



High accumulation of ^{210}Po concentration in muscle tissue and hepatopancreas gland organs of Asian green mussel (*Perna viridis*) at the coastal area of Binh Thuan, Vietnam: Radiological protection perspectives

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ABSTRACT

^{210}Po (polonium) has high radiotoxicity that tends to accumulate in marine bivalves inhabiting coastal zones with elevated background levels of primordial radionuclides. In this study, the ^{210}Po concentration in two organs of the Asian green mussel (*Perna viridis*), collected from the coastal region of Binh Thuan, Vietnam, was determined using alpha spectrometry. The results showed a significant difference in ^{210}Po activity concentration between the two organs of *P. viridis*, with markedly higher concentrations observed in the hepatopancreas gland compared to the muscle tissue, approximately six times greater. The mean ^{210}Po activities were $74.9 \pm 7.8 \text{ Bq}\cdot\text{kg}^{-1}$ (range: 30.3 ± 16.7 to $111 \pm 10.6 \text{ Bq}\cdot\text{kg}^{-1}$) in muscle tissue and $431 \pm 7.8 \text{ Bq}\cdot\text{kg}^{-1}$ (range: 187 ± 8 to $763 \pm 7 \text{ Bq}\cdot\text{kg}^{-1}$) in the hepatopancreas. This marked difference may be attributed to the affinity of ^{210}Po for certain proteins such as ferritin and metallothionein. The elevated accumulation of ^{210}Po in two organs may be linked to its filter-feeding behavior, its diet of plankton and organic particles, its biological characteristics, and local environmental conditions (relating to the titanium mining). Insignificant correlations were observed between ^{210}Po concentrations and shell length, total body mass, or estimated age of the mussels. This suggests that mussels of any size, age, or weight can serve as suitable sampling organisms for environmental biomonitoring programs targeting marine ^{210}Po contamination. Radiological risk assessment using the ERICA tool indicated negligible ecological impact of ^{210}Po on marine biota in the study area, except for sample group 15, which exhibited a Risk Quotient (RQ) of 1.00 and a total dose rate of $10 \mu\text{Gy}\cdot\text{h}^{-1}$, equivalent to the screening reference level. This suggests that ^{210}Po activity in the body may have a potential impact on this mussel species. Annual committed effective doses from dietary intake of mussels, particularly from the hepatopancreas, exceeded the recommended dose limit of $1 \text{ mSv}\cdot\text{y}^{-1}$ in most cases. This study provides essential baseline data for radiological

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protection and environmental monitoring along the Vietnamese coastline. The findings emphasize the necessity for targeted radiation risk management strategies and reinforce the utility of Asian green mussel as a reliable biomonitor of ^{210}Po contamination in tropical marine ecosystems.

1. Introduction

Vietnam has a coastline stretching 3260 km and a sea area covering over a million square kilometers. The marine economy is vital to the country of Vietnam's strategy, security, and economic development. The country has many titanium placers with reserves totaling hundreds of millions of tons (MONRE, 2017). However, the extraction and processing of these resources have released significant amounts of radioactive waste, such as ^{226}Ra , ^{228}Ra , ^{210}Pb , ^{210}Po , ^{238}U , and ^{234}U into seawater and seabed sediment. The extraction and processing of radioactive-rich minerals release pollutants, transported to marine ecosystems via aerosols and runoff. Oceans accumulate hazardous contaminants, including heavy metals and radionuclides, threatening marine life and ecological balance. Binh Thuan province was chosen as the study area (sample location point: $10^{\circ}44'13''$ N, $107^{\circ}57'40''$ E). The province is known for its thriving tourism, particularly in the popular Mui Ne area, which attracts both domestic and international visitors (Hoang et al., 2022). Binh Thuan has a territorial sea of 52,000 km² with 190,000 tons of fishing reserves and an abundance of titanium placers. The current titanium mining and refining processes require large amounts of water, and the resulting wastewater can become contaminated with radionuclides before being released into the surrounding marine environment. The radionuclide waste, including ^{210}Po , can be absorbed by organic particles and plankton, entering the food web of coastal marine ecosystems, including bivalve species. The ^{210}Po is a highly toxic radionuclide, a decay product of the ^{238}U , a naturally occurring radionuclide in the marine environment. The ^{210}Po and ^{210}Pb were estimated to account for about 83 % of the annual effective dose to humans via ingestion (UNSCEAR, 2000). And ^{210}Po has direct relevance to human health through seafood consumption. Therefore, it is crucial to assess the radiological impact of ^{210}Po as well as other radionuclides on marine species in this region, which can harmfully affect marine ecosystems (Santhanabharathi et al., 2023; Pradhoshini et al., 2023) as well as human consumption of seafood.

^{210}Po deposition could arise from the atmosphere, surface runoff, seawater, and sediments (Shareef and Khan, 2024). As mentioned above, ^{210}Po binds strongly to organic matter and plankton, which are ingested by bivalves, leading to significant accumulation in their tissues (Tateda et al., 2003). These mollusks serve as sensitive bioindicators for radioactive and heavy metal pollution, as their filter-feeding behavior results in the ingestion of phytoplankton, key carriers of bioaccumulated radionuclides in aquatic environments (Khan et al., 2014). In Vietnam, bivalves such as mussels are widely consumed, especially in coastal communities where they represent an important source of affordable protein and traditional cuisine. In many nations, bivalves like mussels are not only a valued food source but also used in environmental monitoring (Shareef et al., 2023). The ^{210}Po in edible marine species (including bivalves) can transfer to humans when these organisms are consumed, posing a potential health risk (Yamamoto et al., 2009; Shareef and Khan, 2024). Therefore, studying the characteristics of ^{210}Po and radiological risk assessment associated with bivalve consumption are becoming necessary.

Bivalves, particularly mussels are widely recognized as effective bioindicators in ecological monitoring due to their sedentary nature, widespread distribution, and high capacity to bioaccumulate contaminants, including radionuclides, from their surrounding environment (Khan et al., 2014). Consequently, bivalves (mussels) are not only critical for assessing risks to human health through seafood consumption but also for evaluating radiological impacts on marine ecosystems (Tateda et al., 2003). Globally, many researchers have focused on the

radiological hazards linked to seafood consumption, especially involving ^{210}Po accumulation in marine organisms, due to its high radiotoxicity and dietary relevance (Uddin et al., 2012; Hassona et al., 2008; Štok and Smodiš, 2011; Aközcan and Uğur, 2013; Mársico et al., 2014; Al-Masri et al., 2019; Van, 2020; Srilerd et al., 2024). However, there is a notable lack of baseline data on radionuclide concentrations and associated ecological risks in specific regional environments at study area.

In recent years, attention has increasingly turned to the radiological exposure of non-human biota, recognizing the potential for bioaccumulated radionuclides to pose both internal and external radiation hazards to aquatic organisms (Andersson et al., 2008; ICRP, 2003, 2007; Larsson, 2008; Vetikko and Saxén, 2010; Musthafa and Krishnamoorthy, 2012; Suseno and Prihatiningsih, 2014). To address this, several ecological risk assessment models have been developed, among which the ERICA (Environmental Risk from Ionizing Contaminants: Assessment and Management) Tool stands out as one of the most robust and internationally accepted frameworks (Brown et al., 2004; Brown et al., 2008; Gjelsvik et al., 2012; Aryanti et al., 2022). The ERICA Tool facilitates the calculation of radiation dose rates to biota by integrating radioactivity measurements, biological characteristics, and ecological parameters (Vetikko and Saxén, 2010). In this study, dose estimations to local mussel populations were also carried out using ERICA to assess the potential ecological impacts of observed ^{210}Po concentrations in this sentinel species.

The Asian green mussel (bivalve mollusk), *Perna viridis*, is widely distributed across the Indo-Pacific region and various coastal areas. It can be found along the Indian coast, from Japan and New Guinea to the Persian Gulf, as well as in Malaysia, Trinidad, the Gulf of Paria in Venezuela, Tampa Bay (USA), the Philippines, China, Japan, and parts of North and South America (Siddall, 1980; Jones and Algarwami, 1973; Kuriakose and Nair, 1976; Sivalingam, 1977; Agard et al., 1992; Benson et al., 2001; FAO, 2013). Mussels are mostly collected from the wild as well as through natural farming. The mussels are widely consumed as food in countries such as Thailand, Indonesia, the Philippines, and Vietnam, where seafood is abundant (Agusa et al., 2007). These mussels are not only valuable for their nutritional content but also hold high economic value for local and domestic markets. Furthermore, previous research has explored the potential of green mussel extract for anti-inflammatory treatments, including omega-3 fatty acids (Broadfoot, 2014).

Thus, the green mussel species have high economic and nutritional values and accumulate significant levels of radionuclides, especially of ^{210}Po , in their organ relating to their filter-feeding behavior of bivalves (Bui, 2006; Broadfoot, 2014; Lim and Mohamed, 2019; Hameed et al., 2004; Chen et al., 1997; Makmur et al., 2020; Khan et al., 2014). Recent studies have shown that ^{210}Po accumulates in their muscles and hepatopancreas, raising concerns about high radiological risks associated with the consumption of bivalves (Van, 2020; Duong et al., 2023). Due to the notable lack of baseline data on ^{210}Po and ecological risks/impacts assessment on human consumption and green mussel in specific regional environments, therefore, the baseline data, understanding the radiological risks of ^{210}Po on human health from mussel consumption and its potential impact on mussel species living in coastal areas with high potential of ^{210}Po contamination relating processed titanium ore and zircon refining provinces, are crucial. This paper aims to (1) analyze the ^{210}Po activity in two organs (muscles and hepatopancreas) of various groups based on allometry from the coastal area of Binh Thuan, Vietnam; (2) assess radiological impact on the environment using *Perna viridis* as a reference biota by the ERICA tool; and (3) evaluate the

effective dose and risk to bivalve consumers.

2. Materials and methods

2.1. Sample collection

The wild mussels were caught by local farmers who possess detailed knowledge and experience regarding the species and their natural habitats. To assess the influence of morphological factors (shell length and weight) on the accumulation of ^{210}Po , twenty distinct groups of wild green mussels (*Perna viridis*) in the natural environment with different shell lengths (~5 mm in difference) and weights were collected from the coastal area of Binh Thuan. The samples were collected in the winter season, 2023, to minimize biological variability associated with spawning cycles and seasonal metabolic changes. Each group consisted of twenty individuals to ensure representative sampling. The samples were gathered from a site selected to reflect the similar environment and distribution of ^{210}Po pollution within the study region. The samples were immediately transported to the laboratory, where they were cleaned, and their total mass, shell length, and age were recorded. In this study, the relative age of the green mussels was estimated based on the dating method for bivalve species presented by (Nhuong, 2016). Then the two organs of edible muscle tissue and the hepatopancreas gland were mixed in homogeneous from selected individuals of each organ and group. The samples studied were weighed in a wet state then dried in an oven at 80–90 °C to ensure a constant dry weight and re-weighed to determine the dry/wet ratio, and then they were crushed, mixed in homogeneous (Van, 2020). Both organs were selected for analysis to measure the activity of ^{210}Po across different mussel ages, total mass, and shell lengths. Additionally, a radiological hazard assessment was carried out to evaluate the radiological risks due to consuming Asian green mussels as food. The radiological impact of ^{210}Po on the mussels was also calculated using the total dose rate and risk quotient by the ERICA tool.

2.2. Sample processing for ^{210}Po measurement

The chemical separation of polonium and sample preparation followed the protocols outlined and modified from Skwarzec and Van (Skwarzec, 1997; Van, 2020; Van et al., 2022). At the beginning, approximately 100 mBq of ^{209}Po standard solution (Eckert & Ziegler™) was added to each sample (0.1–0.5 g dry weight sample). The sample digestion used 5–10 mL of 98 % H_2SO_4 (Merk™) and complete decomposition was achieved by adding 2–5 mL of 30 % H_2O_2 (Merk™). The process was done with a temperature below 90 °C. After digestion, the samples were diluted to 1 L of distilled water before precipitation with MnO_2 (Merk™). The precipitation was done by adding 3 mL each of 0.3 M MnCl_2 and 0.3 M KMnO_4 solutions after adjusting the pH > 9 using 25 % ammoniac solution (Merk™), with approximately 20–30 mL added. The obtained samples were followed by magnetic stirring for about 30 min and left overnight to allow precipitation. The precipitates were washed with distilled water using centrifugation at 4000 rpm until neutral pH was achieved, then dissolved in 60 mL of 9 M HCl (Merck™). The solutions were evaporated in glass dishes at temperatures below 90 °C too. The dried residues were re-dissolved in 30–40 mL of 0.5 M HCl , and both ^{209}Po and ^{210}Po were spontaneously plated onto 1 cm² silver plates (0.2 mm thick) over 2–4 h (Van et al., 2022). Finally, the plates were rinsed with distilled water and air-dried at room condition.

2.3. Determination of ^{210}Po in mussel organ samples by alpha spectrometry

An alpha spectrometer, specifically an ALPHA-DUOM1–450 mm² area of PIPS detector, was used to determine ^{210}Po and ^{209}Po activity concentration. A ^{209}Po tracer was used as an internal standard to quantify the activity concentration of ^{210}Po . For quality control, 0.5 g of

the reference material IAEA-414 (dry fish tissue- the fish filleted), which has a matrix comparable to mussel soft tissue, was used and found suitable for ^{210}Po analysis, with measured ^{210}Po values falling within the certified confidence interval. The detection limit (MDL) of the measurement was 0.5 mBq/sample.

The equation for measurement uncertainty of ^{210}Po used the formula as mentioned below:

$$\sigma_{Po-210} = \sqrt{\left(\frac{\sqrt{N_i}}{n_i}\right)^2 + \left(\frac{\sqrt{N_{st}}}{n_{st}}\right)^2 + \left(\frac{\sqrt{N_B}}{n_B}\right)^2}$$

where: σ_{Po-210} – ^{210}Po measurement uncertainty, N_i , N_{st} , N_{sp} are number of counts at measured peak ^{210}Po , ^{209}Po in study sample, and peak ^{210}Po in blank sample, respectively.

2.4. The total dose rate and risk quotient

ERICA calculates radiation doses absorbed by organisms and assesses the potential ecological risks posed by radioactive substances (Brown et al., 2016, 2008). The tool includes three assessment levels, each offering different levels of accuracy and flexibility. It allows researchers to calculate radiation doses based on dose conversion coefficients and reference organisms (Larsson, 2004). The dose conversion factor allows the conversion from the activity of a radioactive substance to the absorbed dose rate in a reference organism. Weighting factors are applied for different radiation types: 10 for alpha radiation, 3 for low-energy beta radiation ($E\beta 10$ keV), and gamma radiation (Ulanovsky et al., 2008; Brown et al., 2008). In this study, the radiological impact of ^{210}Po on Asian green mussels (*Perna viridis*) was assessed using the ERICA Assessment Tool at Tier 2. Input data into Tier 2 of the ERICA tool include the following information: the reference organism selected in ERICA is *Mollusk – Bivalve*; the average ^{210}Po activity in regional seawater and sea sediment samples is 1.73 mBq·L⁻¹ and 60.5 Bq·kg⁻¹, respectively (cited from undergraduate thesis in Vietnamese of the Thanh-Xuan Pham-Thi); and the fraction of time the reference organism spends in a given habitat is Water–surface equal 1.

2.5. Annual committed effective dose

The formula to calculate the annual committed effective dose (ACED):

$$E_{210Po} = A_{210Po} \times f_{210Po} \times m$$

where E_{210Po} is the ACED in (mSv·y⁻¹), A_{210Po} is the average activity concentration of ^{210}Po in the edible tissues and hepatopancreas gland (Duong et al., 2024) of Asian green mussel (Bq·kg⁻¹), m is the annual mass of Asian green mussel organs consumed by an adult (average 18.8 kg·y⁻¹ (Issifu et al., 2022)) (due to lack of information, in this study was also used this referenced value for infants and children as an assumption) and the f_{210Po} is the ^{210}Po dose conversion factor. The dose conversion factors of ^{210}Po for adults, infants, and children to calculate the ACED are 1.2×10^{-6} ; 8.8×10^{-6} and 2.6×10^{-6} Sv·Bq⁻¹ (UNSCEAR, 2000). G factor is 0.5 for adults as per the ICRP (ICRP, 1996). In Vietnam, it is common to consume whole mussels, with preparation methods varying regionally between raw and boiled.

2.6. Statistical analysis

In this study, the differences in ^{210}Po distribution between the two organs of *Perna viridis* were analyzed using the *t*-test method implemented in SPSS software (IBM SPSS Statistics 20). To facilitate effective analysis and visualization of ^{210}Po data, descriptive statistics were presented using box plots generated with OriginPro software. Finally, the relationships between ^{210}Po activity in muscle and hepatopancreas and the mussels' shell length, total body mass, and estimated age were

assessed through correlation matrices constructed using Microsoft Excel.

3. Results and discussions

3.1. The ^{210}Po activity in two organs of twenty groups of shell lengths of mussel

Table 1 presents the ^{210}Po concentration in two organs of the Asian green mussel. The ^{210}Po activities in muscle tissue ranged from 30.3 ± 16.7 to $111 \pm 10.6 \text{ Bq}\cdot\text{kg}^{-1}$, with an average of $74.9 \pm 7.8 \text{ Bq}\cdot\text{kg}^{-1}$, while in the hepatopancreas gland, it ranged from 187 ± 7.6 to $763 \pm 6.6 \text{ Bq}\cdot\text{kg}^{-1}$, with an average of $431 \pm 7.8 \text{ Bq}\cdot\text{kg}^{-1}$. The variability in ^{210}Po activity may be attributed to differences in accumulation and excretion mechanisms in mussels of various ages and sizes, where excretion processes help expel unassimilated or detoxified polonium from the body (Hansen et al., 2022; Srilerd et al., 2024). There is a significant difference in ^{210}Po activity between the two organs, with the hepatopancreas gland showing about six times higher activity than the muscle tissue organ ($p < 0.05$) (Fig. 1).

Previous studies have shown that 80–90 % of radionuclides in bivalves are accumulated in the hepatopancreas, which significantly contributes to the accumulation of polonium (Stepnowski and Kozuch, 1999). Numerous studies have also highlighted elevated ^{210}Po concentrations in the hepatopancreas of marine invertebrates, linked to the food chain, the water column, or physical changes in the hepatopancreas of shellfish (Stepnowski and Skwarzec, 2000; Fowler, 2011). Other studies on the distribution of ^{210}Po in bivalve species, such as sea clams, support these findings (Lim and Mohamed, 2019; Makmur et al., 2020; Khan et al., 2014; Duong et al., 2023). And ^{210}Po tends to accumulate in high concentrations in digestive and metabolic organs such as the hepatopancreas gland of mussels (Carvalho et al., 2017; Hansen et al., 2022; Tan et al., 2023). Furthermore, ^{210}Po has a high affinity for proteins like ferritin, sulfur, selenium, and metallothionein in this organelle, further contributing to its elevated concentration in the hepatopancreas (Godoy et al., 2008).

In this study, the average ^{210}Po activity in the muscle tissue of the mussel was observed to be $74.9 \text{ Bq}\cdot\text{kg}^{-1}$, which is notably high, several to dozens of times higher than the levels observed in marine fish species in Vietnam (Van, 2020). The substantially larger concentration of ^{210}Po

in bivalve soft tissues can be explained due to its stronger binding affinity for organic moieties (Somasundaram and Hameed, 2000). Overall, the concentration of ^{210}Po in both the muscle and hepatopancreas organs of mussels is significantly higher compared to other marine species in the local area. Compared to other seafood species surveyed in the same area by Nguyen (Nguyen et al., 2021), the level of ^{210}Po accumulation in green mussels is particularly high, especially when compared to species with similar feeding habits (omnivores). For example, the slate clam (*Paphia undulata*) exhibited an average activity level of only $58.2 \pm 3.2 \text{ Bq}\cdot\text{kg}^{-1}$, the claw clam (*Anadara inaequalis*) $50.8 \pm 3.5 \text{ Bq}\cdot\text{kg}^{-1}$, and the green crab (*Portunus pelagicus*) $60.1 \pm 3.6 \text{ Bq}\cdot\text{kg}^{-1}$. Notably, the ^{210}Po activity level in the muscle tissue of Asian green mussels was higher than that of many carnivorous fish species, such as red snapper (*Lutjanus russellii*: $13.0 \pm 1.2 \text{ Bq}\cdot\text{kg}^{-1}$), whitefish (*Caranx heberi*: $3.07 \pm 0.38 \text{ Bq}\cdot\text{kg}^{-1}$), and striped fish (*Carangoides bajad*: $8.25 \pm 0.99 \text{ Bq}\cdot\text{kg}^{-1}$). This high accumulation can be attributed to the mussels' continuous filter-feeding behavior, which facilitates the absorption of radioactive suspended particles from the environment. Because of a lack of scientific data about radionuclides contamination relating the titanium mining, the present study focuses on assessing natural ^{210}Po levels in green mussel at the study coastal area. The Asian green mussel, a stalkless filter feeder, primarily absorbs ^{210}Po through contaminated feeding (Carvalho et al., 2010; Ryan et al., 2008; Desideri et al., 2009). Meanwhile, the food of mussels mainly consists of plankton and organic particles, which are well known for their potential to accumulate high concentrations of ^{210}Po (Tateda et al., 2003; Carvalho, 2011; Duong et al., 2024). As primary consumers in the food chain, bivalves are particularly prone to accumulating pollutants. Thus, the high ^{210}Po activity in the study mussel could be related to this species' filter feeder habit, feeding type, and biomagnification of this organism.

Table 2 presents a comparison of the ^{210}Po activities in the muscle tissue of Asian green mussels (*Perna viridis*) from various regions around the world. While many studies have explored ^{210}Po activity in different crustaceans, there is limited research specifically on this species. The ^{210}Po activity in muscle tissue of Asian green mussel in the present study is higher than that has been reported for the coastal areas such as Kalpakam, Bengal Bay, Trad Bay, and Samut Sakhon, Thailand (Porntepkasemsan et al., 2015; Panigrahi et al., 2021; Nochit et al., 2021). However, it is lower than the ^{210}Po activity observed in Arabian

Table 1

^{210}Po activities in muscle tissue and hepatopancreas gland organs of different shell length, total mass and age of Asian green mussel groups.

Group sample no based on shell length	Average shell length (cm)	Average total mass (g) (wt w)	Ages (year)	Average of ^{210}Po ($\text{Bq}\cdot\text{kg}^{-1}$) (wt w) ($n = 20$)		
				Muscle tissue	Hepatopancreas gland	Whole body ^a
Group 1	4.1	7.27	5.0	30.3±6.7	187±7.6	87.9
Group 2	4.5	10.7	6.2	76.2±6.8	520±6.9	221
Group 3	5.0	11.6	7.5	86.3±7.7	763±6.6	178
Group 4	5.6	15.0	8.4	71.3±8.1	453±6.5	207
Group 5	6.1	15.2	8.3	92.6±7.3	549±5.2	268
Group 6	6.5	17.7	9.0	75.6±8.3	370±6.7	219
Group 7	6.9	19.8	10.1	33.6±3.1	242±14	97.4
Group 8	7.4	19.0	10.5	81.0±7.6	379±6.0	235
Group 9	7.9	17.1	11.0	96.5±7.4	511±7.8	279
Group 10	8.5	20.0	11.6	93.4±6.8	501±6.0	271
Group 11	8.9	21.7	12.0	63.0±9.0	404±6.6	183
Group 12	9.4	23.6	13.3	73.6±7.3	309±6.0	213
Group 13	9.9	25.8	14.0	109±6.1	345±12	316
Group 14	10.3	23.5	14.4	89.2±7.2	399±12	258
Group 15	10.8	29.4	15.4	111±10	444±6.7	322
Group 16	11.3	22.2	16.0	44.4±4.0	476±5.6	129
Group 17	11.7	23.9	16.7	100±8.4	458±7.1	290
Group 18	12.1	25.6	17.0	79.5±7.7	385±6.0	231
Group 19	12.6	27.1	17.7	53.0±11	592±11	154
Group 20	13.0	30.3	18.8	62.9±16	331±10	182
Average	8.6	20.3	12.1	74.9±7.8	431±7.8	217
Min	4.1	7.27	5.0	30.3±6.7	187±7.6	87.9
Max	13.0	30.3	18.8	111±11	763±6.6	322

^a ^{210}Po activities in the whole mussel body (fresh weight) were based on the mass balance method by Yankovich et al., 2010.

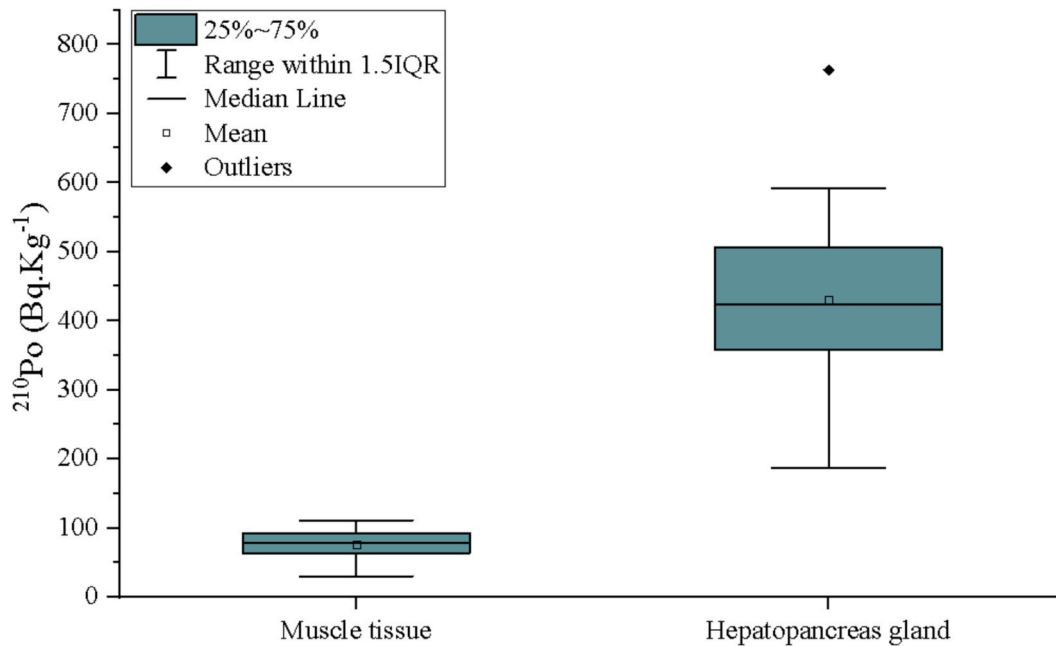


Fig. 1. Box plots for ^{210}Po activities in two organs of Asian green mussel ($p < 0.05$).

Table 2

^{210}Po activities in the muscle tissue of Asian green mussel (*Perna viridis*) comparing with other studies.

Species	Region	^{210}Po activities (Bq.kg ⁻¹) (wet weight)	References
Asian green mussel (<i>Perna viridis</i>)	Arabian Sea, India	79.7 ± 16.7	Shareef et al., 2023
Asian green mussel (<i>Perna viridis</i>)	Johore Straits, Malaysia	79.33 ± 0.87	Lim and Mohamed, 2019
Asian green mussel (<i>Perna viridis</i>)	Kalpakkam coast, Bengal Bay	20.66 ± 1.0	Panigrahi et al., 2021
Asian green mussel (<i>Perna viridis</i>)	Trad Bay, Thailand	3.31 ± 0.20	Nochit et al., 2021
Asian green mussel (<i>Perna viridis</i>)	Samut Sakhon, Thailand	1.04–6.95	Porntepkasemsan et al., 2015
Asian green mussel (<i>Perna viridis</i>)	Binh Thuan, Vietnam	74.9 ± 7.8	This study

Sea, India and Johore Straits, Malaysia (Lim and Mohamed, 2019). The elevated ^{210}Po levels in Johore Straits have been linked to pollution from untreated domestic and industrial wastewater (Lim and Mohamed, 2019), while in the Arabian Sea, the high levels are attributed to placer mining and processing activities (Shareef et al., 2023). In contrast, the ^{210}Po activity in the mussel muscle tissue from farming areas in Thailand ranges from 1.04 to 6.9 Bq.kg⁻¹, indicating relatively low values (Porntepkasemsan et al., 2015). The elevated ^{210}Po activity observed in this study may be related to bioaccumulation of polonium within the species. One possible factor contributing to the higher levels of ^{210}Po in the area is the presence of titanium mining and zircon refining activities along the coast, which may lead to localized enrichment of ^{210}Po in the

environment. However, detailed sampling and analysis of industrial processing waste and direct investigation of waste discharge points are necessary to fully understand their impact in further study. The concentration of ^{210}Po in mussel tissues can be influenced by their habitat. When ^{210}Po is released into the coastal environment, it may be absorbed by plankton or organic particles, which the mussels filter from the water. This filtering process may help reduce ^{210}Po activity in seawater and limit its deposition into surface sediments. Therefore, the ^{210}Po activity observed in mussel tissues may not directly correlate with the ^{210}Po levels in seawater or surface sediments at each sampling location (with the reference of the average ^{210}Po activity in regional seawater and sea sediment samples is 1.73 mBq.L⁻¹ and 60.5 Bq.kg⁻¹, respectively). The observed variations in ^{210}Po activity in Asian green mussels (*Perna viridis*) across different regions can be attributed to factors such as geographical differences, environmental pollutant levels, and species-specific physiological mechanisms governing ^{210}Po accumulation and excretion under varying environmental conditions (Garcia-Orellana et al., 2016; Ababneh et al., 2018; Van, 2020). In the present study, all mussel samples analyzed were naturally collected from the wild and not obtained from aquaculture sources.

Data presented in Table 3 indicate that ^{210}Po activity in the muscle tissue and hepatopancreas of the Asian green mussel (*Perna viridis*) was only weakly correlated with biological parameters, including shell length, total body weight, and age. The correlation coefficients between ^{210}Po activity in muscle tissue and age, shell length, and total mass were

Table 3

Relationship between ^{210}Po activity in muscle and hepatopancreas gland on shell length, total mass and age of mussels.

	Shell length	Total mass	Ages	^{210}Po (M. tissue)	^{210}Po (H. gland)
Shell length	1.00				
Total mass	0.93	1.00			
Ages	1.00	0.94	1.00		
^{210}Po (M. tissue)	0.15	0.24	0.15	1.00	
^{210}Po (H. gland)	-0.05	-0.14	-0.04	0.39	1.00

M. tissue: Muscle tissue.

H. gland: Hepatopancreas gland.

0.15, 0.15, and 0.24, respectively, while those for the hepatopancreas were -0.04 , -0.05 , and -0.14 . These results suggest that ^{210}Po accumulation is not significantly driven by growth-related factors. This finding is consistent with previous studies indicating that ^{210}Po exhibits strong affinity for proteins and amino acids rather than lipids, which are more susceptible to fluctuations associated with reproductive cycles, gonadal maturation, and nutritional status (Orban et al., 2002; Gosling, 1992).

Although mussel total mass was highly correlated with both age ($r = 0.94$) and shell length ($r = 0.93$), no corresponding increase in ^{210}Po levels was observed. Typically, radionuclide concentrations tend to decrease with increasing mussel size due to growth dilution effects, as reported by Carvalho (Carvalho et al., 2017). This discrepancy in our findings may be attributed to site-specific factors such as local contamination sources or biological variability influencing ^{210}Po accumulation. This further supports the hypothesis that ^{210}Po accumulation is primarily influenced by metabolic processes or environmental exposure rather than organism size or age. These findings support the suitability of *P. viridis* as a bioindicator species for marine ^{210}Po contamination, regardless of individual age or size, thereby facilitating effective environmental monitoring strategies.

3.2. The total dose rate and risk quotient

This study used the ERICA tool to assess the radiological impact of the ^{210}Po on Asian green mussel groups in this study area (Table 4). The ^{210}Po are calculated for the whole body of the Asian green mussel groups using the input data from Table 1 and Section 2.4. Based on the calculation, the total dose rate per organism ranges from 2.74 to 10.0 and 6.77 $\mu\text{Gy/h}$ on average which is lower than the reference value (10 $\mu\text{Gy/h}$), and the Risk Quotient (RQ) values range from 0.274 to 1.00 and 0.677 on average which are below threshold value (1). This indicates that the current ^{210}Po concentration in mussels does not pose a significant risk to this study organism. However, one group of 15 mussels had an RQ value of 1.00 and a total dose rate of 10 $\mu\text{Gy/h}$, which equal to the screening and threshold values. This indicates that the activity of ^{210}Po in the mussel could potentially begin to impact radiation on this specific group of mussels species. Therefore, further research is needed to assess

Table 4

Tier 2 assessment results with ERICA for Asian green mussel groups - Total dose rate and risk quotient.

Group sample based on shell length	Total Dose Rate per Organism ($\mu\text{Gy/h}$)	Screening Value ($\mu\text{Gy/h}$)	Risk Quotient (Expected Value)	RQ threshold value
Group 1	2.74	10	0.274	1
Group 2	6.89	10	0.689	1
Group 3	5.55	10	0.555	1
Group 4	6.45	10	0.645	1
Group 5	8.37	10	0.837	1
Group 6	6.84	10	0.684	1
Group 7	3.04	10	0.304	1
Group 8	7.33	10	0.733	1
Group 9	8.73	10	0.873	1
Group 10	8.45	10	0.845	1
Group 11	5.70	10	0.570	1
Group 12	6.66	10	0.666	1
Group 13	9.86	10	0.986	1
Group 14	8.07	10	0.807	1
Group 15	10.0	10	1.000	1
Group 16	4.02	10	0.402	1
Group 17	9.04	10	0.904	1
Group 18	7.19	10	0.719	1
Group 19	4.79	10	0.479	1
Group 20	5.69	10	0.569	1
Average	6.77		0.677	
Min	2.74		0.274	
Max	10.0		1.00	

the long-term radiological effects of ^{210}Po on Asian green mussels in this area.

3.3. The radiological risk assessment

Estimating the potential radiation dose to humans is an important aspect of this study. The daily intake and annual committed effective dose (ACED) for the infants, children, and adults were calculated based on the ^{210}Po activity levels in mussels. A high seafood consumption scenario was evaluated to estimate the potential ^{210}Po exposure from both natural and human-induced sources. In the context radiological risk assessment of ^{210}Po , the ACEDs due to the consumption of Asian green mussel is presented in Table 5. According to Issifu (Issifu et al., 2022), the average annual seafood consumption is 18.8 $\text{kg}\cdot\text{y}^{-1}$ per person (2011), and the value applies to the general population in this study.

The ACED varies by age due to different dose conversion factors and the absorption of gastrointestinal tract for each age group. Infants are most affected, followed by children and adults (if they have similar consumption of mussel). The ACED from ^{210}Po intake through consumption of Asian green mussels is notably higher than the recommended dose limit of 1 $\text{mSv}\cdot\text{y}^{-1}$ (UNSCEAR, 2008; WHO, 2011). Specifically, the average ACED from ^{210}Po intake due to the consumption of edible muscle tissue and hepatopancreas organs of Asian green mussels are as follows: for infants, 12.4 $\text{mSv}\cdot\text{y}^{-1}$ (muscle) and 71.3 $\text{mSv}\cdot\text{y}^{-1}$ (hepatopancreas); for children, 3.7 $\text{mSv}\cdot\text{y}^{-1}$ (muscle) and 21.1 $\text{mSv}\cdot\text{y}^{-1}$ (hepatopancreas); and for adults, 1.7 $\text{mSv}\cdot\text{y}^{-1}$ (muscle) and 9.7 $\text{mSv}\cdot\text{y}^{-1}$ (hepatopancreas). Therein, the dose limit of 1 $\text{mSv}\cdot\text{y}^{-1}$ is the value of dose over the dose average caused from normal natural exposure (2.4 $\text{mSv}\cdot\text{y}^{-1}$) and the above values of ACED will reduce by about 50 % when mention about G factor of 0.5. Consumption of the hepatopancreas organ of mussels could pose a significant health risk, as the ACED from this organ far exceeds the recommended reference values. Although Asian green mussels are a nutritious food source, excessive consumption up to 18.8 $\text{kg}\cdot\text{y}^{-1}$, especially of the hepatopancreas organ, could lead to harmful health effects. Therefore, to minimize the risk of ^{210}Po exposure, it is advisable to limit the consumption of large quantities of Asian green mussels, particularly their hepatopancreas organ.

4. Conclusions

The study determined the ^{210}Po activity in the two organs (edible muscle tissue and the hepatopancreas gland) of different shell length, total mass and age of Asian green mussel. The relatively high activity was compared to other local marine organisms and selected regions worldwide. This high activity could be related to this species' filter feeder habit, feeding type, biomagnification, the specific mechanisms governing the ^{210}Po accumulation and excretion in response to varying environmental conditions, and geographical differences relating to the titanium mining and zircon refining activities along this coastal study. There was a significant difference in ^{210}Po activity between the two organs of Asian green mussels with the hepatopancreas gland show about six times higher activity than the muscle tissue organ ($p < 0.05$). This could be due to the role of digestive and metabolic organs and the strong affinity of ^{210}Po for proteins such as ferritin and metallothionein present in this organelle. There was weak correlation between ^{210}Po activities in two organs of Asian green mussel and their shell length, total mass and age. Thus, mussels of any size, age, or weight could be used as suitable sampling subjects for environmental biomonitoring programs targeting marine ^{210}Po pollution.

This study used the ERICA tool to assess the radiological impact of the ^{210}Po on Asian green mussels. The results showed that the ^{210}Po activity concentration in mussels does not pose a significant risk to this study organism. However, one group of 15 mussels had an RQ value of 1.00 and a total dose rate of 10 $\mu\text{Gy/h}$, which equal to the screening and threshold values. This indicates that the activity of ^{210}Po in the mussel

Table 5The ACED contribution from ^{210}Po in Asian green mussel for adults, children, and infants due to consumption.

Group sample	^{210}Po (mSv.y $^{-1}$)					
	Infants		Children		Adult	
	Muscle tissue	Hepatopancreas gland	Muscle tissue	Hepatopancreas gland	Muscle tissue	Hepatopancreas gland
Group 1	5.00	30.9	1.5	9.1	0.7	4.2
Group 2	12.6	86.0	3.7	25.4	1.7	11.7
Group 3	10.1	126	3.0	37.3	1.4	17.2
Group 4	11.8	74.9	3.5	22.1	1.6	10.2
Group 5	15.3	90.9	4.5	26.9	2.1	12.4
Group 6	12.5	61.3	3.7	18.1	1.7	8.4
Group 7	5.6	40.0	1.6	11.8	0.8	5.5
Group 8	13.4	62.6	4.0	18.5	1.8	8.5
Group 9	16.0	84.5	4.7	25.0	2.2	11.5
Group 10	15.5	82.8	4.6	24.5	2.1	11.3
Group 11	10.4	66.8	3.1	19.7	1.4	9.1
Group 12	12.2	51.0	3.6	15.1	1.7	7.0
Group 13	18.0	57.1	5.3	16.9	2.5	7.8
Group 14	14.8	65.9	4.4	19.5	2.0	9.0
Group 15	18.4	73.5	5.4	21.7	2.5	10.0
Group 16	7.30	78.8	2.2	23.3	1.0	10.7
Group 17	16.5	75.7	4.9	22.4	2.3	10.3
Group 18	13.2	63.6	3.9	18.8	1.8	8.7
Group 19	8.80	98.0	2.6	29.0	1.2	13.4
Group 20	10.4	54.8	3.1	16.2	1.4	7.5
Average	12.4	71.3	3.7	21.1	1.7	9.7
Min	5.00	30.9	1.5	9.1	0.7	4.2
Max	18.4	126	5.4	37.3	2.5	17.2

could potentially begin to impact radiation on this specific group of mussels. Therefore, further research is needed to assess the long-term radiological effects of ^{210}Po on Asian green mussels in this area.

Regarding the ACED for Asian green mussel consumption containing ^{210}Po , the ACED from ^{210}Po intake through high consumption scenario of Asian green mussels is notably higher than the recommended dose limit of 1 mSv.y $^{-1}$ (UNSCEAR, 2008; WHO, 2011). Although Asian green mussels are a nutritious food source, excessive consumption, particularly of the hepatopancreas, could potentially lead to harmful health effects. Therefore, to minimize the risk of ^{210}Po exposure, it is advisable to limit the consumption of large quantities of Asian green mussels, particularly their hepatopancreas organ.

CRediT authorship contribution statement

Van-Hao Duong: Writing – review & editing, Validation, Project administration, Investigation, Formal analysis, Conceptualization, Writing – original draft, Supervision, Methodology, Funding acquisition, Data curation. **Thanh-Xuan Pham-Thi:** Writing – original draft, Software, Investigation, Data curation, Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Trung-Tien Chu:** Writing – review & editing, Methodology, Data curation, Writing – original draft, Formal analysis. **Thanh-Nam Nguyen:** Writing – original draft, Methodology, Formal analysis, Writing – review & editing, Validation, Investigation, Data curation. **Tue Nguyen Tai:** Writing – review & editing, Formal analysis, Writing – original draft, Data curation. **Dung Luu Viet:** Writing – review & editing, Formal analysis, Writing – original draft, Data curation. **Van-Dung Nguyen:** Writing – review & editing, Formal analysis, Writing – original draft, Data curation. **Thi-Lan Tran:** Writing – review & editing, Formal analysis, Writing – original draft, Data curation. **Van-Khanh Nguyen:** Writing – review & editing, Formal analysis, Writing – original draft, Data curation. **Marckasagayam Priyadharshini:** Writing – review & editing, Validation, Formal analysis, Writing – original draft, Software, Data curation. **Mohamed Saiyad Musthafa:** Writing – review & editing, Validation, Formal analysis, Writing – original draft, Investigation, Data curation. **Obid Tursunov:** Writing – review & editing, Formal analysis, Writing – original draft, Data curation. **Hue Nguyen Thanh Kim:** Writing – original draft, Methodology, Formal analysis, Writing – review & editing, Software,

Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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