as well as the type and age of species. The diverse pollution profiles observed among sites indicate that metal levels differ significantly across different parts of the world. Nevertheless, the findings from this study exhibit comparable and higher concentrations of the different metals in various invertebrates and seaweeds compared to the cited studies (Table 6). For instance, the concentration of Cu in this study was higher compared to the levels found in Belgium (9.8–44.8 mg/kg) and Sardinia coast (0.10–0.42 mg/kg), while it was lower than in samples from the Black Sea (797.93 mg/kg) and Cape Town Harbour (496.8–913.8 mg/kg); the concentration of Mn was comparable to those found in the Adriatic coastal area (1.00–2.18 mg/kg) and in the Eastern Aegean coast (4.33–8.21 mg/kg).

The observation that metal concentrations in this study were significantly higher compared to certain findings in the literature (Table 6) underscores the urgent need to reduce or eliminate ongoing pollution inputs into False Bay. Without intervention, the ecological integrity of the marine system will continue to deteriorate, with serious consequences for resident organisms and for human communities relying on seafood harvested from the bay. Globally, numerous studies have documented the accumulation of metals in seaweed, but the levels reported vary widely depending on species, geography and local pollution pressures. For example, combined concentrations of Cd, Pb, Ni, Cr, Zn, Cu, Al, Se and Fe have been recorded across multiple regions: in *Sargassum glaucescens* (brown algae), *Acanthophora muscoides* (red algae) and *Ulva fasciata* (green algae) from Oman Sea which ranged from 0.04 to 15.97 mg/kg, 0.05 to 63.5 mg/kg and 0.05 to 16.85 mg/kg respectively [53], in *Ulva intestinalis* from Bangladesh (0.00–43.60 mg/kg) [54], *Eucheuma cottoni* from Malaysia (1.63–227 mg/kg) [55]. Similarly, *Sargassum ilicifolium* from the northern coasts of the Oman Sea contained 0.03–1.15 mg/kg [56], while *Eucheuma denticulatum* from Malaysia exhibited much higher levels (1.30–391 mg/kg) [55]. Extreme variability has been reported in macroalgae from Bengal coastal waters (0.04–12,600 mg/kg) [57,58], Rhodophyta species from the Sudanese Red Sea coast (0.09–105.51 mg/kg) [59], seaweeds from Iran (4.8–2843.96 mg/kg) [60], and even Antarctic species from King George Island (4.8–2824.96 mg/kg) [61].

Similar to trends noted globally, the False Bay findings reflect the influence of coastal activities such as shipping, tourism, and industrial operations, as well as high volumes of sewage effluent discharges, all of which contribute to elevated metal contamination in marine ecosystems. As studies have shown that salinity plays a key role in shaping the bioavailability and uptake of metals in seaweed [62], though its influence can differ depending on the specific metal and seaweed species, this could be one of the reasons why metal content varies across the different species of seaweed and across the sites. To prevent the likelihood of these contaminants entering the food chain and bioaccumulating, strict measures must be implemented to halt the various anthropogenic activities, such as the discharge of poorly treated sewage effluent from wastewater treatment plants near the study area.

Additionally, the public needs to be informed and educated about the importance of continually protecting the marine environment from hazardous metals. This can be achieved through stricter control of industrial activities and by modifying lifestyle practices of individuals residing around the bay to prevent further pollution of this delicate environment.

Table 6. Metal concentration (mg/kg dw) in invertebrates from this study and other studies.

Region/Species	Cu	Pb	Zn	Cr	Cd	As	Ni	Mn	Fe	Co	Mo	Ti	Sr	Al	Be	Se	Source
Blaar-meersen, Belgium/ <i>Mytilus edulis</i>	9.8–44.8	0.5–9.6	16.1–320	1.55–10.9	0.39–11.9	na	na	na	na	na	na	na	na	na	na	na	[63]
Sardinia coast/ <i>Padina pavonica</i>	0.10–0.42	0.11–0.71	0.23–104.40	0.02–0.18	0.01–0.07	0.26–0.73	<dl	<dl–2.88	11.41–225.5	<dl	<dl	0.20–2.60	5.39–77.46	7.30–104.40	<dl	<dl	[64]
Adriatic coastal area/ <i>Mytilus galloprovincialis</i>	0.31–1.67	0.34–1.85	6.35–69.0	na	0.17–0.64	na	0.17–1.26	1.00–2.18	17.80–82.44	0.51–1.03	na	na	na	na	na	na	[47]
Marudu Bay, Malaysia/ Marsh Clam	6.42	0.95	135.5	na	0.24	1.95	2.58	66.1	783.0	na	na	na	na	na	na	na	[65]
Northern coast of Messina/ <i>T. decussatus</i>	1.30	0.02	4.22	1.1	0.08	0.08	1.77	7.1	157.9	0.90	na	na	na	na	<dl	na	[66]
Northern Morocco/ <i>M. galloprovincialis</i>	5.28–6.16	<dl	160.4–164.2	1.96–3.33	0.65	0.85	2.03–3.82	na	340.1–673.2	<dl	na	na	na	na	na	na	[67]
Montenegrin coast/ <i>M. galloprovincialis</i>	6.08–13.2	1.37–3.55	85.6–241	0.72–4.05	1.01–2.87	na	na	na	na	na	na	na	na	na	na	na	[68]
Northern coast of Messina/ <i>M. galloprovincialis</i>	3.1	<dl	16.5	0.51	0.05	<dl	0.65	3.15	86.2	0.11	na	na	na	na	<dl	na	[66]
BBE, Argentina/ <i>B. rodriguezii</i>	20.10	nd	56.93	0.64	1.98	na	2.06	na	na	na	na	na	na	na	na	na	[69]
Mangrove Areas of Alagoas (Brazil) <i>C. rhizophorae</i>	14.33	na	413.58	13.14	4.65	na	na	17.20	278.06	na	na	na	na	na	na	na	[70]
Sardinia coast/ <i>Osilinus turbinata</i>	1.58–2.29	<dl–0.18	0.62–2.16	0.03–0.11	0.08–0.10	<dl	0.25–7.93	0.21–0.69	14.91–40.22	<dl	<dl	0.09–0.10	7.58–19.08	2.80–8.77	1.57–1.98	<dl	[64]
Algerian coast/ <i>M. galloprovincialis</i>	21.67	159.5	37.76	21.37	0.59	na	104	300	2.37	3.51	na	na	na	na	na	na	[71]
El-Qalyubia Egypt/ <i>Procambarus clarkii</i>	3.81–100.1	na	na	0.38–19.85	na	na	0.45–2.34	4.36–63.40	na	na	na	na	na	na	na	na	[72]
Toulon Bay/ <i>M. galloprovincialis</i>	4.56–5.59	2.08–3.15	149–248	0.65–0.82	0.65–1.50	36–57	0.71–1.42	3.78–4.28	na	na	na	na	na	na	na	na	[73]
Antibes S/ <i>M. galloprovincialis</i>	4.04	2.07	282	2.47	1.45	113	2.31	5.70	na	na	na	na	na	na	na	na	[73]
Cape Town Harbour/ <i>M. galloprovincialis</i>	496.8–913.8	2.44–26.04	87.52–710.30	1.35–157.4	0.27–2.70	1.63–15.89	0.97–105.98	23.50–46.91	1.15–943.06	0.37–18.86	na	na	116.36–334.64	na	na	na	[74]
False Bay/ <i>C. granatina</i>	91.6–529.5	nd–225	75.7–400.2	nd–20.5	3.5–43.9	nd–70.5	nd–78.8	0.6–24.9	104.2–2653.8	nd–6.89	nd–5.71	0.7–7.2	99.9–484.5	na	na	na	This study

nd = not detected; <dl = below detection limit; na = not available.

Human Health Risk Assessment

The THQ and hazard index (HI) are critical metrics for assessing potential non-carcinogenic health risks from long-term exposure to metals through seafood consumption. A THQ value above 1 indicates that exposure to a specific metal exceeds the safe threshold for daily intake over a lifetime, meaning that there is a possibility of adverse health effects for those who regularly consume contaminated seafood. For instance, metals such as As, Cr and Pb detected in the samples have THQ values significantly above 1, particularly in mussels and sea snails, indicating a risk of toxicity (Figure 5a,b).

The elevated hazard index (HI) values highlight the potential cumulative health risks associated with prolonged consumption of contaminated seafood from False Bay, emphasising the need for continued environmental monitoring and risk management. Moreover, the high variability in metal concentrations found at different sites for the same species indicates that the inadvertent consumption of a high dose of a particular toxic metal is probable. The likelihood of metal contamination of other edible species such as fish inhabiting the bay should also be considered, since metals are known to bioaccumulate up the food chain. In addition, this variability illustrates that relying on metal content only may not serve as an adequate measure of health risk, food safety or anthropogenic contamination. Furthermore, the data presented herein show that relying on a single indicator or sentinel species such as mussels for determining pollution may not give an adequate insight into the impact on other biota. Moreover, the metal analysis by itself underestimates the risk from other contaminants. In addition, these marine organisms have been previously reported to accumulate other emerging contaminants [14,18]. To minimise these risks, public health advisories may recommend limiting the consumption of seafood from heavily contaminated areas, especially species with high metal concentrations, such as mussels, limpets, and sea snails. Moreover, further regulatory interventions should focus on reducing pollution sources and conducting regular monitoring to ensure seafood safety for the public. However, the risk to humans does not consider the risk to the actual biota continuously exposed to high levels of toxic metals.

5. Conclusions

The current study showed that marine biota sampled from eight sites along False Bay accumulate low to high concentrations of metal(loid)s, with significant interspecies and intraspecies variability. Notably, the concentrations of several metal(loid)s measured in the studied marine organisms were generally higher than those reported for comparable species from many other coastal regions, indicating that False Bay remains an important area of concern with respect to metal(loid)s contamination. The comprehensive assessment of metal(loid) accumulation in diverse marine species revealed the intricate interactions between environmental contaminants and the delicate marine ecosystems, with species-specific accumulation patterns reflecting differences in ecological roles, exposure pathways, and sensitivities to environmental stressors. Our study points to the need for an urban ecology perspective when evaluating the impacts of metal(loid)s contamination in coastal ecosystems. The implications extend beyond immediate ecosystem health, as the estimated non-carcinogenic health risks indicate that continuous consumption of contaminated seafood over a 30-year period may pose potential risks to human health in coastal areas of Cape Town. The estimated risks were within acceptable limits for some exposure scenarios but not for all cases; thus, the potential health risks associated with long-term seafood consumption should not be overlooked, and the risk of adverse effects on marine species exposed to significant levels of metal(loid)s should also be considered. These results not only inform food safety monitoring and environmental regulation but also demonstrate the value of using a multi-species biomonitoring approach to assess pollutant exposure

in dynamic coastal ecosystems. However, the high variability in metal(loid) concentrations among marine biota also highlights the issues arising from using only metal/tissue metal(loid) concentration as a metric for health risk and anthropogenic contamination. Furthermore, a limitation of the present study is the absence of solid-phase metal(loid) data, particularly sediment analyses. Such data would have provided valuable information on the environmental reservoirs, bioavailability, and potential sources of metal(loid)s, thereby strengthening the interpretation of the accumulation patterns observed in marine biotas. To mitigate the ongoing consequences of metal and other pollution, sustained and collaborative efforts are essential. Achieving a balance between sustainable resource use and effective environmental protection requires the integration of scientific research, policy interventions, and community engagement. This interdisciplinary approach could hold the potential to safeguard both marine biodiversity and public health, particularly for communities that rely on seafood from these coastal systems. Continued monitoring is strongly recommended to enable early detection of pollution trends and to support proactive measures that minimise the toxicity risk to diverse marine organisms and the humans who consume them.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/environments13080430/s1>.

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