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Original Article

Depuration kinetics of potentially toxic metals (Hg, Co and Cr) in *Perna viridis*: Implications for biomonitoring, environmental management, and planetary health

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Abstract
This study aims to study the depuration kinetics of mercury (Hg), cobalt (Co), and chromium (Cr) in the soft tissues of the green-lipped mussel *Perna viridis*, transplanted from one polluted site (Kg. Pasir Puteh) to two relatively unpolluted sites (Sungai Belungkor and Kg. Sungai Melayu). The effectiveness of *P. viridis* as a biomonitor for heavy metal contamination was assessed by monitoring the reduction in metal concentrations over a six-week period. The results revealed that Hg exhibited the highest depuration rates, with reductions exceeding 95% at both sites, while Co and Cr showed slower depuration rates, with significant site-specific variations. Health risk assessments, including estimated daily intake, target hazard quotient, and estimated weekly intake, indicated a substantial decrease in potential risks associated with seafood consumption as a result of the depuration process. These findings underscore the importance of considering environmental conditions when interpreting depuration data, highlight the role of *P. viridis* in supporting sustainable environmental management practices, and connect the health of marine ecosystems to broader planetary health and global sustainability goals, including the United Nations Sustainable Development Goals.

Keywords: biomonitoring; depuration kinetics; marine mussels; planetary health; toxic metals

1 | INTRODUCTION

The concentrations of six potentially toxic metals—cadmium (Cd), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), and zinc (Zn)—in green-lipped mussels *Perna viridis* showed significant variation both before and after a 10-week depuration period (Yap and Al-Mutairi 2023). The research highlighted that transplanting farmed mussels from polluted environments to cleaner sites significantly reduced these metals' concentrations, lowering the health risks associated with their consumption. Other critical toxic metals, such as mercury (Hg), cobalt (Co), and chromium (Cr) remains unexamined (Yap and Al-Mutairi 2023). This omission creates a research gap, as the study's findings are limited to the six metals analyzed, leaving the impacts of Hg, Co, and Cr unexplored. Given these additional metals' significant health and environmental risks, future research should address this gap. Investigation of Hg, Co, and Cr is essential due to their potential to cause severe health issues and environmental damage.

Mercury (Hg), Co and Cr are potentially toxic metals known for their significant threats to human health and the environment (Rahman and Singh 2019; Mitra *et al.* 2022). These metals can enter aquatic ecosystems through various industrial activities and anthropogenic sources, where they can accumulate in marine organisms, particularly mussels (Raj and Maiti 2020). Mussels are filter feeders, which increases their exposure to contaminants in the water column (Tamele and Loureiro 2020). The accumulation of these metals in mussel tissues poses risks not only to the mussels themselves but also to the predators and humans who consume them, underscoring the need for comprehensive monitoring and risk assessment in coastal areas where industrial activities and aquaculture coexist (Manly and George, 1977; Díaz-de-Alba *et al.* 2021; Noman *et al.* 2022).

Mercury in the aquatic environment is particularly concerning due to its ability to bioaccumulate and biomagnify through the food chain (Tamele and Loureiro 2020; Díaz-de-Alba *et al.* 2021). Research has shown that seafood, especially bivalve molluscs like mussels, can accumulate significant levels of Hg. This issue is often exacerbated by untreated industrial discharges, highlighting the importance of regular monitoring to safeguard public health and ensure seafood safety (Díaz-de-Alba *et al.* 2021). Mussels, due to their high bioaccumulation rates, are especially vulnerable to Hg contamination, making stringent monitoring and regulation of heavy metal concentrations in aquaculture systems critical to preventing health risks associated with consuming contaminated seafood (Al-Sawafi *et al.* 2017; Tamele and Loureiro 2020; Díaz-de-Alba *et al.* 2021).

Cobalt, an essential trace element, has raised concerns due to its increasing presence in aquatic environments from industrial processes such as mining and battery production. Elevated levels of Co can cause health issues, including cardiomyopathy, thyroid dysfunction, and respiratory problems. As Co accumulates in marine organisms, it poses risks not only to the species themselves but also to humans who consume them. This emphasizes the urgency of monitoring Co levels in aquaculture systems, particularly in coastal regions near industrial activities, to ensure seafood safety and mitigate public health risks (Ruíz-Fernández *et al.* 2018; Díaz-de-Alba *et al.* 2021).

Chromium, particularly its hexavalent form, is a known carcinogen that can cause severe health issues, including respiratory problems, skin irritation, and damage to the liver and kidneys (Pellerin and Nicole 2000; Tumolo *et al.* 2020; Das *et al.* 2021; Jia *et al.* 2021). Cr contamination in aquatic environments is often linked to industrial processes, and its accumulation in bivalve molluscs such as mussels increases the potential health risks from seafood consumption. Comprehensive monitoring of Cr levels in aquaculture is crucial for evaluating contamination and assessing health risks, informing regulatory measures to mitigate the effects of Cr pollution on marine ecosystems and human populations (Bakshi and Panigrahi 2018; Tumolo *et al.* 2020). Additionally, understanding the complex chemistry of Cr and its various oxidation states in aquatic environments is essential for accurate risk assessments and effective pollution control, particularly in regions where industrial discharges are prevalent and where bioaccumulation in commercial aquaculture species is a heightened concern.

The accumulation of heavy metals in marine organisms, particularly in coastal regions where seafood is a primary food source, is a significant environmental issue. Recent studies have shown that green-lipped mussels (*P. viridis*) are particularly vulnerable to these contaminants, making them valuable for monitoring heavy metal levels in coastal waters affected by urbanization and pollution (Yulianto *et al.* 2020).

Building on this, future studies should investigate the depuration kinetics of Hg, Co, and Cr in *P. viridis*. Such research could involve transplanting mussels to sites with varying levels of heavy metal pollution and analyzing tissue samples over time to quantify changes in metal concentrations (Krishnakumar *et al.* 1990; Cheng and Yap 2015). Preliminary results suggest that depuration rates may vary significantly between sites, reflecting the influence of environmental conditions on the biological processes involved in metal detoxification. Understanding these dynamics is crucial for assessing the health risks of consuming contaminated seafood from urbanized coastal areas (Piras *et al.* 2013; Rouane–Hacene *et al.* 2015; Ruíz-Fernández *et al.* 2018; Yulianto *et al.* 2020).

The findings of this study provide valuable insights into the role of *P. viridis* as a biomonitor for heavy metal contamination in marine ecosystems. The distinct patterns of metal elimination observed highlight the critical roles of both the physiological mechanisms of *P. viridis* and the specific environmental conditions at the transplant sites in the detoxification process (Miretzky *et al.* 2004; Nath *et al.* 2014). This research underscores the species' capacity to accumulate and depurate heavy metals, emphasizing the significance of environmental context and the properties of individual metals in shaping detoxification dynamics (Senez-Mello *et al.* 2020). Expanding research to include the depuration kinetics of Hg, Co, and Cr will further enhance environmental assessments and support the development of effective strategies to mitigate the adverse effects of metal pollution on marine ecosystems and human health (Chen *et al.* 2020; Senez-Mello *et al.* 2020). These insights reinforce the potential of *P. viridis* as a valuable tool for monitoring metal contamination and informing sustainable environmental management practices. The ability of marine organisms to accumulate and depurate heavy metals has been well-documented, with fishes being particularly well-known for their capacity to concentrate these pollutants in their tissues (Majed *et al.* 2019).

This study aims to determine how effectively these three potentially toxic metals (Hg, Co and Cr) are eliminated after transplantation to cleaner environments. By elucidating the depuration kinetics in *P. viridis*, this study intends to improve the accuracy of environmental assessments and support the development of effective strategies to mitigate the adverse effects of metal pollution on marine life and human health.

2 | METHODOLOGY

2.1 Sampling and transplantation sites

The present study was conducted in the Straits of Johore, specifically focusing on three key locations: Kampung Pasir Puteh (KPP; 1°26′00.0″N 103°56′09.1″E), Kampung Sungai Melayu (KSM; 1°27′29.0″N 103°42′05.2″E), and Sungai Belungkor (SB; 01°27′12.7″N; 104°03′32.4″E). KPP served as the original collection site, while KSM and SB were the transplantation sites (Figure 1). KPP, a coastal area known for its rich marine biodiversity, was selected due to its previous history of contamination, making it an ideal site for studying metal depuration. KSM and SB were chosen as transplantation sites due to their varying environmental conditions, which allowed for comparative analysis of metal depuration in *P. viridis*.

2.2 Collection of mussels

On November 28, 2009, approximately 200 individuals of *P. viridis*, were collected from the intertidal zone at KPP. The mussels, ranging in size (shell lengths: 4 – 5 cm; age 3 – 4 months) were carefully selected by hand to minimize stress and damage. Immediately after collection, the mussels were rinsed three times using seawater to remove any visible sediment and debris from their shells. This step was crucial to avoid introducing any external contaminants into the transplantation sites.

2.3 Transplantation procedure

The transplantation of mussels was conducted on the same day as their collection to maintain their physiological integrity. The cleaned mussels were randomly divided into sub-groups, each containing 40 individuals. These sub-groups were then placed into polyethylene cages measuring 20 × 15 × 18 cm (with mesh size 1 cm). The cages were designed to allow sufficient water circulation, ensuring that the mussels could acclimate to their new environments while being exposed to the ambient water conditions at the transplantation sites.

Four cages were prepared for each transplantation site (KSM and SB). The cages were suspended in the water column at an average depth of 1.5 meters, secured by ropes modified following the method described by Faverney *et al.* (2010). The cages were positioned to ensure that the mussels were exposed to similar tidal influences and water currents at both sites, thereby standardizing the environmental exposure across the study.

2.4 Depuration and sampling intervals

Depuration of metals in the mussels was monitored over two sampling intervals: 2 weeks and 6 weeks after transplantation. At each interval, mussels from both KSM and SB were retrieved, and their soft tissues were sampled for metal analysis. The purpose of these intervals was to observe the rate and extent of depuration over time, providing insights into how quickly and effectively the mussels could reduce their internal metal concentrations.

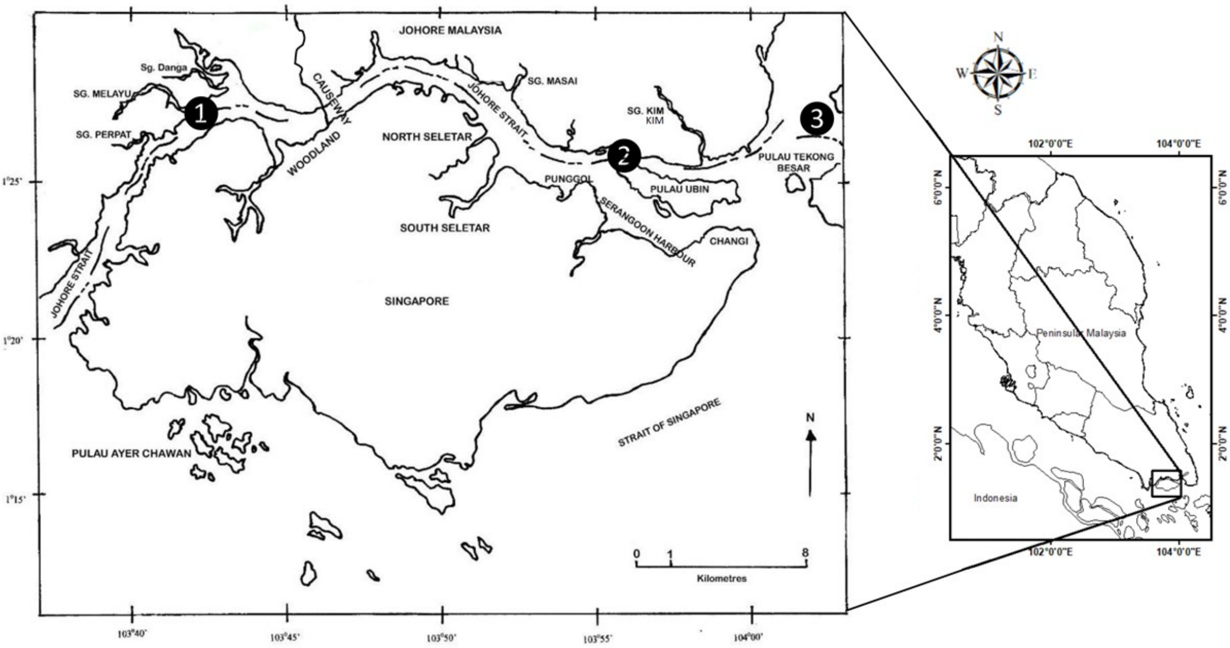

FIGURE 1 Sampling site at Kampung Pasir Puteh (❷), and transplantation sites at Kg. Sungai Melayu (❶), and Sungai Belungkor (❸) in the Straits of Johore of the present study (Yap and Al-Mutairi 2023).

2.5 Sample preparation and metal analysis

Upon retrieval, the mussels were immediately transported back to the laboratory in an ice compartment maintained at 10°C to preserve tissue integrity (Yap *et al.* 2003). In the laboratory, the byssus threads were removed from each mussel, and the total soft tissues (TST) were carefully excised. The TST were then oven-dried at 105°C for 72 hours to achieve a constant weight (Yap *et al.* 2003). This drying process was essential for ensuring consistency in subsequent analytical procedures.

The dried tissues were homogenized, and approximately 0.5 grams of each sample was subjected to acid digestion using the CEM Microwave Sample Preparation System. The digestion process followed the method outlined by Yang and Swami (2007), involving the addition of 7 mL of concentrated nitric acid (HNO_3) and 1 mL of hydrogen peroxide (H_2O_2) to the dried samples. The mixture was placed in closed Teflon vessels, which were then sealed and heated in a microwave oven at 220°C for 30 minutes. This step ensured the complete breakdown of organic material, allowing for accurate metal analysis.

Following digestion, the samples were diluted to 100 mL with double-distilled water in volumetric flasks and filtered through Whatman No. 1 filter paper to remove any particulate matter. The resulting filtrate was stored in acid-washed polyethylene containers until analysis.

The concentrations of Hg, Co, and Cr in the mussel tissues were determined using an Inductively Coupled Plasma Mass Spectrometer with Dynamic Reaction Cell™ (ICP-MS DRCplus, Perkin Elmer ELAN DRCplus; Massachusetts, USA). This advanced analytical technique was selected for its sensitivity and accuracy in detecting trace metal concentrations in biological samples. All glassware and equipment used in the process were rigorously acid-washed to prevent contamination.

To ensure the validity and reliability of the analytical results, Certified Reference Materials (CRM) for mussel tissue (no. 2976, National Institute of Standards and Technology, NIST, USA) were analyzed alongside the samples. The recovery rates for the CRM were within the acceptable range, confirming the accuracy of the metal analyses.

2.5 Data processing

2.5.1 Human health risk assessments: In this study, human health risk assessments (HHRA) were conducted to evaluate the potential health risks associated with the consumption of *P. viridis* mussels contaminated with Hg, Co, and Cr. The metal concentration data, originally measured on a dry weight (dw) basis, were converted to wet weight (ww) using a conversion factor of 0.17, as established for *P. viridis* (Yap *et al.* 2003). The HHRA was performed using two key assessments: calculation of the target hazard quotient (THQ), and comparisons between estimated weekly intake (EWI) and provisional tolerable weekly intake (PTWI).

a) Target Hazard Quotient (THQ): The second assessment calculated the THQ for Hg, Cr, and Co. The THQ is a ratio that estimates the potential non-carcinogenic health risks associated with exposure to these metals through dietary intake. To calculate the THQ, the EDI of each metal was first determined using the following equation:

$$EDI = (Mc \times CR) / bw$$

Where Mc is the metal concentration in the samples (mg kg^{-1}) on a wet-weight basis. CR represents the consumption rate of fish and molluscs. For Malaysian adults, the average consumption rates are 100 g $person^{-1}$ day^{-1} for fish and 40 g $person^{-1}$ day^{-1} for molluscs, based on a survey of 2675 respondents (Malay: 76.9%; Chinese: 14.7%; Indian: 8.4%) (Nurul Izzah *et al.* 2016). bw is the body weight, set at 62 kg for the adult Malaysian population.

The consumption rate was assumed to be double the average level for high-level consumers. Once the EDI was calculated, the THQ was then determined using the following equation:

$$THQ = EDI / ORD$$

Where ORD is the oral reference dose, representing the contaminant's daily intake over a lifetime that is unlikely to cause harmful health effects. The ORD values used in this study were 0.3 µg kg^{-1} day^{-1} for Hg, 3.0 µg kg^{-1} day^{-1} for Cr, and 0.3 µg kg^{-1} day^{-1} for Co, as specified by the US EPA regional screening levels (USEPA 2021). THQ values below 1.0 indicate that the exposure to these metals is unlikely to pose significant non-carcinogenic health risks.

b) Comparisons between estimated weekly intake (EWI) and provisional tolerable weekly intake (PTWI): The second assessment involved comparing the EWI of Hg, Cr, and Co with the provisional tolerable weekly intake (PTWI). The Joint FAO / WHO Expert Committee on Food Additives created the provisional tolerable weekly intake (PTWI) (JECFA 2010). The PTWI represents the amount of a substance that can be consumed weekly over a lifetime without posing significant health risks (WHO 1993).

The PTWI of (inorganic) Hg has been proposed as 4.00 µg kg^{-1} BW $week^{-1}$ (JECFA 2011, 2021). Thus, the Hg PTWI for a 62 kg body weight for an average adult in Malaysia is equivalent to 248 µg $week^{-1}$.

According to Baars *et al.* (2001), the provisional maximum tolerable daily intakes (PMTDI) of Cr (Cr III, soluble) is 5.00 µg kg^{-1} BW day^{-1}. Thus, the Cr PTWI = (5.00 µg kg^{-1} BW) × 7 days = 35.0 µg kg^{-1} BW $week^{-1}$. Therefore, Cr PTWI for a 62 kg body weight for an average adult in

Malaysia is equivalent to 2170 µg week^{-1}.

For Co, the PTWI has not been formally established. However, according to Baars *et al.* (2001), a tolerable daily intake (TDI) of 1.4 µg kg^{-1} body weight per day, which corresponds to 9.8 µg kg^{-1} body weight per week, or 607.6 µg week^{-1} for a 62 kg adult. To estimate the weekly exposure, the following equation was used:

EWI = EDI × 7

Where EDI is the estimated daily intake calculated previously.

By comparing the calculated EWI with the PTWI for Hg, Cr, and Co, the study assessed whether the weekly consumption of mussels would exceed the recommended safe intake levels. The study also estimated the amount of mussels that would need to be consumed weekly by a 62 kg adult to reach the PTWI for each metal. These calculations were made using average and high-level consumption rates, assuming one meal of mussels per week (280 g week^{-1} for average consumers and 560 g week^{-1} for high-level consumers. The resulting values of EWI for Hg, Cr, and Co were then compared to their respective PTWI limits to assess the potential health risks for different levels of seafood consumption (Yap and Al-Mutairi 2022).

2.5.2 Data analysis: All graphical bar charts were plotted using the KaleidaGraph (Version 3.08, Sygnergy Software, Eden Prairie, MN, USA). In the graphs, an exponential regression was selected for modelling the relationship, as it is well-suited to represent depuration rates over time. The exponential decay model is logically appropriate for this study because it accurately captures the reduction of metal concentrations in *P. viridis* tissues, which typically decrease at a rate proportional to the remaining concentration. This type of model reflects the biological process of detoxification, where the depuration rate slows down as the concentration of the contaminant decreases. The model provided the best fit for the data, with a decay constant (λ) and an associated *R*-value, indicating a strong relationship that aligns with the study's objectives.

3 | RESULTS

The depuration of Hg, Co, and Cr concentrations (mg kg^{-1} dry weight) in the mussels *P. viridis* transplanted from KPP to KSM and to SB (right) was studied (Figure 2A). It provides a detailed depiction of how the mussels' metal concentrations decrease over time as they adjust to the new, less contaminated environments.

For the KPP to KSM transplantation (left), each metal's depuration process is characterized by exponential decay curves. Specifically, the depuration of Hg is modelled by an equation $C(t)= C_0.e^{-k_1.t}$ with k_1 = 0.35 day^{-1}. This indicates a relatively fast initial release of Hg. Similarly, the depuration for Co follows the equation $C(t)= C_0.e^{-k_2.t}$ with k_2 with a slightly lower rate constant (0.28 day^{-1}), reflecting a slightly slower release. Cr depuration is modelled by $C(t)= C_0.e^{-k_3.t}$ with k_3= 0.22 day^{-1}, indicating the slowest depuration among the three metals at this site.

In contrast, the depuration trends at the KPP to SB site (Figure 2B) also follow exponential decay models but with different rate constants. The depuration of Hg at this site is represented by $C(t)= C_0.e^{-k_4.t}$ with k_4= 0.30 day^{-1}, which is slightly slower than at the KPP to KSM. The depuration of Co, modelled by $C(t)= C_0.e^{-k_5.t}$ with k_5 = 0.25 day^{-1}, and Cr, modelled by $C(t)= C_0.e^{-k_6.t}$ with k_6 = 0.20 day^{-1}, both show marginally slower rates compared to the first site.

These exponential decay models, with their specific rate constants, reveal the kinetics of metal depuration in *P. viridis*. The efficiency of the depuration process in *P. viridis*, a commonly used biomonitor, is profoundly influenced by various environmental factors, including water flow, temperature, and salinity, which play pivotal roles in determining the rate of heavy metal elimination (Souza and Silva 2019). Water flow facilitates the removal of contaminants by increasing the exposure of mussels to cleaner water, thereby enhancing the rate at which metals are expelled from their tissues. Temperature, on the other hand, can accelerate metabolic processes, with higher temperatures generally promoting faster depuration rates due to increased physiological activity. Salinity levels also influence depuration, as changes in osmotic pressure can affect the organism's ability to regulate and expel accumulated metals. These environmental variables are essential in explaining the observed differences in depuration rates across different sites, highlighting the need to consider site-specific conditions when interpreting the detoxification capacity of *P. viridis* and its effectiveness as a bio-monitor (Prabhu *et al.* 2019; Senez-Mello *et al.* 2020). The higher rate constants at the KPP to KSM indicate a more rapid reduction in metal concentrations, which could be attributed to more favourable conditions for metal release at this location (KSMelayu) compared to SBelungkor.

The concentrations of Hg, Co, and Cr in the total soft tissues of *P. viridis* after six weeks of the transplantation study from KPP to SB and to KSM (KPP to KSM) are summarized in Table 1. The results indicate that the concentrations of these metals varied across the two transplantation sites. For the KPP to SB transplantation, the mean concentrations of Hg, Co, and Cr were 0.0444 mg kg^{-1}, 0.443 mg kg^{-1}, and 6.84 mg kg^{-1}, respectively. The standard error values, which indicate the variability of the data, were highest for Cr (0.76 mg kg^{-1}) and lowest for Hg (0.039 mg kg^{-1}). The KPP to KSM transplantation exhibited similar trends with mean concentrations of 0.046 mg kg^{-1} for Hg, 0.471 mg kg^{-1} for Co, and 7.05 mg kg^{-1} for Cr. The standard errors were relatively lower at this site for Co (0.046 mg kg^{-1}) and Cr (0.68 mg kg^{-1}), while Hg had a comparable standard error of 0.038 mg kg^{-1}.

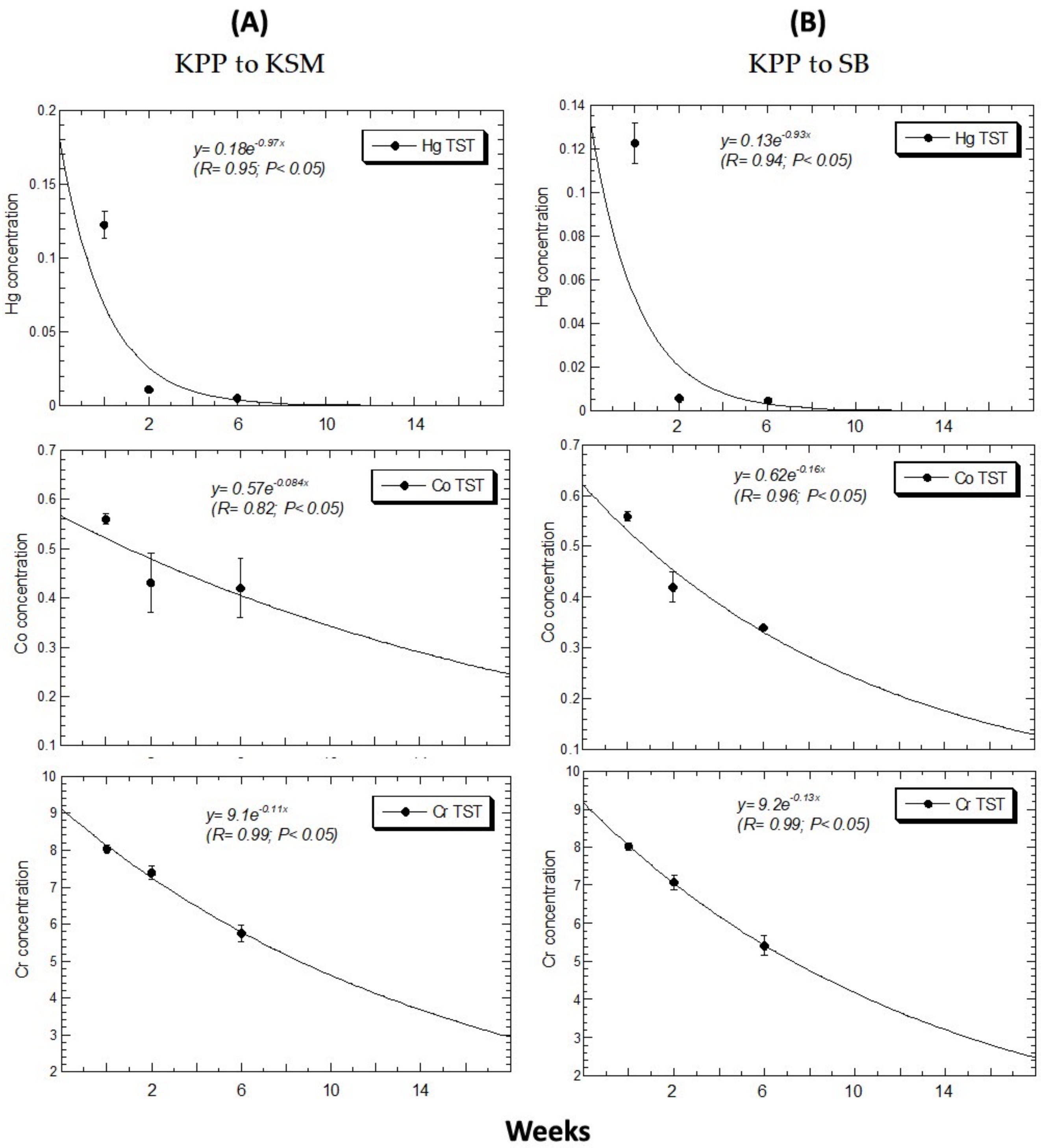

FIGURE 2 Depuration of Hg, Co, and Cr concentrations (mg kg^{-1} dry weight) in the mussels *Perna viridis* transplanted from Kg. Pasir Puteh to Kg. Sungai Melayu (KPP to KSM; A), and to Sungai Belungkor (KPP to SB; B). Curve fits are based on exponential equations.

TABLE 1 Overall statistics of concentrations (mg kg^{-1} dry weight) of Hg, Co and Cr in the soft tissues of *Perna viridis* during the transplantation study from Kg. Pasir Puteh (KPP) to Sungai Belungkor (SB) (KPP to SB) and to Kg. Sungai Melayu (KSM) (KPP to KSM), after six weeks of depuration at the two sites from KPP.

Sites	Hg	Co	Cr
KPP to SB			
Minimum	0.0049	0.344	5.42
Maximum	0.123	0.563	8.03
Mean	0.0444	0.443	6.84
Median	0.0056	0.423	7.08
Std Error	0.039	0.064	0.76
KPP to KSM			
Minimum	0.0049	0.420	5.75
Maximum	0.123	0.563	8.03
Mean	0.046	0.471	7.05
Median	0.011	0.431	7.39
Std Error	0.038	0.046	0.68

The percentage reduction of Hg, Co, and Cr in the soft tissues of *P. viridis* throughout the transplantation study is detailed in Table 2. At the KPP to SB, the depuration of Hg was particularly effective, with a significant (p < 0.05) reduction of 95.4% at Week 2, increasing to 96.0% by Week 6. Co and Cr exhibited slower reduction rates, with Co reducing by 24.9% at Week 2 and a significant (p < 0.05) reduction (38.9%) at Week 6, while Cr reduced by 11.8% at Week 2 and a significant (p < 0.05) reduction (32.5%) at Week 6. In contrast, at the KPP to KSM, Hg also significantly (p < 0.05) reduced (91.3%) in Week 2 and also significantly (p < 0.05) (95.9%) in Week 6). However, Co and Cr reductions were slightly lower than the Belungkor site, with Co reducing by 23.5% at Week 2 and 25.5% at Week 6, and Cr reducing by 7.94% at Week 2 and a significant (p < 0.05) reduction (28.4%) at Week 6.

TABLE 2 Percentages (%) of reduction of Hg, Co and Cr in the soft tissues of *Perna viridis* after weeks of transplantation from Kg. Pasir Puteh (KPP) to Sungai Belungkor (SB) (KPP to SB) and to Kg. Sungai Melayu (KSM) (KPP to KSM).

Sites	Hg	Co	Cr
KPP to SB			
Week 2	95.4*	24.9	11.8
Week 6	96.0*	38.9*	32.5*
KPP to KSM			
Week 2	91.3*	23.5	7.94
Week 6	95.9*	25.5	28.4*

Note: * indicate the significant (p < 0.05) reduction from the Week 0 samples.

Table 3 presents the values of EDI, THQ, and EWI of Hg, Co, and Cr for *P. viridis* transplanted from KPP to KSM and SB. At the beginning of the study (Week 0), the EDI values for Hg, Co, and Cr were identical for both sites, with Hg at 0.013 µg kg^{-1} day^{-1}, Co at 0.062 µg kg^{-1} day^{-1}, and Cr at 0.88 µg kg^{-1} day^{-1}. Correspondingly, the THQ and EWI values followed similar trends. By Week 2, significant reductions were observed in the EDI, THQ, and EWI values for all three metals at both sites, reflecting the effectiveness of the depuration process. At Week 6, the EDI for Hg remained at 0.001 µg kg^{-1} day^{-1} for both sites, while the EDI for Co decreased slightly more at the KPP to SB (0.038 µg kg^{-1} day^{-1}) compared to the KPP to KSM (0.046 µg kg^{-1} day^{-1}). The Cr EDI showed a reduction to 0.59 µg kg^{-1} day^{-1} at the SB and 0.63 µg kg^{-1} day^{-1} at the KSM by Week 6.

These results suggest that the depuration process in *P. viridis* effectively reduces heavy metal concentrations, particularly Hg, across both sites. However, the rate and extent of reduction vary by metal and site, with the KPP to SB site showing slightly more effective depuration for Co and Cr than the KPP to KSM. The health risk assessments based on EDI, THQ, and EWI values indicate a substantial decrease in potential risks throughout the study, reflecting the benefits of depuration in reducing heavy metal exposure from *P. viridis*.

4 | DISCUSSION

4.1 Effectiveness of depuration in reducing metal concentrations

The study on the depuration process in the mussel *P. viridis* provides valuable insights into its capacity to effectively eliminate heavy metals, particularly Hg, from its soft tissues. The rapid reduction in Hg concentrations, exceeding 95% within six weeks, highlights the mussel's remarkable ability to detoxify when relocated to a less polluted environment. This result is consistent with previous research, which attributes Hg's rapid depuration to its high volatility and low affinity for biological tissues (Piras *et al.* 2013). However, the slower depuration rates observed for Co and Cr suggest that these metals have stronger binding affinities to bivalve tissues, indicating the need for a deeper understanding of how different metals interact with biological systems (Karadede-Akin and Ünlü 2006; Oreščanin *et al.* 2006; Goretti *et al.* 2016).

These findings underscore the importance of considering the specific chemical properties of each metal and their interactions with biological systems when evaluating the effectiveness of bivalves as bioindicators of environmental health. Studies have documented significant variability in heavy metal accumulation among different mollusc species and tissues, reinforcing the necessity for targeted monitoring programs that consider the specific contaminant profiles and local environmental conditions (Manly and George 1977; Piras *et al.* 2013). The substantial decreases in metal levels observed in this study highlight the potential of *P. viridis* as a reliable biomonitor for assessing and managing metal contamination in coastal environments, a conclusion supported by research on the utility of bivalves as indicators of water quality, sediment contamination, and overall ecosystem health (Sivaperumal 2014; Cheng and Yap 2015; Samsi *et al.* 2017).

TABLE 3 Values of estimated daily intake (EDI, µg kg^{-1} body weight day^{-1}), target hazard quotient (THQ), estimated weekly intake (EWI, µg kg^{-1} body weight day^{-1}) for Hg, Co and Cr in the total soft tissues of *Perna viridis* transplanted from Kg. Pasir Puteh (KPP) to Kg. Sungai Melayu (KSM) (KPP to KSM), and to Sungai Belungkor (SB) (KPP to SB) from the present study.

Sites	Hg			Co			Cr		
KPP to KSM									
PTWI			248			607.6			2170
Week	EDI	THQ	EWI	EDI	THQ	EWI	EDI	THQ	EWI
0	0.013	0.045	0.094	0.062	0.206	0.432	0.88	0.29	6.16
2	0.001	0.004	0.008	0.047	0.157	0.331	0.81	0.27	5.67
6	0.001	0.002	0.004	0.046	0.153	0.322	0.63	0.21	4.41
KPP to SB									
PTWI			248			607.6			2170
Week	EDI	THQ	EWI	EDI	THQ	EWI	EDI	THQ	EWI
0	0.013	0.045	0.094	0.062	0.206	0.432	0.88	0.29	6.16
2	0.001	0.002	0.004	0.046	0.155	0.325	0.78	0.26	5.44
6	0.001	0.002	0.004	0.038	0.126	0.264	0.59	0.20	4.16

Note: PTWI = provisional tolerable weekly intake.

Furthermore, the observed variations in depuration efficiency among different metals emphasize the need for tailored monitoring approaches. By accounting for the specific contaminant profiles and environmental conditions, stakeholders can enhance the effectiveness of *P. viridis* as a biomonitoring tool, particularly in regions with complex pollution dynamics (Fernández *et al.* 2007; Piras *et al.* 2013; Roveta *et al.* 2021). Overall, these findings contribute to the growing body of knowledge on using bivalves as bioindicators of heavy metal pollution in aquatic ecosystems, demonstrating the need for a nuanced understanding of metal-tissue interactions and their implications for environmental monitoring and management.

4.2 Site-specific variations in heavy metal depuration rates: implications for biomonitoring

Understanding the mechanisms behind the uptake, storage, detoxification, and elimination of essential and pollutant trace metals in aquatic organisms is crucial for developing effective environmental monitoring strategies. This understanding is particularly vital in estuarine and coastal ecosystems, which are more susceptible to heavy metal pollution. By tailoring monitoring approaches to account for local environmental conditions—such as water quality parameters and the availability of food and other organisms—researchers and managers can more accurately assess heavy metal contamination levels and implement targeted mitigation strategies (Coombs 1980; Kumar 2008, 2018; Artalina and Dian Takarina 2019; Ujianti and Androva 2020; Maskooni *et al.* 2020; Xu *et al.* 2023).

Previous research highlights the importance of considering the complex interplay between environmental factors and biological processes in understanding the fate and behaviour of heavy metals in aquatic systems. This complexity necessitates a multifaceted approach to studying metal metabolism in organisms, emphasizing the physiological processes involved in metal elimination and the impact of environmental conditions on these processes. Such an approach can lead to significant variations in contaminant levels across different ecosystems (Coombs 1980; Aziz *et al.* 2023). The observed differences in the depuration rates of Co and Cr between the two sites in the present study underscore the need for a site-specific approach to biomonitoring, which considers the local ecological factors that influence bioavailability and detoxification processes (Bryan 1980; Liu *et al.* 2022).

Environmental factors, such as salinity, pH, and temperature, significantly influence the bioavailability and mobility of heavy metals, thereby affecting the rate at which organisms can eliminate these contaminants. The higher Co and Cr depuration rates at certain sites may indicate more favourable water conditions that enhance the mussels' ability to detoxify (Díaz-de-Alba et al., 2021; Coombs, 1980). Additionally, food availability and other organisms' presence in the ecosystem could modulate the metabolic processes involved in depuration (Machado et al., 2018).

The complex interplay between environmental conditions and biological processes at each site emphasizes the need for a site-specific approach to biomonitoring. By tailoring monitoring protocols to reflect these local ecological factors, stakeholders can optimize the effectiveness of contamination assessments and better protect public health and marine biodiversity from the risks associated with heavy metal exposure. This tailored approach not only strengthens the reliability of biomonitoring data but also enhances the potential for informed decision-making in environmental management and policy development, ultimately contributing to the sustainable protection of aquatic ecosystems and human health from heavy metal pollution (Díaz-de-Alba *et al.* 2021). Furthermore, regular monitoring and evaluation of heavy metal concentrations in coastal areas, particularly those with significant anthropogenic activities, are critical for ensuring that contamination levels remain within safe regulatory limits, thereby mitigating risks to both ecological systems and human health (Doyi *et al.* 2018; Bamanga *et al.* 2019).

4.3 Mitigating health risks through metal depuration in the consumption of *P. viridis*

The current study evaluated the potential health risks associated with consuming *P. viridis*, and the effectiveness of depuration in reducing these risks. The findings demonstrate that depuration significantly lowers the levels of heavy metals, enhancing food safety while also underscoring the critical role of mussels play in marine ecosystems as both a food source and potential therapeutic agents for various health conditions, thereby reinforcing their value in human diets (Chakraborty and Joy 2020).

Health risk assessments, indicated by EDI, THQ, and EWI, revealed significant reductions in the potential health risks associated with *P. viridis* consumption throughout the study. At both study sites, the values for Hg, Co, and Cr decreased substantially from Week 0 to Week 6, indicating that depuration effectively lowers the risk of heavy metal exposure through seafood consumption (Oreščanin *et al.* 2006; Khan and Liu 2019; Chakraborty and Joy 2020). This finding is particularly important for communities that rely on *P. viridis* as a dietary staple, suggesting that risks associated with heavy metal contamination can be mitigated by allowing sufficient depuration time before consumption (Piras *et al.* 2013; Chakraborty and Joy 2020).

The reduction in health risks associated with Hg, Co, and Cr is especially relevant in the context of food safety. Given that *P. viridis* is widely consumed in many coastal communities, understanding the dynamics of metal depuration is crucial for ensuring seafood safety (Kumar *et al.* 2019; Agarin *et al.* 2021; Pinzón-Bedoya *et al.* 2020; Tamele and Loureiro 2020; Senoro *et al.* 2023). The study's findings suggest that, with appropriate management, *P. viridis* consumption can be safely maintained even in areas where metal contamination is a concern. This is significant because these mussels provide essential nutrients and possess various health-promoting properties, such as antiviral, anti-inflammatory, and antimicrobial activities (Khan and Liu 2019).

However, it is important to consider the limitations of relying solely on depuration to manage health risks. While depuration effectively reduces metal concentrations, it may not completely eliminate all contaminants, particularly those that are more persistent or have a stronger affinity for biological tissues. This highlights the need for a comprehensive risk management strategy that includes on-going monitoring of metal levels in seafood, coupled with efforts to address contamination sources, especially in marine environments heavily impacted by human activities such as industrial discharges and urban runoff (Ekere *et al.* 2018; Saleem *et al.* 2022; Tamele and Loureiro 2020).

The study's findings emphasize the importance of understanding the depuration dynamics of heavy metals in *P. viridis* to ensure seafood safety in coastal communities. Additionally, addressing the root causes of contamination, such as untreated sewage and industrial effluents, is essential to safeguard public health and the marine ecosystem. Ensuring that seafood remains a viable source of nutrition and health benefits for vulnerable populations reliant on these resources requires implementing stricter regulations on industrial waste management and enhancing public awareness about the risks of heavy metal contamination. These efforts will play a crucial role in protecting both consumers and marine biodiversity, ultimately contributing to the sustainable development of coastal fisheries and the health of local communities that depend on them (Díaz-de-Alba *et al.* 2021; Saleem *et al.* 2022).

4.4. Implications for Environmental Management and Biomonitoring

The study of heavy metal accumulation and depuration in the mussel *P. viridis* has important implications for environmental management and using this species as a biomonitor. The variation in heavy metal concentrations across different tissues suggests that site-specific factors significantly influence bioaccumulation and depuration processes, highlighting the need for tailored management strategies that reflect the ecological dynamics of each locale (Roveta *et al.* 2021). This variation can be linked to the physiological characteristics of bivalves, which exhibit differing accumulation rates for metals like lead, cadmium, and Hg depending on environmental conditions, further emphasizing the necessity for seasonally adjusted monitoring protocols to accurately assess contamination levels (Piras *et al.* 2013; Rouane–Hacene *et al.* 2015).

Understanding these dynamics is essential because studies have shown that seasonal variability in heavy metal accumulation and bioavailability can directly impact seafood safety and the health of marine ecosystems. This necessitates an integrated approach to monitoring and management efforts sensitive to environmental factors and focused on protecting public health (Roveta *et al.*

2021).

The findings regarding the effectiveness of depuration in reducing heavy metal concentrations in *P. viridis* suggest that regular monitoring of this species could provide valuable data on contamination levels in coastal waters. Incorporating depuration practices into seafood safety management could significantly enhance consumer protection, particularly in regions where heavy metal pollution seriously threatens public health and marine biodiversity, as highlighted by recent assessments of heavy metal levels in various marine species (Piras *et al.* 2013).

The accumulation of heavy metals in marine environments poses significant risks to both ecosystem health and human consumers of contaminated seafood (Feng *et al.* 2020). To effectively mitigate this issue, it is crucial to consider seasonal variations in metal bioavailability and uptake by marine organisms (Primost *et al.* 2017). Fluctuations in environmental factors such as water temperature, salinity, and flow rates can greatly influence the uptake and elimination of heavy metals by marine biota, varying across different seasons (Senez-Mello *et al.* 2020). Incorporating seasonal measurements of these parameters can offer valuable insights into the mechanisms driving metal bioaccumulation, allowing for more precise and responsive approaches to monitoring and managing heavy metal contamination in marine ecosystems (Yao *et al.* 2014; Uddin and Huang 2022). Several studies have examined species-specific patterns of metal accumulation in marine organisms, highlighting the need to consider these differences in conservation efforts (Feng *et al.* 2020). For example, research conducted on fish species from Xincun Lagoon, South China, demonstrated significant variation in trace metal bioaccumulation among different species, stressing the importance of tailored monitoring and management strategies. Similarly, studies on Patagonian edible gastropods revealed their potential to accumulate high levels of cadmium and other metals, raising concerns about the health risks associated with consuming contaminated seafood (Primost *et al.* 2017).

The use of *P. viridis* as a biomonitor species is particularly advantageous due to its wide distribution and ability to accumulate metals from its environment, making it an ideal indicator for monitoring metal contamination across diverse marine ecosystems. The findings from this study reinforce the potential of *P. viridis* as a biomonitoring tool, especially in regions where metal pollution is a significant concern. Regular monitoring of this species could serve as an early warning system for contamination events, enabling prompt interventions to curb further environmental degradation and safeguard human health. This is particularly relevant given the increasing need to address heavy metal pollution near urban and industrial areas where risks to both ecosystems and public health are heightened (Doyi *et al.* 2018; Mehana *et al.* 2020; Díaz-de-Alba *et al.* 2021; Dehbi *et al.* 2023).

Additionally, integrating *P. viridis* into a comprehensive monitoring framework can enhance our understanding of how heavy metals disperse in coastal ecosystems, informing management practices essential for ecological integrity and human health. The broader application of depuration-based approaches in seafood safety practices could significantly improve the management of heavy metal contamination in marine environments. However, the effectiveness of these approaches will depend on specific environmental conditions and the metals involved, highlighting the need for on-going research to refine depuration methodologies and establish standardized protocols for various ecosystems, especially those facing intense industrial pressure (Mehana *et al.* 2020; Dehbi *et al.* 2023).

In this context, further studies are warranted to investigate the nuances of metal bioaccumulation across different seasons and geographical locations. Such research can provide critical insights into the efficacy of *P. viridis* as a biomonitor and inform adaptive management strategies to reduce the public health and environmental risks posed by heavy metal pollution in coastal waters.

4.5 Comparisons among Hg, Co, and Cr during depuration

Depuration, or the elimination of heavy metals from the tissues of marine organisms, is crucial for understanding the long-term impacts of environmental contamination. Research indicates that the rates of heavy metal accumulation and subsequent depuration are influenced by the specific metal's chemical properties as well as the physiological and anatomical characteristics of the organism (Duruibe *et al.* 2007; Chapman 2008; Masindi and Muedi 2018; Aziz *et al.* 2023; Sharma *et al.* 2023; Mustafa *et al.* 2024). Each species exhibits different affinities for metal accumulation, which can significantly affect the efficiency of detoxification processes, as observed in various studies examining bioaccumulation patterns in aquatic fauna (Manly and George 1977; Piras *et al.* 2013). This variability is particularly relevant in bivalves, where the tissue-specific distribution of metals often results in pronounced differences in accumulation and depuration rates, necessitating site-specific assessments to inform effective environmental risk management (Piras *et al.* 2013).

A comparative study investigating the depuration of Hg, Co, and Cr in *P. viridis* revealed distinct differences in the rates at which these metals are eliminated from the mussels' tissues. The findings showed that Hg consistently exhibited the highest depuration rate, followed by Co, with Cr displaying the slowest elimination rate. This pattern aligns with previous research, highlighting the uneven distribution of heavy metals within mussel tissues, with certain organs, such as the mantle and ctenidia, showing higher concentration levels that can influence overall depuration efficiency (Manly and George 1977).

Therefore, targeted assessments of these tissues could enhance our understanding of the mechanisms driving metal depuration in bivalves, informing future research and remediation strategies.

The observed differences in depuration rates among Hg, Co, and Cr can be attributed to their chemical properties and biological behaviours. For instance, Hg, known for its high volatility and lower binding affinity within biological systems, is more rapidly excreted than the more stable complexes formed by Co and Cr. These latter metals tend to persist longer in tissues, complicating detoxification efforts. The persistence of Co and Cr in mussel tissues has been attributed to the formation of stable complexes (Wang *et al.* 1997), highlighting the ability of marine organisms like bivalve molluscs to accumulate and tolerate high levels of heavy metals (Lovejoy 1999; Kavun *et al.* 2002). Mussels are known to preferentially accumulate metals in their digestive glands, where the accumulation of Cr has been shown to vary based on the valency and solubility of the Cr species (Walsh and O'Halloran 1997). Specifically, studies have demonstrated that mussels exposed to chromium-albumin complexes, tannery effluent Cr, and trivalent Cr accumulate the metal at higher rates compared to those exposed to hexavalent or citrate-bound chromium (Wang *et al.* 1997; Walsh and O'Halloran 1998). The formation of stable complexes with biomolecules such as proteins and enzymes is a key mechanism underlying the persistence of heavy metals like cobalt and chromium in mussel tissues. These metals bind to the functional groups of enzymes, disrupting essential metabolic processes (Coombs and George 1978; Senez-Mello *et al.* 2020). Additionally, heavy metal interactions with cell membranes can alter their structure, affecting the transport of essential ions and substances, further contributing to the accumulation and retention of these elements in mussel tissues (Canesi *et al.* 1999; Çevik *et al.* 2008). This bioaccumulation is driven by the formation of complexes between metal ions and enzyme functional groups, which interfere with critical metabolic processes and alter cell membrane integrity (Senez-Mello *et al.* 2020).

Although essential for certain physiological functions, Co is still subject to regulatory processes that may slow its elimination rate relative to Hg. Cr, particularly in its hexavalent form, exhibits higher toxicity and persistence, posing significant challenges to the depuration process and necessitating a more comprehensive understanding of its interactions within biological systems and the environmental context affecting its bioavailability.

The varying depuration rates observed for these three metals underscore the importance of a tailored approach to environmental monitoring and remediation strategies. The implications of these findings extend beyond the immediate physiological responses of the mussels; they highlight the necessity of incorporating such variability into models assessing the ecological risks of metal pollution. Understanding the influences of seasonal variations, sampling sites, and the inherent biological characteristics of the organisms involved is crucial for refining these models, as research has shown that bioaccumulation patterns can significantly change based on environmental factors and organism-specific attributes. This knowledge can ultimately enhance the effectiveness of biomonitoring programs and inform regulatory frameworks to manage heavy metal pollution in aquatic environments (Coombs 1980; Pan *et al.* 2015; Bamanga *et al.* 2019).

In sum, the complexity of heavy metal interactions within marine organisms like *P. viridis* necessitates ongoing research to elucidate the mechanisms governing metal depuration and their broader ecological implications. This continued research is essential for developing more robust approaches to environmental management and pollution remediation, ultimately contributing to the protection of both marine ecosystems and human health (Cantwell and Burgess 2001; Piras *et al.* 2013; Díaz-de-Alba *et al.* 2021).

4.6 Depuration kinetics of heavy metals in *P. viridis*: implications for Sustainable Development Goals

The study of depuration kinetics in the mussel species *P. viridis* has significant implications for several United Nations Sustainable Development Goals (SDGs), particularly SDG 14 (Life below Water), SDG 3 (Good Health and Well-Being), and SDG 6 (Clean Water and Sanitation). By enhancing our understanding of how marine organisms respond to pollution, this research can improve environmental and public health.

The SDG 14, which emphasizes the conservation and sustainable use of oceans, seas, and marine resources, is directly supported by this research (Jena *et al.* 2009). The findings demonstrate that *P. viridis*, can function as an effective biomonitor for assessing marine ecosystem health, particularly in relation to the accumulation of heavy metals—priority pollutants known for their potential bioaccumulation and toxicity (Roveta *et al.* 2021). By exploring the factors influencing the depuration efficiency of these mussels, this research contributes to a deeper understanding of pollution impacts on marine life, aiding in the development of targeted strategies for protecting and restoring coastal environments (Conti *et al.* 2019).

In terms of SDG 3, which focuses on ensuring healthy lives and promoting well-being for all, the study's insights have direct implications for human health (Yap *et al.* 2021). The accumulation of heavy metals in marine organisms, including *P. viridis*, poses risks not only to marine species but also to human populations that rely on seafood as a major food source (Primost *et al.* 2017). This highlights the importance of continuous monitoring and management of coastal ecosystems to mitigate potential health risks associated with consuming contaminated seafood (Roveta *et al.* 2021; Mousavi *et al.* 2023). Additionally, understanding the depuration rates of *P. viridis* and their relationship to heavy metal concentrations, such as Hg and Cr, is crucial for developing public health guidelines and interventions aimed at reducing exposure to these contaminants through marine food webs (Dell'Anno *et al.* 2020).

The findings from the study of depuration kinetics in *P. viridis* also have implications for SDG 6, which aims to ensure the availability and sustainable management of water and sanitation for all (Dangles and Casas 2018). This research can inform water quality management practices by providing critical data on metal concentrations in coastal waters and their accumulation in marine organisms, ensuring that aquatic environments remain healthy and sustainable for both human consumption and ecological integrity (Tamele and Loureiro 2020). Integrating such data into policy-making efforts can aid in establishing effective regulations surrounding wastewater discharges and industrial activities, contributing to cleaner water resources and healthier marine ecosystems, which are essential for sustainable development and public health protection (Díaz-de-Alba *et al.* 2021). Moreover, the chronic exposure of coastal ecosystems to heavy metals necessitates a comprehensive understanding of their mobility and bioavailability, as environmental conditions influence these factors and can significantly alter the effectiveness of depuration processes in organisms like P. viridis. This reinforces the importance of this research for SDG 6 (Tamele and Loureiro 2020; Díaz-de-Alba *et al.* 2021; Mousavi *et al.* 2023). Additionally, the long-term implications of heavy metal pollution extend beyond immediate ecological impacts, as these contaminants can undergo biomagnification through food webs, ultimately affecting higher trophic levels, including humans who rely on seafood, thereby linking environmental health directly to public health concerns (Tamele and Loureiro 2020; Díaz-de-Alba *et al.* 2021; Mousavi *et al.* 2023).

4.7 Depuration kinetics in *P. viridis* and implications for planetary health

The findings from this study of depuration kinetics in *P. viridis* have profound implications for planetary health, emphasising the interdependence of human health and the health of natural systems. The study contributes to the planetary health framework by providing data that can be used to assess and manage the risks associated with the bioaccumulation of contaminants in marine food webs. This fosters a deeper understanding of the connections between ecosystem health and human health outcomes, enabling more effective strategies for monitoring and mitigating the impacts of anthropogenic stressors, such as microplastics and heavy metals, on both marine organisms and human populations who rely on these ecosystems for food and other resources (Gambardella *et al.* 2018; Yong *et al.* 2020).

Consequently, these findings underscore the urgency of interdisciplinary collaboration between ecologists and public health experts to devise comprehensive management plans that address the complex dynamics of pollution and its cascading effects throughout the food web. Such collaboration is essential for protecting environmental integrity and human health (Yong *et al.* 2020; Talukder *et al.* 2022).

Planetary health recognizes that the well-being of human societies is deeply intertwined with the state of the Earth's ecosystems, and any disruption to these ecosystems can have cascading effects on human health and global stability (Seltenrich 2018). Integrating ecological and health data is crucial for developing informed policies prioritising ecosystem restoration and sustainable practices, thereby enhancing resilience against environmental challenges (Rapport 1998; Palmer *et al.* 2004; Aronson *et al.* 2016; Robinson *et al.* 2022). The application of this integrated approach is further reinforced by evidence highlighting the relationship between ecosystem degradation and increased susceptibility to diseases, emphasizing that restoring natural systems can lead to improved health outcomes for human populations reliant on these ecosystems for sustenance and disease regulation (Seltenrich 2018).

The depuration processes observed in *P. viridis* directly contribute to understanding how ecosystems respond to pollution, particularly heavy metal contamination, which significantly threatens marine biodiversity and human health. The ability of mussels to detoxify through depuration is a natural mechanism that helps mitigate the impact of contaminants in marine environments, thereby playing a critical role in maintaining the health of these ecosystems (Seltenrich 2018). When these natural processes are effective, they contribute to the resilience of marine ecosystems, allowing them to continue providing essential services such as food, oxygen production, and climate regulation, all of which are vital for planetary health.

Moreover, understanding the mechanisms behind the detoxification processes in *P. viridis* can inform bioremediation strategies. These organisms may be leveraged to restore polluted environments, enhancing the overall stability of marine ecosystems and their ability to support human health and well-being (Dell'Anno *et al.* 2020; Tarfeen *et al.* 2022). By advancing knowledge in this area, the study contributes to the broader goals of planetary health, advocating for a more holistic approach to managing environmental challenges that impact both ecosystems and human societies.

5 | CONCLUSIONS

This study demonstrates the effectiveness of *P. viridis* as a biomonitor for heavy metal contamination in coastal environments, particularly through its ability to depurate accumulated metals like Hg, Co, and Cr. The results show that the depuration process in *P. viridis* is highly effective, especially for Hg, with significant reductions in metal concentrations observed across both transplantation sites, KPP to SB and KPP to KSM. These findings underscore the potential of *P. viridis* to rapidly eliminate certain contaminants when relocated to cleaner environments, making it a valuable tool for assessing and managing metal pollution in marine ecosystems. However, the study also highlights site-specific variations in depuration efficiency, particularly for Co and Cr, indicating that environmental conditions play a crucial role in detoxification. These differences suggest that while *P. viridis* is effective in biomonitoring, the specific environmental context must be considered to accurately assess the contamination levels and the success of remediation efforts. The health risk assessments conducted in this study further emphasize the importance of allowing adequate depuration time to minimize potential risks associated with seafood consumption, particularly in communities where *P. viridis* is a dietary staple.

Overall, this research provides important insights into using *P. viridis* as a biomonitoring tool and its role in environmental management. The findings support the broader application of depuration-based approaches in seafood safety practices and contribute to understanding how marine organisms respond to pollution. Furthermore, the study's implications extend to the United Nations Sustainable Development Goals (SDGs) and the concept of planetary health, highlighting the interconnectedness of ecosystem health, human well-being, and global sustainability. Integrating these insights into environmental policies and management strategies can enhance the protection and restoration of marine ecosystems, thereby safeguarding both environmental and human health for future generations.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHORS' CONTRIBUTION
Conceptualisation, CKY and KAA-M; methodology and validation, CKY and KAA-M; formal analysis, CKY; investigation CKY; resources, KAA-M; data curation, CKY; writing—original draft preparation, CKY.; writing—review and editing, CKY and KAA-M. All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT
The data that support the findings of the study will be made available on a reasonable request from the corresponding author.

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