Journal of Fisheries
Volume 12 Issue 3 December 2024
Peer Reviewed | Open Access

eISSN 2311-3111
pISSN 2311-729X

DOI: https://doi.org/10.17017/j.fish.724

Original Article

Bioaccumulation of iron (Fe) and lead (Pb) in various body tissues of *Telescopium telescopium* in Peninsular Malaysia: Implications for biomonitoring and sustainability

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Manuscript history
Received 26 July 2024 | Accepted 9 September 2024 | Published online 11 September 2024

Citation
Yap CK, Al-Mutairi KA (2024) Bioaccumulation of iron (Fe) and lead (Pb) in various body tissues of *Telescopium telescopium* in Peninsular Malaysia: Implications for biomonitoring and sustainability. Journal of Fisheries 12(3): 123203. DOI: 10.17017/j.fish.724

Abstract
Heavy metal contamination in marine environments poses a significant threat to aquatic ecosystems and human health. This study investigates the accumulation patterns of iron (Fe) and lead (Pb) in seven different body tissues (cephalic tentacle [CT], digestive caecum, foot, gill, mantle, muscle, and remaining soft tissues) of *Telescopium telescopium* collected from Peninsular Malaysia. Using heat map visualization and correlation analysis, we examined the relationships between Fe and Pb levels in various body tissues. High positive correlations were observed in Fe levels between the foot- CT ($r = 0.86$), and Pb levels between the muscle and CT ($r = 0.95$). Factor analysis highlighted the complex interplay of environmental and physiological factors influencing metal accumulation. Our findings underscore the importance of considering multiple tissues for accurate biomonitoring of metal pollution in marine environments, particularly in the context of sustainability and, environment, social and governance considerations.

Keywords: bioaccumulation; biomonitoring; ESG; gastropods; heavy metals; sustainability

1 | INTRODUCTION

Marine pollution, particularly heavy metal contamination, poses a significant threat to aquatic ecosystems worldwide. Heavy metals such as iron (Fe) and lead (Pb) are prevalent pollutants that can accumulate in marine organisms, leading to toxic effects and disrupting ecological balance (Phillips and Rainbow 1993; Rainbow 2007). The bioaccumulation of these metals in marine species, especially mollusks, has been extensively studied due to their role as both bioindicators and integral components of marine food webs (Amiard *et al.* 2006; Mateo-Sagasta *et al.* 2017; Häder *et al.* 2020).

Iron (Fe) is an essential trace element necessary for various physiological functions in marine organisms, including oxygen transport, enzyme function, and electron transfer processes (Bryan 1976; Jeong *et al.* 2023). Despite its essentiality, excessive accumulation of Fe can lead to oxidative stress and cellular damage. In contrast, lead (Pb) is a non-essential and highly toxic metal with no known biological function (Phillips and Rainbow 1993; Goher *et al.* 2019). Pb exposure can result in severe toxic effects, including neurotoxicity, reproductive impairment, and disruption of metabolic processes (Wu *et al.* 2024).

Understanding the distribution and accumulation of these metals in different tissues of marine organisms is crucial for assessing environmental health and developing effective biomonitoring strategies (Ruelas-Inzunza *et al.* 2009; Cao *et al.* 2010). Mollusks, such as *Telescopium*

telescopium (Linnaeus, 1758), are often used in environmental monitoring studies due to their widespread distribution, sedentary nature, and ability to bioaccumulate heavy metals in their tissues (Yap *et al.* 2009, 2012, 2013; Yap and Noorhaidah 2011, 2012). These organisms are particularly useful for monitoring because they reflect the metal concentrations of their surrounding environment, providing valuable information about the levels and potential sources of contamination (Bryan 1976; Abdel Meguid *et al.* 2017; Amadi *et al.* 2022; Al-Alam *et al.* 2023).

The growing emphasis on sustainability, and environment, social and governance (ESG) considerations in environmental management necessitates a comprehensive understanding of how pollution impacts marine ecosystems (Ereira *et al.* 2015; Mateo-Sagasta *et al.* 2017; Häder *et al.* 2020; Jeong *et al.* 2023; Wu *et al.* 2024). Sustainable development goals highlight the importance of preserving aquatic biodiversity and ensuring the health of marine organisms, which are integral to the functioning of marine ecosystems and human livelihoods (Mateo-Sagasta *et al.* 2017). Effective biomonitoring using species like *T. telescopium* can provide critical data to support these goals and inform policy decisions aimed at mitigating pollution and promoting sustainable practices (Amiard *et al.* 2006; Jeong *et al.* 2023).

The specific objectives of the present study are to (i) investigate the accumulation patterns of iron (Fe) and lead (Pb) in different tissues of *T. telescopium* collected from Peninsular Malaysia; (ii) analyze the relationships between Fe and Pb levels in various tissues using heat map visualization and correlation analysis; (iii) identify tissue-specific correlations, particularly high positive correlations between Fe levels in the foot and cephalic tentacle (CT), and Pb levels between the muscle and CT; (iv) perform factor analysis to understand the environmental and physiological factors influencing metal accumulation in the organism; and (v) highlight the importance of multi-tissue biomonitoring in the context of metal pollution and its relevance to sustainability and ESG considerations.

2 | METHODOLOGY

2.1 Study area and sample collection

Samples of *T. telescopium* were collected from 18 geographical sampling sites of intertidal mudflats along the coast of Peninsular Malaysia, between 2006 and 2008 (Figure 1; Table S1). The data of Pb and Fe in the different tissues of *T. telescospium* were cited from Yap and Noorhaidah (2011) and Yap (2013), respectively. However, the above two papers did not focus on the objectives of the present study.

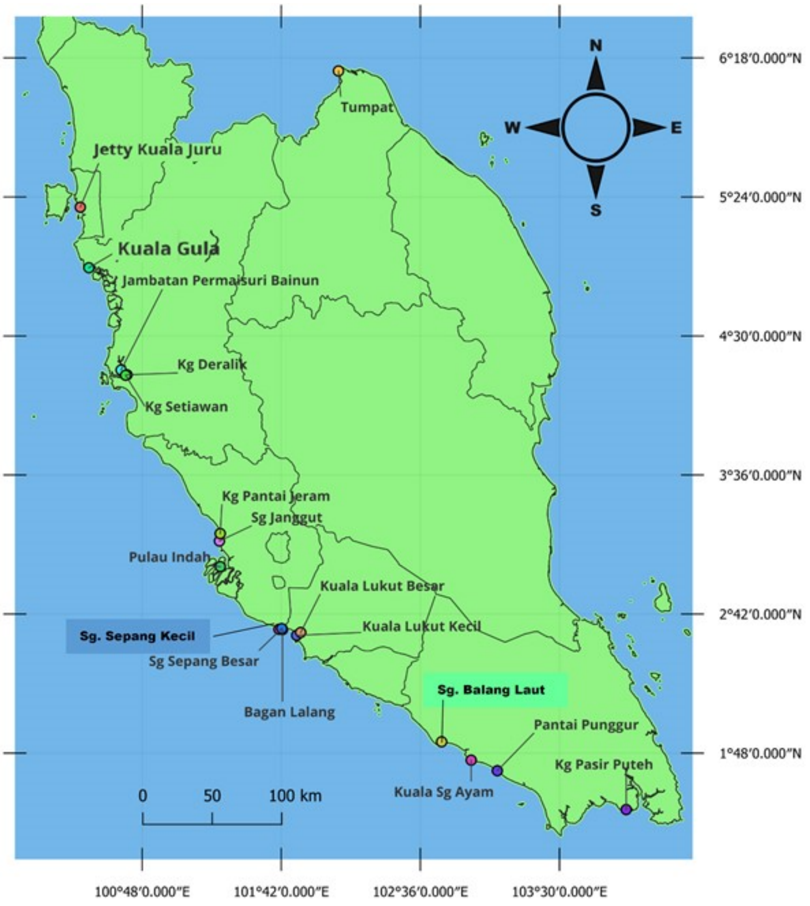

FIGURE 1 Sampling map for *Telescopium telescopium* in Peninsular Malaysia.

The sampling sites were chosen based on their varying degrees of anthropogenic impact, including industrial discharges and agricultural runoff. About 20 specimens were collected from each sampling site, ensuring a representative sample for analysis (Table S2) (Yap and Noorhaidah 2011; Yap 2013).

2.2 Metal analysis

After deshelling, the soft tissues were dissected and separated into cephalic tentacle (CT), digestive caecum (DC), foot, gill, mantle, muscle, and remaining soft tissues (REM). Each tissue type was weighed, homogenized, and digested using nitric acid (HNO_3) only, following the methods described by Yap *et al.* (2002). Approximately 0.5 g of each dried tissue sample was placed into a digestion flask, and 10 ml of concentrated HNO_3 was added. The mixture was firstly heated at 40°C for one hour, and then at 140°C for three hours until the solution became clear. The digested samples were diluted to 40 ml with deionized water and filtered. Using a Perkin-Elmer Model AAnalyst 800 air-acetylene flame Atomic Absorption Spectrophotometer (Perkin Elmer LLC., Shelton, CT, USA), the prepared samples were determined for Fe and Pb. Calibration standards and quality control samples were included in each analytical batch to ensure accuracy and precision. The quality of the methods used were checked with the Certified Reference Materials using Dogfish Liver (DOLT-3, National Research Council Canada) and the recoveries of Fe and Pb are acceptable between 80 and 115% (Yap and Noorhaidah 2011; Yap 2013).

2.3 Data analysis

In this study, the statistical analysis was conducted to assess the differences in Fe and Pb concentrations across seven parts of *T. telescopium* collected from 18 sampling sites. A one-way ANOVA was used to compare the mean concentrations of Fe and Pb between the seven tissue types (CT, DC, foot, gill, mantle, muscle, and REM). ANOVA tests whether there are statistically significant differences between the means of multiple groups. For this analysis, the tissue type was treated as the independent variable, and metal concentration (Fe or Pb) was the dependent variable. The assumption of homogeneity of variances was tested using Levene's test, ensuring that the variances between groups were not significantly different. For post-hoc Analysis, when the ANOVA indicated significant differences ($p < 0.05$), a post-hoc test was conducted to determine which tissue types differed from each other.

Overall statistical analyses, including correlation analysis, factor analysis, and heat map generation, were performed using NCSS software (version 2024). These analyses were used to examine the relationships between metal concentrations in different tissues and to identify common factors influencing metal accumulation.

The use of heat maps and correlation analyses in environmental studies allows researchers to visualize and understand the complex relationships between metal concentrations in different tissues. These tools help identify patterns of co-accumulation, competitive uptake, and independent regulation of metals, offering insights into the physiological and environmental factors influencing metal distribution (Pleil *et al.* 2011). By examining the correlations between Fe and Pb levels in various tissues of *T. telescopium*, this study aims to elucidate the underlying mechanisms of metal bioaccumulation and their implications for biomonitoring (Amiard-Triquet 2019).

For correlation analysis, we utilized Pearson's correlation coefficient to examine the strength and direction of the linear relationships between variables, providing insights into the associations between the traits and demographic factors. Additionally, for factor analysis, we employed principal component analysis (PCA) to reduce the dimensionality of the data and identify underlying patterns. Factors were extracted based on eigenvalues greater than 1, and varimax rotation was applied to enhance interpretability. The interpretation of factor loadings followed standard thresholds in which loadings above 0.4 were considered significant at $p < 0.05$.

3 | RESULTS AND DISCUSSION

3.1 Distribution and bioaccumulation of Fe and Pb

The analysis of Fe concentrations across the different tissues of *T. telescopium* revealed significant variability (Table 1). The highest mean Fe concentration was observed in the Fe-DC at 1510 mg kg^{-1}, which was significantly ($p < 0.05$) higher than the concentrations in all other tissues. The Fe-CT, Fe-Foot, Fe-Mantle, and Fe-Muscle exhibited relatively low and similar Fe concentrations, ranging between 118 and 186 mg kg^{-1}, with no statistically significant ($p > 0.05$) differences among them. The Fe-Gill and Fe-REM demonstrated intermediate Fe concentrations, with the gill reaching 968 mg kg^{-1} and the REM showing 667 mg kg^{-1}. Both were statistically distinct ($p < 0.05$) from the lower-concentration body tissues, and were significantly ($p < 0.05$) higher than the CT, foot, and muscle. These results suggest that the DC, gill, and REM are the primary sites of Fe bioaccumulation in *T. telescopium*, with the digestive caecum showing the highest capacity for Fe storage. This pattern of bioaccumulation likely reflects differences in the physiological roles of these tissues, with the DC being responsible for nutrient absorption and detoxification, which could account for its higher Fe content. The gill, as a respiratory organ, may also be exposed to higher levels of Fe from the surrounding environment, while the REM may serve as a secondary site of Fe storage. In contrast, tissues such as the foot and muscle, which are less involved in detoxification processes, had lower concentrations of Fe, indicating that these tissues are not primary sites of metal accumulation.

TABLE 1 Overall statistics of iron (Fe) and lead (Pb) concentrations (mg kg^{-1} dry weight) between seven parts of *Telescopium telescopium* collected from 18 sampling sites in the mangrove mudflats of Peninsular Malaysia. *n* = 18.

Variables	Mean	SD
Fe-CT	118^{a}	52.8
Fe-DC	1510^{b}	502
Fe-Foot	119^{a}	53.6
Fe-Gill	968^{c}	717
Fe-Mantle	186a	113
Fe-Muscle	131^{a}	82.5
Fe-REM	667^{c}	506
Pb-CT	6.55^{a}	5.42
Pb-DC	17.4^{b}	13.8
Pb-Foot	4.91^{a}	4.49
Pb-Gill	20.7^{c}	19.8
Pb-Mantle	5.51^{a}	4.25
Pb-Muscle	5.68^{a}	4.20
Pb-REM	15.9^{b}	6.30

Note: CT, cephalic tentacle; DC, digestive caecum; REM, remaining soft tissues; SD, standard deviation. Superscript letters (e.g. a, b, c) were assigned to mean values in table to represent statistically distinct groups based on the Tukey HSD posy-hoc test results ($p < 0.05$).

The analysis of Pb concentrations in the tissues of *T. telescopium* also revealed significant differences between tissue types (Table 1). The Pb-Gill exhibited the highest Pb concentration at 20.74 mg kg^{-1}, significantly exceeding the levels observed in most other tissues. The Pb-DC and Pb-REM also showed elevated Pb concentrations, with mean values of 17.4 and 15.9 mg kg^{-1}, respectively, both significantly ($p < 0.05$) higher than the Pb-CT, Pb-Foot, Pb-Mantle, and Pb-Muscle. The CT, foot, mantle, and muscle tissues exhibited similarly low Pb concentrations, ranging from 4.91 to 6.55 mg kg^{-1}, with no significant differences between them ($p > 0.05$).

The results indicate that the DC, gill, and REM are the primary sites of Fe bioaccumulation in *T. telescopium*, with the digestive caecum showing the highest Fe storage capacity. This pattern likely reflects the distinct physiological roles of these tissues, as the DC is involved in nutrient absorption and detoxification, which could explain its higher Fe content. Similar findings have been reported in other species, such as *Mytilus galloprovincialis* and *Callista chione*, where digestive organs and gills are the main sites of metal accumulation due to their roles in nutrient absorption and filtration (Chalkiadaki *et al.* 2014).

In *Perna viridis*, the digestive gland and mantle also exhibited significant metal accumulation, likely due to detoxification processes that are enhanced during heavy metal exposure (Prakash and Rao 1995). Likewise, in *Littorina littorea*, high cadmium accumulation was observed in the gills and kidneys, which are involved in detoxification and respiration (Bebianno and Langston 1998). In *Lymnaea stagnalis*, Pb accumulation was prominent in the gills and visceral hump, suggesting that respiratory and digestive organs are consistent sites for metal accumulation across various species (Pyatt *et al.* 1997).

Further studies on land snails such as *Helix vladika* and *Helix secernenda* revealed that the hepatopancreas and digestive tract are critical in accumulating toxic metals like cadmium, reinforcing the role of detoxification organs in metal bioaccumulation (Vukašinović-Pešić *et al.* 2020). Similarly, research on *Helix pomatia* from polluted environments showed that the digestive gland accumulated higher concentrations of heavy metals compared to locomotory tissues like the foot, supporting the idea that detoxification organs are the primary sites for metal sequestration (Ciric *et al.* 2018). Studies on *Viviparus mamillatus* also revealed that non-detoxifying tissues, such as the head and its associated structures, can act as secondary bioaccumulation sites for metals like Fe and cadmium (Vukašinović-Pešić *et al.* 2017).

When it comes to lead, the gills of *T. telescopium* are the primary site of accumulation, likely due to their role in respiration and filtration, where they are directly exposed to waterborne Pb particles. This pattern mirrors findings in *Lymnaea stagnalis*, where the gills showed significant Pb accumulation (Pyatt *et al.* 1997). The DC and REM also act as important reservoirs for Pb, likely due to their roles in digestion and detoxification, similar to observations in *Littorina littorea*, where the kidneys and gills exhibited high Pb and cadmium accumulation (Bebianno and Langston 1998). In contrast, lower Pb concentrations were found in connective tissues, foot, mantle, and muscle, suggesting that these tissues have a limited capacity for Pb bioaccumulation. This is consistent with findings in *H. pomatia* and *H. vladika*, where detoxifying organs such as the digestive gland accumulated more metals than tissues involved in movement and structure (Ciric *et al.* 2018; Vukašinović-Pešić *et al.* 2020).

These results highlight that metal bioaccumulation is closely tied to the physiological functions of specific tissues. Organs involved in detoxification, respiration, and nutrient absorption tend to accumulate more metals than structural or locomotory tissues. This pattern of organ-specific bioaccumulation, observed across multiple species, provides key insights into the mechanisms of metal detoxification and storage, which are crucial for biomonitoring and environmental risk assessments.

The concentrations of Fe and Pb varied significantly across different tissues of *T. telescopium*. The gill and DC exhibited the highest levels of Fe, suggesting that these tissues might be primary sites for iron uptake due to their extensive surface area and direct contact with the surrounding environment (Goher *et al.* 2019). Elevated levels of Pb were found in the gill and DC, indicating that these tissues might play significant roles in lead metabolism and detoxification (Jeong *et al.* 2023; Wu *et al.* 2024). These findings are consistent with previous studies that highlight the varying capacities of different mollusk tissues to accumulate heavy metals (Phillips and Rainbow 1993; Amiard *et al.* 2006).

Further analysis revealed that the average concentrations of Fe and Pb across all tissues were within the permissible limits for marine organisms, as set by international standards. However, localized hotspots of contamination were identified, indicating potential sources of anthropogenic pollution. These hotspots were primarily found in areas with high industrial activity and agricultural runoff, underscoring the impact of human activities on marine ecosystems (Cao *et al.* 2010; Ruelas-Inzunza *et al.* 2009). The variability in metal concentrations across different tissues highlights the importance of using multiple tissues for comprehensive biomonitoring (Yap *et al.* 2012, 2013; Yap and Noorhaidah 2011, 2012).

The differential accumulation of metals in various tissues suggests that each tissue may have distinct physiological roles and metal handling mechanisms. For example, the high Fe concentrations in the gill and DC might be attributed to these tissues' roles in respiration and filtration, exposing them directly to dissolved metals in the water (Bryan 1976). In contrast, the DC's role in nutrient absorption could explain its higher Pb levels, reflecting the metal's dietary intake and subsequent storage or detoxification (Amiard-Triquet 2019; Jeong *et al.* 2023). Furthermore, the muscle tissue, being more involved in locomotion and movement, may exhibit lower levels of both Fe and Pb due to its less direct exposure to environmental sources of metals.

3.2 Correlation patterns

High positive correlations were observed between Fe levels in the foot and CT (r = 0.86), indicating similar uptake mechanisms or exposure histories for these tissues (Figure 2; Table 2). This strong correlation suggests that both tissues are similarly influenced by environmental iron concentrations, likely due to their roles in respiration and filtration, which expose them directly to waterborne metals (Phillips and Rainbow 1993; Rainbow 2007). The significant positive correlations between Fe levels in the gill and REM (r = 0.41) further support the idea that the gill plays a central role in the initial uptake and distribution of iron within the organism (Jeong *et al.* 2023; Wu *et al.* 2024). Strong positive correlation (r = 0.95) is also found in the Pb levels between muscle and CT.

Negative correlations were observed between Pb levels in the gill and CT (r = –0.05), suggesting competitive uptake mechanisms or differential metal binding capacities. This competitive interaction indicates that higher lead concentrations in the CT might limit the metal's availability for accumulation in the muscle (Rainbow 2007; Goher *et al.* 2019). Such competitive interactions are crucial for understanding the bioaccumulation processes and potential toxicity in different tissues, as they highlight the complexity of metal distribution within marine organisms.

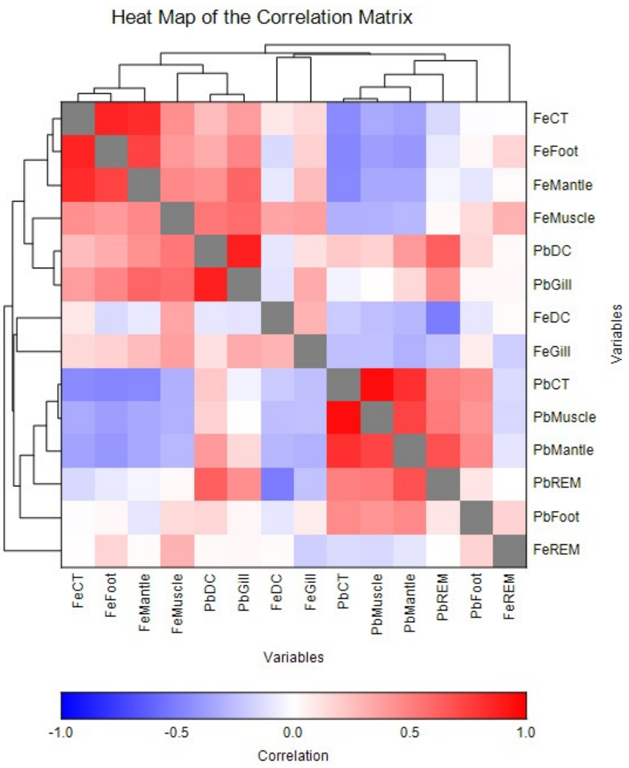

FIGURE 2 A heat map based on correlation coefficients of Fe and Pb levels between the seven parts of *Telescopium telescopium* collected from 18 sampling sites in Peninsular Malaysia. n = 18. Note: CT, cephalic tentacle; DC, digestive caecum; REM, remaining soft tissues.

Additionally, the negative correlation between Fe levels in the foot and Pb levels in the muscle (r = –0.38) supports the notion of competitive uptake. The DC, involved in nutrient absorption and processing, might compete with the muscle for metal binding sites, leading to differential accumulation patterns (Phillips and Rainbow 1993). Understanding these interactions is essential for interpreting the ecological impacts of metal pollution on marine organisms and for developing effective biomonitoring strategies (Amiard *et al.* 2006; Amiard-Triquet 2019).

3.3 Hierarchical clustering patterns

Figures 3 and 4 show the hierarchical clustering patterns of the concentrations of Fe and Pb, respectively, in the eight body parts of *T. telescopium* collected from 18 sampling sites of Peninsular Malaysia. The use of cluster analysis for the biomonitoring of heavy metal pollution has been suggested (Simeonova *et al.* 2013).

TABLE 2 Correlation coefficients of iron (Fe) and lead (Pb) levels between seven parts of *Telescopium telescopium* collected from 18 sampling sites in the mangrove mudflats of Peninsular Malaysia.

Variables	Fe-CT	Fe-DC	Fe-Foot	Fe-Gill	Fe-Mantle	Fe-Muscle	Fe-REM	Pb-CT	Pb-DC	Pb-Foot	Pb-Gill	Pb-Mantle	Pb-Muscle	Pb-REM
Fe-CT	1.00	0.09	0.86*	0.14	0.83*	0.43	0.00	-0.46	0.26	-0.01	0.38	-0.37	-0.34	-0.15
Fe-DC		1.00	-0.15	0.29	-0.08	0.35	0.01	-0.20	-0.09	-0.10	-0.11	-0.28	-0.25	-0.51
Fe-Foot			1.00	0.18	0.74	0.40	0.17	-0.48	0.32	0.03	0.47	-0.41	-0.38	-0.09
Fe-Gill				1.00	0.26	0.37	-0.19	-0.25	0.12	0.07	0.33	-0.31	-0.24	-0.24
Fe-Mantle					1.00	0.47	0.02	-0.47	0.43	-0.10	0.60	-0.34	-0.34	-0.04
Fe-Muscle						1.00	0.30	-0.31	0.53	0.14	0.57*	-0.28	-0.31	0.02
Fe-REM							1.00	-0.14	0.02	0.17	0.03	-0.10	-0.15	0.00
Pb-CT								1.00	0.21	0.46	-0.05	0.81*	0.95*	0.50
Pb-DC									1.00	0.16	0.88*	0.39	0.18	0.63*
Pb-Foot										1.00	0.03	0.46	0.41	0.10
Pb-Gill											1.00	0.14	0.01	0.44
Pb-Mantle												1.00	0.73*	0.68*
Pb-Muscle													1.00	0.52
Pb-REM														1.00

Note: CT, cephalic tentacle; DC, digestive caecum; REM, remaining soft tissues; Values with * is significant at $p < 0.05$.

The hierarchical clustering analysis, based on Fe concentrations in *T. telescopium* from 18 sampling sites, reveals distinct spatial patterns across Peninsular Malaysia (Figure 3). Four major clusters were identified, with sites grouped according to their similarity in Fe accumulation. The blue cluster includes sites such as KDeralik, SepangB, KS Ayam, SepangK, KLukutB, and KLukutK, which displayed relatively similar Fe concentrations. SBLaut formed a separate cluster, indicating a unique Fe accumulation pattern at this location. Meanwhile, the green cluster, comprising Tumpat, KGula, PIndah, SJanggut, KPJeram, KSetiawan, and BLalang, represents the largest group with closely related Fe concentrations. Lastly, the red cluster, consisting of JP Bainun, KPPuteh, and KJuru, indicates sites with different Fe bioaccumulation levels compared to other regions.

The clustering of sites highlights potential environmental and anthropogenic factors contributing to Fe bioaccumulation in *T. telescopium*. Sites in the blue cluster may be located in areas affected by similar sources of Fe contamination, such as industrial discharges or agricultural runoff. The clustering of SBLaut into its own group suggests that it may experience distinct environmental conditions, potentially linked to localized industrial activities or natural variations in sediment composition. The large green cluster, encompassing multiple sites, could be indicative of shared regional influences, such as riverine inputs or sediment resuspension that contribute to similar Fe bioaccumulation patterns across these locations (Ciric *et al.* 2018; Carbone and Faggio 2019; Baroudi *et al.* 2020).

The red cluster, comprising JP Bainun, KPPuteh, and KJuru, stands out due to the noticeable differences in Fe concentrations compared to the other sites. These sites might be subject to varying levels of pollution, geographic isolation, or distinct ecological factors that influence Fe accumulation in *T. telescopium*. This variation underscores the importance of using *T. telescopium*, to identify and assess regional differences in metal contamination. The observed clustering patterns provide valuable insights into Fe pollution sources and can help inform future environmental monitoring and remediation strategies in Peninsular Malaysia (Dhiman and Pant 2021; Ibrahim *et al.* 2023).

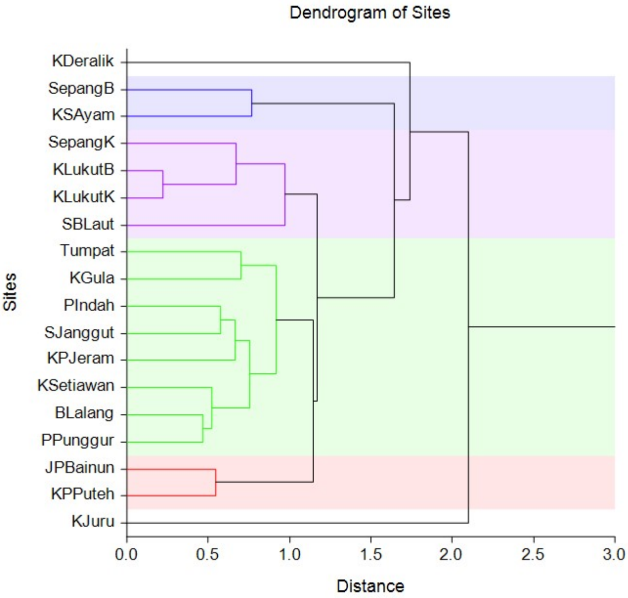

FIGURE 3 Hierarchical clustering patterns (Euclidean Distance method; clustering method group average unweighted pair-group) of the concentrations (mg kg^{-1} dry weight) of iron (Fe) in the eight body parts of *Telescopium telescopium* collected from 18 sampling sites of Peninsular Malaysia. *n* = 18.

Figure 4 illustrates the hierarchical clustering of 18 sampling sites across Peninsular Malaysia based on the concentrations of Pb in the eight body parts of *T. telescopium*. The analysis was conducted using the Euclidean distance method with the group average unweighted pair-group clustering approach. The dendrogram categorizes the sites into two primary clusters. The first cluster, represented in blue, includes sites such as KSAyam, KSetiawan, PIndah, KPJeram, KGula, SepangK, and SepangB, all exhibiting similar Pb concentrations. The second, larger cluster, shaded in red, includes sites such as KDeralik, PPunggur, JP Bainun, SBLaut, Tumpat, and KJuru, reflecting distinct patterns of Pb bioaccumulation.

The clustering of sites based on Pb concentrations reveals regional differences in bioaccumulation patterns, suggesting potential sources of Pb contamination or varying environmental conditions. The blue cluster, which groups sites such as KSAyam, KGula, and PIndah, indicates areas with similar Pb contamination levels, potentially due to shared environmental factors like proximity to industrial activities or transportation routes. The red cluster, containing sites such as KDeralik, PPunggur, and JP Bainun, suggests regions with different Pb accumulation dynamics, possibly reflecting more severe pollution or different local sources of contamination. The clustering pattern further emphasizes the role of *T. telescopium* as a biomonitor for metal contamination in diverse environments (Mleiki *et al.* 2017; Mahmutovic *et al.* 2018; Qaysi *et al.* 2022).

The significant distinction between the blue and red clusters highlights the variability in Pb bioavailability across the different sites. The sites in the red cluster, which generally demonstrate higher dissimilarity in Pb concentrations, may be influenced by localized factors such as industrial discharges or specific land-use practices. On the other hand, the relative homogeneity of the blue cluster suggests that these regions experience more uniform environmental conditions, possibly due to shared geological or hydrological characteristics. This analysis is crucial for identifying hotspot areas of lead contamination and developing targeted management strategies for mitigating environmental risks (Santos *et al.* 2009; Wu *et al.* 2017, 2023).

3.4 Factor analysis

Factor analysis identified four main factors influencing metal accumulation in *T. telescopium* (Table 3). Factor 1 included Fe levels in the foot and central tissues and Pb levels in the muscle, suggesting similar environmental exposures or physiological processes. This finding aligns with previous research indicating that certain tissues can share common pathways for metal uptake and storage due to their physiological functions and exposure histories (Phillips and Rainbow 1993; Rainbow 2007; Ereira *et al.* 2015).

Factor 2 encompassed Pb levels in the REM and DC, indicating shared physiological pathways for Pb metabolism. The DC's role in nutrient absorption and processing could explain its involvement in Pb uptake, while the REM, including various internal organs, might reflect the overall metal load experienced by the organism (Jeong *et al.* 2023; Wu *et al.* 2024). Understanding these factor structures is crucial for developing targeted biomonitoring strategies that consider the specific roles and exposure histories of different tissues.

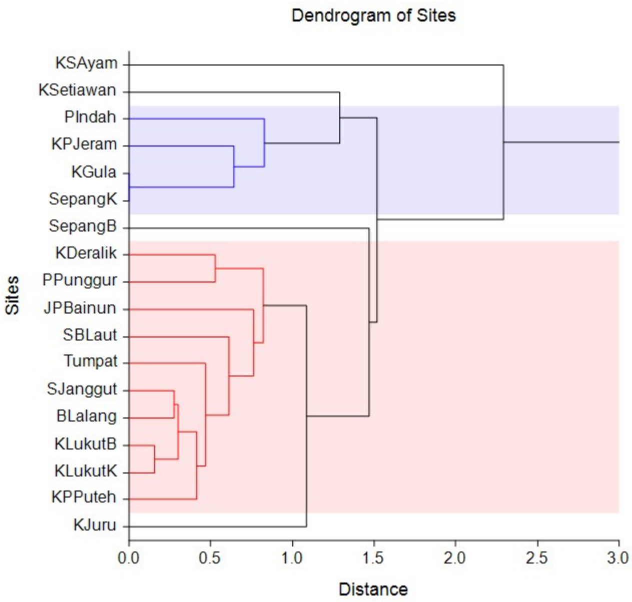

FIGURE 4 Hierarchical clustering patterns (Euclidean distance method; clustering method group average unweighted pair-group) of the concentrations (mg kg^{-1} dry weight) of lead (Pb) in the eight body parts of *Telescopium telescopium* collected from 18 sampling sites of Peninsular Malaysia. *n* = 18.

Factor 3 highlighted the independent regulation of Fe levels in the mantle and foot, suggesting that these tissues might have distinct metal handling mechanisms or exposure routes. This finding is consistent with the idea that different tissues can exhibit varied accumulation patterns depending on their physiological roles and environmental interactions (Bryan 1976; Amiard-Triquet 2019). Such independent variation in metal levels across different tissues underscores the complexity of bioaccumulation processes and the importance of considering multiple tissues in environmental monitoring (Mateo-Sagasta *et al.* 2017; Häder *et al.* 2020).

3.5 Essential iron (Fe) vs. non-essential lead (Pb) accumulation

The bioaccumulation patterns of Fe and Pb in *T. telescopium* reveal important insights into the physiological roles and environmental interactions of these metals. Iron, an essential trace element, is critical for various biological functions, including oxygen transport and enzyme activity (Bryan 1976; Jeong *et al.* 2023). The high concentrations of Fe in the gill and DC suggest these tissues play significant roles in iron metabolism, likely due to their direct exposure to the environment and their involvement in respiration and nutrient absorption (Amiard-Triquet 2019).

TABLE 3 Factor Structure Summary after varimax rotation based on iron (Fe) and lead (Pb) levels between seven parts of *Telescopium telescopium* collected from 18 sampling sites in the mangrove mudflats of Peninsular Malaysia. Values in bold are the tissues selected using the factor analysis.

Metal-Tissue	Factor 1	Factor 2	Factor 3	Factor 4
Fe-CT	**0.27**	**0.25**	0.00	**0.21**
Fe-DC	0.02	0.02	**0.60**	0.00
Fe-Foot	**0.28**	**0.29**	0.03	**0.25**
Fe-Gill	0.04	0.06	**0.25**	0.00
Fe-Mantle	**0.26**	**0.45**	0.01	0.07
Fe-Muscle	0.02	**0.33**	**0.28**	0.09
Fe-REM	0.00	0.00	0.00	0.15
Pb-CT	**0.86**	0.00	0.03	0.00
Pb-DC	0.09	**0.82**	0.00	0.00
Pb-Foot	**0.26**	0.00	0.00	**0.31**
Pb-Gill	0.00	**0.88**	0.01	0.00
Pb-Mantle	**0.76**	0.02	0.07	0.00
Pb-Muscle	**0.69**	0.00	0.06	0.00
Pb-REM	**0.31**	**0.25**	0.16	0.05

Note: CT, cephalic tentacle; DC, digestive caecum; REM, remaining soft tissues.

In contrast, Pb, a non-essential and highly toxic metal, was found in significant concentrations in the same tissues, indicating that these organs are also primary sites for Pb uptake and detoxification (Phillips and Rainbow 1993; Goher *et al.* 2019). The elevated Pb levels in the gill and DC reflect the organism's exposure to polluted environments and its attempt to sequester and detoxify this harmful metal. The negative impacts of Pb accumulation, including potential oxidative stress and disruption of metabolic processes, highlight the environmental risks associated with heavy metal pollution (Wu *et al.* 2024).

The contrasting roles of Fe and Pb in marine organisms emphasize the importance of understanding both essential and non-essential metal accumulation. While Fe is necessary for biological function, its overaccumulation can be detrimental, similar to the inherently toxic nature of Pb. This dual perspective is crucial for developing comprehensive biomonitoring strategies that address the ecological and health impacts of both types of metals (Phillips and Rainbow 1993; Mateo-Sagasta *et al.* 2017; Häder *et al.* 2020).

The bioaccumulation of Fe and Pb in various tissues of *T. telescopium* also provides a model for studying metal homeostasis and toxicity in other marine organisms. Understanding the mechanisms underlying metal uptake, storage, and detoxification can inform broader ecological and environmental health assessments (Jeong *et al.* 2023). Moreover, these findings contribute to the development of targeted mitigation strategies to reduce metal pollution and its associated risks to marine ecosystems and human health (Amiard *et al.* 2006).

The patterns of metal accumulation observed in this study underscore the importance of multi-tissue analysis in environmental monitoring. By examining the concentrations of essential and non-essential metals in different tissues, researchers can gain a more comprehensive understanding of the bioaccumulation processes and their implications for marine health and pollution management (Amiard-Triquet 2019).

3.6 Correlation patterns and environmental implications

The observed positive correlations between Fe levels in the foot and CT (r = 0.86) suggest similar uptake and storage mechanisms for this essential metal in these tissues. This pattern indicates that both tissues are influenced by environmental Fe concentrations and highlights their roles in maintaining iron homeostasis within the organism (Rainbow 2007). The significant positive correlations between Fe levels in the gill and REM (r = 0.41) further underscore the gill's central role in iron uptake and distribution, reflecting its direct interaction with the surrounding environment (Phillips and Rainbow 1993).

Conversely, the negative correlations between Pb levels in certain tissue pairs, such as the gill and CT (r = –0.05), indicate competitive uptake or differential metal binding capacities. This competitive interaction suggests that higher Pb concentrations in the CT limit its availability for accumulation in the muscle, highlighting the strategies of organism for managing toxic metal exposure (Goher *et al.* 2019). Understanding these competitive interactions is essential for interpreting the ecological impacts of metal pollution and developing effective biomonitoring protocols (Amiard *et al.* 2006; Cao *et al.* 2010).

The negative correlation between Fe levels in the foot and Pb levels in the muscle (r = –0.38) supports the notion of competitive uptake, indicating that these tissues may prioritize different metals based on their physiological roles and exposure histories (Phillips and Rainbow 1993). Such insights are crucial for understanding the complex dynamics of metal accumulation and their implications for marine health and pollution management.

The competitive interactions observed in the correlation patterns between Fe and Pb highlight the complexity of metal bioaccumulation in marine organisms. These interactions are influenced by various factors, including metal availability, tissue-specific binding affinities, and the physiological roles of different tissues (Phillips and Rainbow 1993). For instance, the DC, being a primary site for nutrient absorption, might prioritize the uptake of essential metals like Fe over non-essential and toxic metals like Pb (Jeong *et al.* 2023). This prioritization can lead to differential accumulation patterns, as reflected in the negative correlations between Fe and Pb levels in certain tissues.

Understanding these complex interactions is crucial for developing effective biomonitoring strategies. By identifying tissues that exhibit distinct metal accumulation patterns, researchers can better assess the overall metal load and its potential impacts on marine organisms. This knowledge can also inform the development of targeted mitigation strategies to reduce metal pollution and its associated risks (Cao *et al.* 2010). For example, areas identified as hotspots for Pb contamination can be prioritized for pollution control measures, while monitoring efforts can focus on tissues that are primary sites for Fe accumulation to assess the overall health of marine ecosystems (Mateo-Sagasta *et al.* 2017).

3.7 Independent variation and physiological mechanisms

The independent regulation of Fe levels in the mantle and foot, as suggested by Factor 3, indicates that these tissues might have distinct metal handling mechanisms or exposure routes. This finding aligns with the idea that different tissues can exhibit varied accumulation patterns based on their physiological roles and environmental interactions (Bryan 1976; Amiard-Triquet 2019). For instance, the mantle, being involved in shell formation and protection, might regulate Fe levels differently compared to the foot, which is primarily involved in locomotion and substrate interaction (Wu *et al.* 2024).

Such independent variation in metal levels across different tissues highlights the complexity of bioaccumulation processes and the importance of considering multiple tissues in environmental monitoring. By examining the specific roles and exposure histories of different tissues, researchers can gain a more comprehensive understanding of metal accumulation and its implications for marine health (Mateo-Sagasta et al., 2017; Häder et al., 2020). This approach can also help identify tissues that are particularly sensitive to metal exposure, providing valuable insights into the mechanisms of metal toxicity and resistance (Jeong et al., 2023).

The study of independent variation patterns in metal accumulation can also inform broader ecological and conservation strategies. By identifying tissues that independently regulate metal levels, researchers can develop more accurate models for predicting the impacts of metal pollution on marine organisms and ecosystems (Amiard-Triquet 2019). These models can then be used to guide conservation efforts and policy decisions aimed at protecting marine biodiversity and ensuring the sustainability of marine resources (Mateo-Sagasta *et al.* 2017; Häder *et al.* 2020).

Furthermore, understanding the independent regulation of metals in different tissues can contribute to the development of targeted biomonitoring programs that focus on specific tissues as indicators of environmental health. This targeted approach can enhance the efficiency and effectiveness of biomonitoring efforts, providing more accurate assessments of metal pollution and its impacts on marine ecosystems (Amiard *et al.* 2006).

In general, the independent variation in Fe and Pb levels across different tissues of *T. telescopium* underscores the complexity of metal bioaccumulation processes and the importance of multi-tissue analysis in environmental monitoring. By considering the specific roles and exposure histories of different tissues, researchers can gain a more comprehensive understanding of metal accumulation and its implications for marine health and pollution management.

3.8. Implications for sustainability and UN SDGs

The bioaccumulation patterns of Fe and Pb in *T. telescopium* have significant implications for sustainability and the United Nations Sustainable Development Goals (UN SDGs). The ability of *T. telescopium* to accumulate both essential and non-essential metals makes it a valuable biomonitor for assessing environmental health and pollution levels. The high levels of Fe in certain tissues, such as the gill and DC, reflect the organism's ability to manage essential metals critical for physiological processes (Jeong *et al.* 2023). However, the presence of elevated Pb levels in the same tissues highlights the persistent threat of anthropogenic pollution and its detrimental effects on marine life (Wu *et al.* 2024).

The accumulation of Pb, a non-essential and toxic metal, underscores the need for targeted interventions to reduce industrial discharges and agricultural runoff that contribute to heavy metal pollution (Ruelas-Inzunza *et al.* 2009). Achieving the UN SDGs, particularly Goal 14 (Life below water), requires comprehensive monitoring and management strategies that address the sources and impacts of metal pollution in marine environments (Mateo-Sagasta *et al.* 2017). Effective biomonitoring using species like *T. telescopium* can provide critical data to guide policy decisions and promote sustainable practices (Amiard *et al.* 2006; Jeong *et al.* 2023).

The differential accumulation patterns observed in this study also highlight the importance of considering multiple tissues in biomonitoring programs. By analyzing the concentrations of Fe and Pb in various tissues, researchers can gain a more nuanced understanding of the bioaccumulation processes and identify specific tissues that are particularly sensitive to metal exposure. This approach can enhance the accuracy and effectiveness of biomonitoring efforts, supporting the achievement of

SDG targets related to marine ecosystem health and biodiversity conservation (Häder *et al.* 2020).

The findings also emphasize the need for international collaboration and data sharing to address the global challenge of marine pollution. By integrating biomonitoring data from different regions, scientists and policymakers can develop a more comprehensive picture of metal pollution patterns and their impacts on marine ecosystems (Mateo-Sagasta *et al.* 2017; Häder *et al.* 2020). This collaborative approach is essential for implementing effective strategies to mitigate pollution and protect marine biodiversity in line with the UN SDGs.

In sum, the bioaccumulation of Fe and Pb in *T. telescopium* provides valuable insights into the environmental health of marine ecosystems and supports the development of sustainable management practices. The integration of biomonitoring data into policy frameworks can help achieve the UN SDGs by promoting the conservation and sustainable use of marine resources. Continued research and monitoring are essential to track progress towards these goals and ensure the long-term health and resilience of marine ecosystems (Mateo-Sagasta *et al.* 2017).

3.9 ESG considerations

The findings of this study have important implications for ESG considerations in marine ecosystem management. The bioaccumulation of Fe and Pb in *T. telescopium* reflects the environmental impact of industrial activities and agricultural practices, highlighting the need for improved governance and corporate responsibility to address pollution sources (Phillips and Rainbow 1993; Mateo-Sagasta *et al.* 2017).

Corporate strategies must incorporate environmental considerations into their operational frameworks to mitigate the adverse impacts of heavy metal pollution. Companies involved in industries that contribute to metal contamination should adopt best practices for waste management and invest in cleaner technologies to reduce their environmental footprints (Häder *et al.* 2020). These efforts align with the principles of ESG, promoting sustainable practices that protect marine environments and support long-term ecological health (Mateo-Sagasta *et al.* 2017).

Socially, the contamination of marine environments with heavy metals poses risks to human health and community livelihoods, particularly for populations relying on seafood as a primary protein source. The accumulation of toxic metals like Pb in marine organisms can lead to health issues in humans who consume contaminated seafood (Wu *et al.* 2024). Addressing these risks requires a comprehensive approach that includes public education, community engagement, and the implementation of policies to ensure the safety of seafood products.

Governance plays a critical role in regulating and monitoring environmental pollutants. Effective governance frameworks should enforce stringent environmental regulations, promote transparency, and ensure accountability for pollution control. This includes setting and enforcing limits on industrial discharges and agricultural runoff, as well as implementing monitoring programs to track pollution levels and assess the effectiveness of regulatory measures (Mateo-Sagasta *et al.* 2017; Häder *et al.* 2020).

The integration of biomonitoring data into ESG reporting can enhance corporate transparency and accountability. By providing accurate and up-to-date information on environmental pollution and its impacts, companies can demonstrate their commitment to sustainability and responsible environmental stewardship. This transparency can build trust with stakeholders, including investors, consumers, and regulatory bodies, and drive continuous improvement in environmental performance.

Therefore, the bioaccumulation of Fe and Pb in *T. telescopium* underscores the need for comprehensive ESG strategies that address environmental, social, and governance aspects of marine pollution. By incorporating biomonitoring data into corporate practices and policy frameworks, stakeholders can promote sustainable development, protect marine ecosystems, and ensure the health and well-being of communities reliant on marine resources (Phillips and Rainbow 1993; Mateo-Sagasta *et al.* 2017; Häder *et al.* 2020).

While the data collection period of 2006-2008 may seem outdated, this dataset provides critical insights into long-term trends of heavy metal contamination in Peninsular Malaysia's marine environment. The stable environmental conditions in the region, coupled with rigorous scientific methods, ensure the relevance and reliability of the findings. This historical baseline is essential for comparative studies with more recent data, offering a deeper understanding of cumulative environmental impacts. Furthermore, the research aligns with sustainability and ESG considerations, where past data is crucial for informing current environmental policies and management practices.

4 | CONCLUSIONS

This study provides a comprehensive analysis of the bioaccumulation patterns of Fe and Pb in various tissues of *T. telescopium*. The high positive correlations between Fe levels in the foot and mantle suggest similar physiological mechanisms for metal uptake in these tissues. Negative correlations between Pb levels in the CT and muscle indicate competitive uptake or differential metal binding capacities. Factor analysis highlights the complex interplay of environmental and physiological factors influencing metal accumulation. These findings underscore the importance of considering multiple tissues for accurate biomonitoring of metal pollution in marine environments.

Understanding the independent and competitive accumulation patterns of essential and non-essential metals in different tissues enhances our knowledge of the complex mechanisms driving bioaccumulation. This study's findings contribute to the broader field of environmental monitoring, particularly in the context of sustainability and ESG considerations. Reducing industrial discharges and agricultural runoff can help mitigate the impact of anthropogenic pollution on marine ecosystems, promoting sustainability and resilience. The role of *T. telescopium* as a biomonitor supports ESG initiatives by providing accurate assessments of metal pollution, informing policies to protect marine biodiversity and human health.

ACKNOWLEDGEMENTS

We acknowledge the research funding from the Putra Grant (Grant Ref / Vote No.: 9752600), granted by Universiti Putra Malaysia. We would like to thank postgraduate students for laboratory analysis of the metal data presented in this paper.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTION

Conceptualization, 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. Both 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.

SUPPLEMENTARY INFORMATION

Supplementary data to this article can be found online at https://doi.org/10.17017/j.fish.724.

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