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*Short Communication*

# Evaluating Marine Mussels' Lithium, Strontium, and Vanadium Detoxification for Coastal Ecosystem Conservation

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## Abstract

The green-lipped mussel *Perna viridis*, transplanted from the polluted Kg. Pasir Puteh (KPP) to relatively unpolluted sites at Sungai Belungkor (SB) and Kg. Sg. Melayu (KSM) was examined for lithium (Li), strontium (Sr), and vanadium (V) depuration kinetics. After six weeks of depuration, v levels were found to have the greatest decline (41.7% at SB and 38.9% at KSM). The present study also demonstrated significant declines for Li (20.5% and 24.1%) and Sr (26.7% and 21.7%) at the locations. The estimated daily intake and target hazard quotient values showed that *P. viridis* detoxifies the bioaccumulated Li, Sr, and V by reducing human health risks. This is also well supported by the lower percentages between the comparison of estimated weekly intake and the provisional tolerated weekly intake of the three metals. These findings highlight the species' heavy metal biomonitor potential. Depuration rates vary by site, indicating unique environmental circumstances and the need for customized conservation efforts. These findings could affect conservation, especially given climate change. Due to rising temperatures, sea-level rise, and ocean acidification, coastal ecosystems are already stressed, which might increase harmful metal bioavailability. Metal pollution monitoring and management are crucial to ecosystem health and food security in Southeast Asian coastal regions like Peninsular Malaysia, which are prone to these changes. This work will help create adaptive conservation techniques to reduce pollution's effects on biodiversity and human health in rapidly changing ecosystems.

**Keywords:** Depuration kinetics, toxic elements, coastal conservation, biomonitoring, Perna viridis

## Introduction

The escalation of industry, urbanization, and human activity in coastal environments has contaminated rare earth elements in valuable coastal ecosystems, such as marine mussels [1-62]. Industrial effluents, mining activities, and agricultural runoff introduce lithium (Li) [6-7], strontium (Sr) [21, 38], and vanadium (V) [1, 18, 35, 37] into marine ecosystems. The literature documents concentrations of V [17, 53-55], Li [6-7, 41], and Sr [21]. Ingesting contaminated seafood can impact ecosystems and human health due to the accumulation of metals in marine organisms. Monitoring these metals in marine environments is important to safeguard

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ecosystem integrity and food safety, particularly when climate change adversely affects coastal areas.

Marine bivalves, such as the green-lipped mussel (*Perna viridis*), are frequently employed as biomonitors for heavy metals due to their tendency to bioaccumulate these substances. *P. viridis*' broad range and susceptibility to environmental toxins render it suitable for monitoring coastal pollution in Southeast Asia [3, 47]. Yap and Al-Mutairi [45] investigated the amounts of six potentially toxic metals—cadmium (Cd), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), and zinc (Zn)—in *P. viridis* before and following a 10-week depuration period. Transplanting mussels from polluted to cleaner environments significantly reduced metal concentrations, alleviating consumer health risks. Their research neglected to investigate dangerous metals such as Li, Sr, and V, resulting in a gap in our comprehension of metal contaminants in marine ecosystems.

The bioaccumulation of heavy metals in marine organisms poses an escalating environmental and public health issue, particularly in coastal regions where seafood is a staple. Although naturally occurring, industrial discharges, agricultural runoff, and urbanization can elevate metal concentrations in marine ecosystems to detrimental levels. This results in seafood bioaccumulation, potentially endangering human health [20]. Assessing the health implications of seafood consumption necessitates understanding these metals' accumulation and depuration processes in cultivated mussels [30, 50]. Prior research has linked Li and Sr to neurotoxic and osteopathic health risks in marine organisms and people [27, 43].

This research addresses a deficiency in marine ecosystem metal pollution by including elements such as Li, Sr, and V, which were not included in previous studies. The study offers essential information on adapting organisms such as *P. viridis* to environmental stressors, advances sustainable aquaculture, and safeguards public health. Given that climate change heightens the susceptibility of coastal ecosystems to heavy metal contamination, these findings are essential for conservation strategies and long-term sustainability. Incorporating Li, Sr, and V addresses a significant deficiency in metal contamination research. Yap and Al-Mutairi [45] investigated elements such as Cd, Cu, and Zn, although their exclusion constrained their conclusions. This research investigates underexplored toxic metals and their effects on marine organisms and people. The mechanisms of metal accumulation and detoxification in *P. viridis*, an essential species for coastal pollution biomonitoring, will be elucidated.

This study aims to (1) quantify the concentrations of Li, Sr, and V in the soft tissues of *P. viridis* before and after transplantation from a contaminated site to two relatively pristine coastal locations in the Straits of Johore; (2) assess the kinetics of depuration for each metal over a six-week period; and (3) evaluate the health risks associated with consumption. The initiative aims to enhance the understanding of marine heavy metal contamination and its implications for environmental management and public health.

## Materials and Methods

### Mussel Collection

More than 300 green-lipped mussels, *P. viridis*, were collected from the contaminated intertidal zone of Kg. Pasir Puteh (KPP) on November 28, 2009. The manual collection of diverse sizes and ages of mussels mitigated stress and damage. Mussels were cleaned three times with seawater immediately after capture to remove dirt and debris from their shells. This procedure was crucial to exclude extraneous contaminants that might influence the detection of Li, Sr, and V in mussel tissue.

### Transplantation Method

The mussels were implanted on the same day they were captured to maintain their physiological integrity. The cleaned mussels were randomly assigned to subgroups of 40 individuals. Subgroups were accommodated in polypropylene cages measuring 20 × 15 × 18 cm. The cages facilitated enough water circulation, enabling the mussels to acclimatize to the new environment while remaining in contact with the ambient water at the transplant sites. The mussels from KPP were relocated to two comparatively unpolluted locations at Sungai Belungkor (SB) and Kg. Sg. Melayu (KSM) (Fig. 1). The cages secured with ropes were positioned in the water column at an average depth of 1.5 meters [54, 46]. The cage arrangement ensured that the mussels had uniform tidal influences and water currents at both locations, hence standardizing environmental exposure for the research [46].

Mussels were tested for Li, Sr, and V depuration two and six weeks post-transplantation. Mussels from KSM and SB were harvested, and their soft tissues were collected for metal analysis at each interval. The selected periods were intended to investigate the temporal depuration and elucidate Li, Sr, and V reduction dynamics in mussel tissue.

### Sample Preparation and Metal Analysis

The mussels were transported back to the laboratory in an ice compartment at 10°C to maintain tissue integrity. The byssus threads and total soft tissues (TST) of each mussel were carefully removed in the laboratory. Following oven-drying at 105°C for 72 hours, the TST was weighed uniformly for analytical procedures.

Homogenized dry tissues were subjected to acid digestion with the CEM Microwave Sample Preparation System at 0.5 grams per sample mass. The digestion procedure involved adding 7 mL of concentrated nitric acid ($HNO_3$) and 1 mL of hydrogen peroxide ($H_2O_2$) to the desiccated samples. The amalgamation was contained

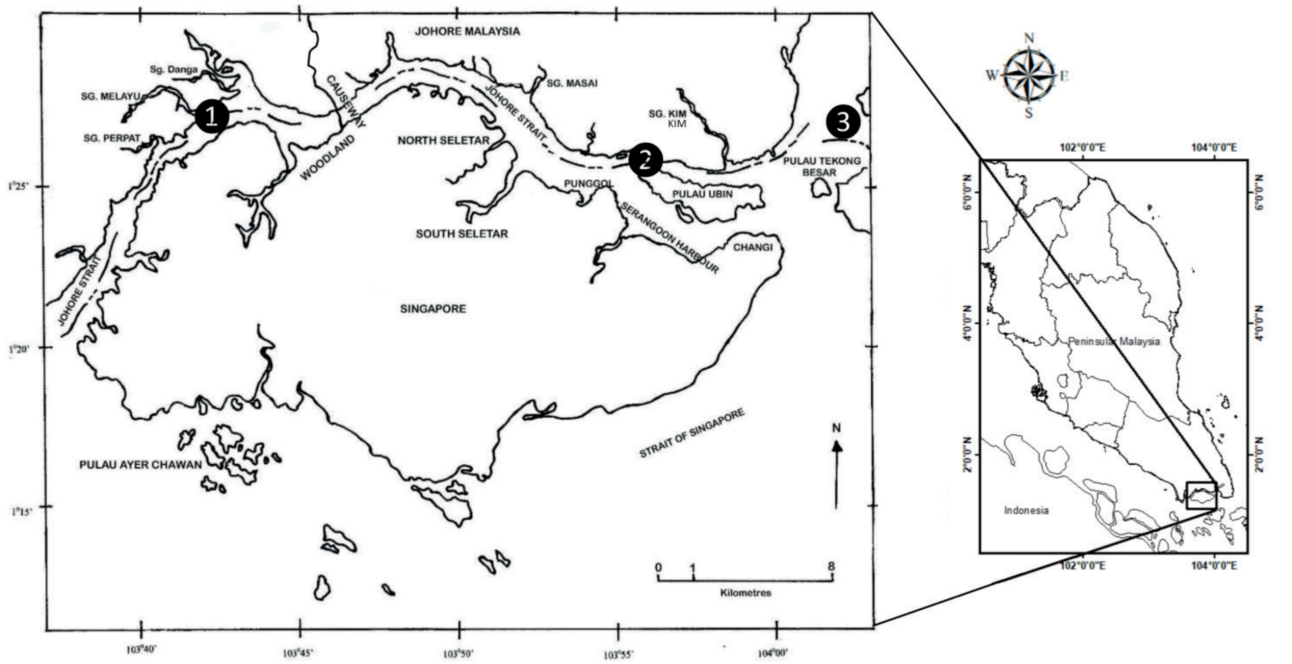


Fig. 1. Sampling site at Kampung Pasir Puteh (1), transplantation sites at Kg. Sungai Melayu (2), and Sungai Belungkor (3) in the Straits of Johore of the present study.

in Teflon vessels and subjected to microwave radiation at 220°C for 30 minutes. The comprehensive analysis of organic material enabled accurate determinations of Li, Sr, and V concentrations.

Post-digestion, samples were diluted to 100 mL with double-distilled water in volumetric flasks and filtered using Whatman No. 1 filter paper to remove particulates. Acid-washed polypropylene containers stored the filtrate before examination. An ICP-MS quantified the amounts of Li, Sr, and V in mussel tissues. This method was selected for its superior sensitivity and precision in detecting trace metals in biological samples. All processing glassware and equipment underwent acid washing to prevent contamination. To verify analytical validity and reliability, Certified Reference Materials (CRM) for mussel tissue (no. 2976, National Institute of Standards and Technology, NIST, USA) were examined alongside the samples. The CRM recovery rates were adequate, hence endorsing the precision of metal analysis.

## Data Treatment and Human Health Risk Assessments

### *Human Health Risk Assessments*

This study conducted human health risk assessments (HHRA) to examine the potential health concerns linked to ingesting *P. viridis* mussels contaminated with Li, Sr, and Va. The metal concentration data, initially quantified on a dry weight (DW) basis, were transformed to wet weight (WW) utilizing a conversion factor of 0.17, as determined for *P. viridis* by Yap et al. [49]. The HHRA was conducted through two primary evaluations: the computation of the target hazard quotient (THQ) and the comparison of estimated weekly intake (EWI) with provisional tolerated weekly intake (PTWI).

### *Target Hazard Quotient (THQ)*

The second assessment involved calculating the THQ for Li, Sr, and V. 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) on a wet-weight basis.

CR represents the consumption rate of fish and mollusks. For Malaysian adults, the average consumption rates are 100 g/person/day for fish and 40 g/person/day for mollusks, based on a survey of 2675 respondents (Malay: 76.9%; Chinese: 14.7%; Indian: 8.4%) [57].

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:

$$THQ = EDI/ORD$$

Table 1. Percentages (%) of reduction of Li, Sr, and V in the soft tissues of *Perna viridis* after weeks of transplantation from Kg. Pasir Puteh to Sungai Belungkor (Puteh to Belungkor) and to Kg. Sungai Melayu (Puteh to Melayu).

| Puteh to Belungkor | Li | Sr | V |
|---|---|---|---|
| Week 2 | 10.08 | 15.10 | 29.02 |
| Week 6 | 20.54 | 26.67 | 41.69 |
| Puteh to Melayu | Li | Sr | V |
| Week 2 | 2.45 | 5.73 | 19.65 |
| Week 6 | 24.09 | 21.71 | 38.86 |

Where:

ORD is the oral reference dose, which represents the contaminant's daily intake over a lifetime that is unlikely to cause harmful health effects. The ORD values used in this study were 2.00 µg/kg/day for Li, 600 µg/kg/day for Sr, and 5.00 µg/kg/day for V, as specified by the US EPA regional screening levels [58].

THQ values below 1.0 indicate that exposure to these metals is unlikely to pose significant non-carcinogenic health risks.

### *Comparisons Between Estimated Weekly Intake (EWI) and Provisional Tolerable Weekly Intake (PTWI)*

The second assessment involved comparing Li, Sr, and V's EWI with the PTWI set by international health agencies. The PTWI represents the amount of a substance that can be consumed weekly over a lifetime without posing significant health risks. In the present study, the PTWI for a 62 kg adult for Li, Sr, and V is 6206.2, 56420, and 781200 µg/week, respectively.

To estimate the weekly exposure, the following equation was used:

$$EWI = EDI \times 7$$

Where:

EDI is the estimated daily intake calculated previously.

### *Statistical Analysis*

All graphical bar charts were generated with KaleidaGraph (Version 3.08, Sygnergy Software, Eden Prairie, MN, USA). The graphs indicate that an exponential regression was chosen to model the connection. This exponential decay model is logically sound and suitable, as it produced the optimal plot with a decay constant (λ) and a corresponding R-value that effectively aligns with this study's objectives.

## Results

### Metal Depuration Kinetics

Fig. 2 illustrates the exponential decline kinetics of Li, Sr, and V in *P. viridis*, demonstrating its capacity to eliminate these metals during the study period. Depuration was statistically studied, revealing that each metal exhibited unique kinetic behaviors influenced by the environmental variables of the two transplanted locales, KSM and SB.

A first-order kinetic model indicated a gradual yet steady decrease in Li concentration over a six-week period. Li concentration decreased by 20.54% in SB and 24.09% in KSM. The exponential fit rate constants indicated that SB has a prolonged Li half-life (t1/2), signifying a reduced depuration rate. This indicates that Li is progressively eliminated from *P. viridis* tissues, possibly owing to its diminished bioavailability or enhanced binding affinity in mussel tissues.

V depuration had a more rapid exponential decline than Li, and Sr contents decreased by 26.7% in SB and 21.7% in KSM by Week 6. The diminished binding affinity of Sr to biological tissues may account for its abbreviated half-life at both sites, leading to accelerated depuration. The Sr rate constant for SB was higher, indicating that either water chemistry or mussel physiology may enhance metal depuration.

V had the greatest depuration rate among the three metals tested. The concentration of V decreased by 41.7% in SB and 38.9% in KSM during the study. V had the briefest half-life, indicating rapid elimination from mussel tissue. The reduced tissue retention and poorer V binding of *P. viridis*, together with the environmental factors of SB, may accelerate depuration. The rate constant for V depuration was higher in SB, indicating that site-specific conditions influence metal depuration kinetics. V exhibited the most rapid depuration kinetics, followed by Sr and Li. The observed dynamical differences indicate that metal chemical properties such as ionic radius, electronegativity, and binding affinities significantly influence depuration. The water quality, salinity, and other ions at the two sites seem to influence these kinetics, with SB consistently exhibiting superior depuration of all three metals.

Table 2. Values of estimated daily intake (EDI, µg/kg body weight/day), target hazard quotient (THQ), estimated weekly intake (EWI, µg/kg body weight/day) for Li, Sr, and V in the total soft tissues of *Perna viridis* transplanted from Kg. Pasir Puteh to Kg. Sungai Melayu (Puteh to Melayu) and to Sungai Belungkor (Puteh to Belungkor) from the present study.

| Puteh to Melayu | Li | | | Sr | | | V | | |
|---|---|---|---|---|---|---|---|---|---|
| PTWI | | | 6206.2 | | | 56420 | | | 781200 |
| Week | EDI | THQ | EWI | EDI | THQ | EWI | EDI | THQ | EWI |
| 0 | 1.43 | 0.71 | 9.99 | 14.3 | 0.024 | 100 | 0.54 | 0.11 | 3.81 |
| 2 | 1.39 | 0.70 | 9.75 | 13.5 | 0.023 | 94.6 | 0.44 | 0.09 | 3.06 |
| 6 | 1.08 | 0.54 | 7.58 | 11.2 | 0.019 | 78.6 | 0.33 | 0.07 | 2.33 |
| Puteh to Belungkor | Li | | | Sr | | | V | | |
| PTWI | | | 6206.2 | | | 56420 | | | 781200 |
| Week | EDI | THQ | EWI | EDI | THQ | EWI | EDI | THQ | EWI |
| 0 | 1.43 | 0.71 | 9.99 | 14.3 | 0.024 | 100 | 0.54 | 0.11 | 3.81 |
| 2 | 1.28 | 0.64 | 8.98 | 12.2 | 0.020 | 85.2 | 0.39 | 0.08 | 2.70 |
| 6 | 1.13 | 0.57 | 7.94 | 10.5 | 0.018 | 73.6 | 0.32 | 0.06 | 2.22 |

Note: PTWI= Provisional Tolerable Weekly Intake.

Therefore, the depuration kinetics of *P. viridis* for Li, Sr, and V exhibit a complex interplay between metal-specific attributes and ambient factors. The exponential decline for each metal illustrates the effectiveness of the depuration process, while site-specific variations demonstrate the influence of local environmental conditions on metal removal. These findings demonstrate *P. viridis*' capacity for depuration and propose its application as a biomonitoring instrument in metal-contaminated coastal environments.

Fig. 2 presents the concentrations of Li, Sr, and V (mg/kg dry weight) in the soft tissues of *P. viridis* during the transplantation study from KPP to SB and KSM.

The transplantation of KPP to SB exhibited Li levels between 10.34 and 13.01 mg/kg, with an average of 11.69 mg/kg. The median concentration of Li was 11.70 mg/kg. Sr levels varied from 9.59 to 130.7 mg/kg, with an average of 112.5 mg/kg. The median Sr concentration was 111 mg/kg. The results for V ranged from 2.89 to 4.96 mg/kg, with a mean of 3.79 mg/kg and a median of 3.52 mg/kg.

The Li concentrations in KPP to KSM transplanting ranged from 9.88 mg/kg to 13.0 mg/kg, with a somewhat elevated mean of 11.9 mg/kg compared to SB. The median Li content was 12.7 mg/kg. Sr values at this site ranged from 102 mg/kg to 131 mg/kg, with a mean of 119 mg/kg and a median of 123 mg/kg. V values ranged from 3.03 to 4.96 mg/kg, with a mean and median of 3.99 mg/kg.

Table 1 illustrates the percentage reduction of Li, Sr, and V in the soft tissues of *P. viridis* at 2 and 6 weeks post-transplantation. The KPP to SB transplantation lowered Li concentrations by 10.1% after two weeks and 20.5% after six weeks. Sr concentrations decreased by 15.1% after two weeks and 26.7% after six weeks. V saw the most significant rate reduction: 29.0% at week 2 and 41.7% at week 6.

In the KPP to KSM transplanting, Li demonstrated a negligible decrease of 2.45% after 2 weeks, which markedly escalated to 24.09% after 6 weeks. Sr concentrations decreased by 5.73% after two weeks and 21.7% after six weeks. V concentrations demonstrated a 19.65% decrease at week 2, attaining 38.9% at week 6. The statistics underscore the disparities in depuration efficiency between the two locations, with KPP to SB exhibiting consistently greater rates of metal reduction.

Table 2 displays the EDI, THQ, and EWI values for Li, Sr, and V in the soft tissues of *P. viridis* transplanted from KPP to KSM (Puteh to Melayu) and SB (Puteh to Belungkor). These values are crucial for evaluating the potential health hazards of ingesting these mollusks.

For the KPP to KSM transplantation, the initial EDI for Li was 1.43 µg/kg body weight/day, which decreased to 1.08 µg/kg by week 6. The THQ for Li correspondingly decreased from 0.71 to 0.54 over the 6-week period, and the EWI dropped from 9.99 µg/kg body weight/day to 7.58 µg/kg. Sr showed an initial EDI of 14.3 µg/kg, which decreased to 11.2 µg/kg by week 6. The THQ for Sr was initially 0.024, reducing to 0.019, while the EWI decreased from 100 µg/kg to 78.6 µg/kg. V showed an initial EDI of 0.54 µg/kg, reducing to 0.33 µg/kg by week 6, with the corresponding THQ decreasing from 0.11 to 0.07 and the EWI from 3.81 µg/kg to 2.33 µg/kg.

For the KPP to SB transplantation, the initial EDI for Li was also 1.43 µg/kg, which decreased to 1.13

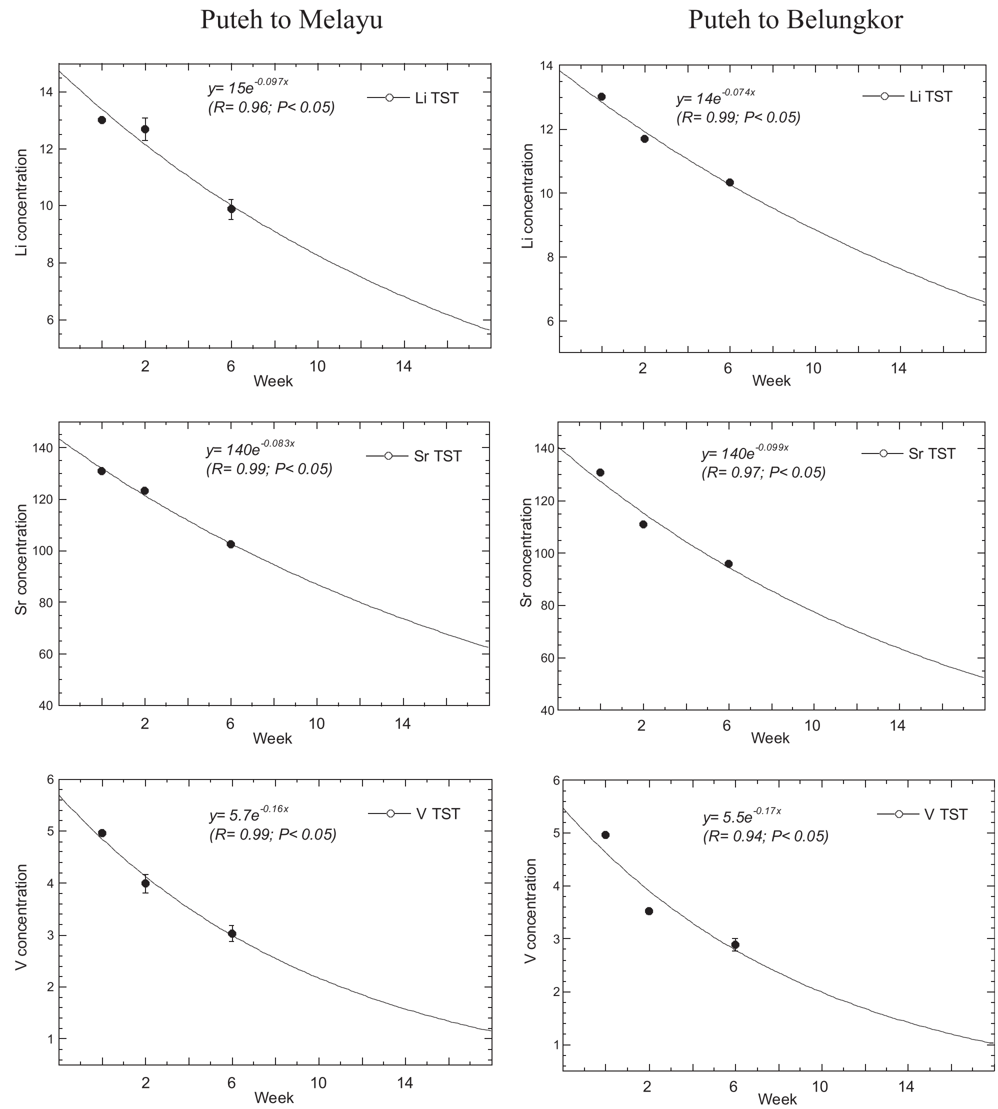


Fig. 2. Li, Sr, and V concentrations (mg/kg dry weight) in the mussels *Perna viridis* transplanted from Kg. Pasir Puteh to Kg. Sungai Melayu (Puteh to Melayu; left) and to Sungai Belungkor (Puteh to Belungkor; right). Curve fits are based on exponential equations.

µg/kg by week 6. The THQ for Li reduced from 0.71 to 0.57, and the EWI from 9.99 µg/kg to 7.94 µg/kg. Sr showed an initial EDI of 14.3 µg/kg, which decreased to 10.5 µg/kg by week 6. The THQ for Sr decreased from 0.024 to 0.018, and the EWI from 100 µg/kg to 73.6 µg/kg. V showed an initial EDI of 0.54 µg/kg, decreasing to 0.32 µg/kg by week 6, with the corresponding THQ decreasing from 0.11 to 0.06 and the EWI from 3.81 µg/kg to 2.22 µg/kg.

## Discussion

The following discussion will focus on conservation implications and strategies.

### Maintaining Seafood Safety and Public Health

Health risk evaluations using EDI, THQ, and EWI measures show the risks of eating infected *P. viridis*. Depuration lowered these hazards throughout the six-week transplanting period, as all metal EDI, THQ, and EWI levels decreased significantly. The SB site had the largest V decrease at 41.7% after six weeks. This significant decrease shows that chemical characteristics and metabolic processes help mussels remove V. This delayed Li depuration, especially in the first week of post-transplantation. Li may be more resistant to depuration because it binds better to mussel tissue matrices [9, 50]. These discrepancies emphasize the need for site-specific public health standards for seafood safety, including metal concentration monitoring and depuration periods. *P. viridis*-dependent communities need this, showing that sufficient depuration duration reduces metal poisoning health concerns [24, 19, 36].

Depuration improves sustainable fisheries management by reducing seafood safety and health concerns from contaminated bivalves. Public health programs should teach hygienic seafood procurement and purification. Seafood safety protects food security and human health. The selective feeding of *P. viridis* affects contamination and depuration. Seston concentration and phytoplankton diversity affect *P. viridis* selective feeding in Marudu Bay, Malaysia [40]. This eating habit affects mussel heavy metal and toxin concentrations early on.

Despite contamination difficulties, *P. viridis*' nutritional and antioxidant characteristics along India's southern coastline suggest it might be a food source. The mussel's oxyradical scavenging activity, key nonessential amino acid ratio, and n-3/n-6 polyunsaturated fatty acid ratio make it a potential nutraceutical [10]. Effective purification reduces health risks and preserves nourishment. *P. viridis* interacts with harmful algal toxins, including paralytic shellfish toxins, worsening health. Though depuration can lower it, mussels may collect toxins during harmful algal blooms. Environmental monitoring and control are necessary to reduce mussel toxin ingestion.

The mussel's physiological responses to stresses like thermal stress show that heat shock proteins strengthen the mussel. Physiological adaptations that increase thermotolerance and defend against *Vibrio* spp. may indirectly alter the mussel's ability to control pollutants. Post-depuration, EDI, THQ, and EWI levels dropped significantly, reducing the health concerns of eating *P. viridis* from polluted settings. With proper depuration and environmental control, mussels constitute a safe and profitable food source due to their selective feeding behavior, nutritional value, and physiological adaptations. Safe seafood like *P. viridis* requires environmental monitoring and sustainable farming.

## Pollution Monitoring for Conservation

The reduction in metal content helps measure coastal contamination over time. The differences in metal depuration between SB and KSM emphasize the need for site-specific environmental evaluations using biomonitors like *P. viridis* for metal pollution monitoring. Significant SB decrease rates suggest that water chemistry, pH, and temperature affect depuration efficiency and must be carefully assessed in environmental monitoring [28, 46].

To understand metal pollution in specific locations, the research recommends long-term monitoring and using multiple biomonitor species. Conservationists can improve environmental evaluations and pollution control using biomonitoring data and site-specific characteristics [12, 45]. This method helps us understand pollution patterns and identify rising dangers [14]. The site-specific metal depuration rates of *P. viridis* show how local environmental factors affect biomonitor performance. Studies show that water hardness and pH affect metal bioaccumulation [25]. The mussel's eating behavior shows that seston concentration and phytoplankton abundance affect contaminant absorption and removal [40].

Biomonitors for metal pollution monitoring are recommended by soil and honeybee product studies, highlighting site-specific evaluations. Enzyme-based soil quality indicators for metal(loid)-contaminated soils emphasize localized assessments of soil functions and metal sensitivity [5]. When tested in different environments, metal levels in honey and other apicultural products may be biomonitors [16]. The mussel's metal depuration rates were inconsistent, highlighting the need for specific environmental evaluations when using biomonitors to measure metal pollution. These evaluations must account for the many environmental factors affecting depuration processes, improving the accuracy of pollution monitoring.

## Protecting Marine Biodiversity with Depuration Kinetics

Li, Sr, and V pollutants in marine environments threaten biodiversity [29, 33]. These metals bioaccumulate in marine creatures, harming their health, reproduction, and survival. The mussel's metal removal rates change over time, demonstrating its adaptive response to pollution. In marine creatures, Li, Sr, and V bioaccumulation can cause genetic alterations, reproductive failure, and death [15, 26]. V and Sr disappeared quickly, whereas Li took longer, presumably due to its better tissue binding [44]. The mussel resists pollution by removing components. Some species are fragile and may not depurate well; thus, they must be protected [22, 34]. Conservation efforts should prioritize pollutant-sensitive species or ecosystems to safeguard keystone species and ecological equilibrium. Environmental health and food security depend on biodiversity and ecosystem services like fisheries and coastal protection.

Some marine creatures, especially bivalve mollusks, may absorb heavy metals and survive toxicity without cellular damage [22, 36]. Oysters bioaccumulate heavy metals through complex metal-enzyme interactions and cell membrane changes. Marine invertebrates, especially sessile species, can detect coastal heavy metal contamination. By employing these species as biomonitors, we can protect marine ecosystems and important services [22].

## Marine Preservation and Climate Change

Climate change's environmental and biological impacts and marine metal bioavailability are growing. According to Mejdoub et al. [28] and Yulianto et al. [50], climate change may affect coastal metal bioavailability and toxicity. Mussels and other marine creatures absorb more metal, increasing the risk of marine food web pollution. Environmental damage and seafood health concerns result from this contamination [15, 32]. V, Li, and Sr depuration kinetics were investigated to determine how marine species control metal concentrations in changing conditions. These findings are crucial for pollution and climate change adaptation measures. Climate refugia, which are expected to remain stable despite climate change, may protect vulnerable species from pollution and environmental stress, helping conserve marine biodiversity [42].

Mussels also metabolize metals. They are useful for environmental monitoring due to their metal toxicity tolerance and damage mitigation. In neighboring water columns, these organisms indicate pollution and environmental deterioration [36]. In recent decades, trace metals from natural and anthropogenic sources have polluted marine habitats, especially coastal areas. Due to harm to marine ecosystems and seafood consumers [31, 39].

### Ecosystem Management Guides Restoration.

Metal reduction rates of *P. viridis* can help coastal ecosystem restoration reduce metal pollution. SB had better depuration circumstances, demonstrating that water velocity, sediment concentration, and pH levels affect depuration. In comparison, KSM depuration may have been hindered by sediment contamination and lower water velocity [23, 49]. Restoration efforts must improve water quality, reduce industrial effluents, and restore damaged habitats to help marine creatures depurate naturally. Pollution-purifying mangrove and seagrass meadow restoration improves coastal ecosystems and biodiversity [8].

This study's findings can be used in ecosystem-based management techniques prioritizing ecosystem health above species. Site-specific depuration statistics emphasize protecting fragile ecosystems and targeting pollution hotspots. By identifying metal-polluted places and species, conservationists can reduce industrial runoff, rehabilitate ecosystems, and create marine protected zones [13]. This technique protects fisheries, nutrient cycling, and coastal protection by strengthening ecosystem resilience to pollution and climate change [57].

### Developing Coastal Ecosystem Resilience Conservation Policies

The mussel's metal removal capacity shows coastal ecosystems' resistance to pollution. The study also found that lower depuration rates make some ecosystems more susceptible to long-term ecological effects, including biodiversity loss and food chain changes. Conservation must emphasize long-term monitoring and specialized treatments for these ecosystems to survive pollution and climate change. Long-term conservation measures that minimize pollution and restore ecosystems strengthen ecosystems. Depuration research helps develop adaptive management solutions that adapt to changing environmental conditions and restore polluted ecosystems [58].

This research is crucial for conservation policymaking. Policymakers can use Li, Sr, and V depuration kinetics to set coastal water pollution limits. These guidelines may regulate the industry, reduce metal pollution, and protect seafood. Marine ecosystems might avoid heavy metal contamination with marine protection and pollution management. The findings may increase marine preservation legislation that addresses pollution and climate change for a comprehensive strategy [59].

### Public Engagement and Education Support Global Environmental Goals

The *Perna viridis* depuration kinetics study supports UNSDGs 14 and 15: life below water and ecosystem conservation. This study examines marine species' pollution reactions to protect biodiversity, coastal ecosystems, and marine resources. Reducing marine pollution is crucial for marine ecosystems and coastal food security [60]. Depuration studies can help the world work together on sustainability by identifying pollution management priorities. Educational programs concerning biomonitors in pollution assessment may help coastal communities restore ecosystems and lobby for cleaner water [61]. Conservation promotes sustainable environmental and public health efforts. Public participation is necessary for environmental success. Metal pollution in *P. viridis* poses health problems that conservationists might use to promote coastal environmental preservation. Knowledge-based public awareness campaigns can encourage customers to support sustainable seafood and reduce pollution [62].

## Conclusions

This study provides critical insights into the depuration kinetics of Li, Sr, and V in *P. viridis*, emphasizing its role in metal regulation within coastal ecosystems under the influence of climate change. The findings indicate that *P. viridis* effectively diminishes metal concentrations over time, with V showing the highest depuration rate, followed by Sr and Li. This suggests that *P. viridis* can serve as a reliable biomonitor for assessing metal contamination in marine environments. Moreover, the differential depuration rates highlight the species' capacity to eliminate hazardous metals, reinforcing its potential application in pollution mitigation strategies. The study also underscores that environmental factors such as water temperature, salinity, and pH significantly influence depuration efficacy, necessitating site-specific conservation approaches. The observed variability in metal elimination rates suggests that integrating depuration kinetics into adaptive management strategies could enhance ecosystem resilience and pollution control efforts. These findings are particularly relevant in light of accelerating climate change, which alters metal bioavailability and may exacerbate contamination risks. Overall, this research advances our understanding of how marine bivalves regulate metal accumulation and depuration, contributing to more informed conservation and pollution management strategies. By incorporating depuration kinetics into ecosystem-based management, policymakers and conservationists can improve marine biodiversity protection, seafood safety, and coastal ecosystem sustainability. Future studies should explore long-term depuration trends under varying climate scenarios to refine biomonitoring applications and strengthen coastal environmental policies.

## Author Contributions

Conceptualization, C.K.Y. and K.A.A.-M.; methodology and validation, C.K.Y. and K.A.A.-M.; formal analysis, C.K.Y.; investigation, C.K.Y.; resources, K.A.A.-M.; data curation, C.K.Y.; writing—original draft preparation, C.K.Y.; writing—review and editing, C.K.Y. and K.A.A.-M. All authors have read and agreed to the published version of the manuscript.

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## Conflicts of Interest

The authors declare no conflict of interest.

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