

Distribution, bioaccumulation and radiological risks of uranium in bivalve mollusks in the tropical coastal waters of Lam Dong, Vietnam: Implications for marine monitoring and uptake pathway

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ABSTRACT

Natural uranium isotopes (^{234}U and ^{238}U) levels have been investigated in muscle and hepatopancreas tissues of twelve ecologically and economically bivalve species from a tropical coastal area, Lam Dong, Vietnam (the titanium placer area). The ^{234}U and ^{238}U activities were observed to be higher in the hepatopancreas organ and varied among species ranging from 0.24 ± 0.02 to 13.1 ± 0.35 and from 0.25 ± 0.03 to 15.5 ± 1.6 Bq/kg in muscle tissues, from 0.32 ± 0.03 to 25.0 ± 2.1 and from 0.61 ± 0.06 to 94.7 ± 9.47 Bq/kg in hepatopancreas, respectively. The preferential accumulation in the hepatopancreas highlights its role in metal uptake, detoxification, and storage. Variations $^{234}\text{U}/^{238}\text{U}$ activity ratio between tissues in the range 1.0 – 3.89 and seawater indicated mixing uptake pathways, primarily through the gill and digestive tract. There was a significant negative correlation between uranium concentration in the hepatopancreas and both body weight and shell length, suggesting that morphological parameters could influence accumulation and providing valuable correction parameters and a sensitive bioindicator for marine radiological biomonitoring applications. Although three species had uranium concentration factors exceeding the IAEA guideline values, the annual effective doses for all age groups were below the guideline value, and ecological doses remained well below ERICA thresholds, indicating negligible radiological risk from uranium isotopes. These findings support the use of bivalves in marine radiation monitoring and contribute to food safety and public health management in similar tropical coastal areas worldwide.

1. Introduction

Uranium is an actinide element and presents natural isotopes that emit ionizing radiation. Although the origin of uranium is natural, an

increase from man-made activities could have both radiological and chemical hazardous effects on animals and human beings (Fournier et al., 2004; Simon and Garnier-Laplace, 2004). Seas and oceans act as the ultimate sinks for uranium through inputs from atmospheric

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deposition, riverine transport, and coastal erosion (Romain Stefanelli et al., 2024). Uranium has been widely utilised as a tracer in research on hydrological processes, ocean circulation, and saltwater-sediment interactions because of its very stable concentration and long residence time in seawater (Andersen et al., 2007; Cole et al., 2020; Kipp et al., 2022; Not et al., 2012; Rutledge et al., 2024; Wang et al., 2017). Moreover, uranium is of particular interest due to its high bioavailability to marine organisms. In fact, uranium has the potential to accumulate significantly in several groups of marine organisms, including brown algae, sea urchins, and bivalves (Romain Stefanelli et al., 2024a,b). Bivalve molluscs are particularly interesting because of their capacity to accumulate significant concentrations of naturally occurring radionuclides and heavy metals (Bustamante et al., 2002; Fonollosa et al., 2017; Le et al., 2025; Liu et al., 2017; Tateda et al., 2003; Yuan et al., 2020). Consequently, they are widely employed in marine environmental monitoring programs due to their distinctive biological and ecological characteristics (Azizi et al., 2018; Carvalho et al., 2010; Connan et al., 2007; Feroz Khan et al., 2014; Hansen et al., 2022; Rouane-Hacene et al., 2015; Scudiero et al., 2014; Romain Stefanelli et al., 2024a,b; Yap et al., 2016). Uranium's accumulation in bivalves has attracted a lot of research on absorption kinetics, accumulation processes, and biological impacts because of its characteristics of both a heavy metal and a natural radionuclide (Fournier et al., 2004; Simon et al., 2011; Simon and Garnier-Laplace, 2004; Tran et al., 2004). Previous studies indicated that uranium could enter bivalve mollusks through multiple uptake pathways, exhibiting heterogeneous distribution among organs that was strongly influenced by environmental concentrations, exposure duration, and in particular, the chemical speciation of the uranium (Simon et al., 2011; Romain Stefanelli et al., 2024a,b). Despite these developments compared to other metals, there are few studies on uranium accumulation in bivalve molluscs. Existing studies have largely emphasized aqueous bioavailability, distribution within single species, and toxicity under specific chemical conditions (Denison, 2004; Hogan et al., 2005; Simon et al., 2011), whereas relatively few have examined interspecific and organ-specific distribution patterns or the influence of morphological characteristics and living habits on uranium accumulation in different bivalves. Elucidating these aspects, particularly the preferential accumulation in the hepatopancreas is crucial for improving toxicity assessments, refining biomonitoring approaches, and evaluating potential health risks associated with seafood consumption.

In recent years, awareness of the radiological risks in seafood has increased due to the significant role of seafood in human diets. According to Mishra et al. (2009), the consumption of seafood containing radionuclides is one of the main sources of natural radiation exposure (Mishra et al., 2009). Bivalve mollusks are considered nutritious food and a vital marine resource of high economic value for coastal communities (Feroz Khan et al., 2014). For aquatic organisms, some natural uranium isotopes are alpha-emitting and can induce significant genotoxic effects (Barillet et al., 2007; Simon et al., 2011). Therefore, assessing the radiation risk to humans from the consumption of uranium-containing bivalves is a crucial task too. Evaluating the impact of ionizing radiation on the environment and organisms has become one of the most important issues in radioecology (Duong et al., 2025; Feroz Khan et al., 2014). In this context, the ERICA tool (Environmental Risks from Ionizing Contaminants: Assessment and Management) was developed as a specialized framework for assessing environmental radioactivity risk by estimating radiation doses in non-human organisms and comparing them with ecological screening reference levels (Brown et al., 2004; Pentreath, 2002). This method is beneficial for determining how uranium ionizing radiation affects bivalve molluscs. The method supports strategies for the conservation of marine biodiversity and the sustainable management of marine resources.

Lam Dong province is a coastal province, located in the tropical monsoon climate. The favourable environmental conditions facilitated the dispersal and release of radioactive materials in/surrounding placer

area. The province's coastal area plays a crucial role in local communities' livelihoods, particularly through aquaculture and fisheries, with an estimated annual output of approximately 190,000 tons (Vietfish, 2020a). The high productivity and substantial seafood consumption typical of tropical marine ecosystems make bivalve mollusks a major food source, with an average catch of approximately 200 kg per vessel per day in the area (Vietfish, 2020b). Alongside its potential for marine resources, Lam Dong also hosts the largest titanium placer deposits in Vietnam and Southeast Asia, with high levels of natural background radiation (Nguyen et al., 2021). The marine environment and coastal ecosystems are at risk because titanium processing operations use a lot of water and produce effluent streams that contain radioactive materials (Duong et al., 2025). Recent findings have raised serious concerns about the level of radioactive exposure on environment of this region. A study by Nguyen et al. (2021) on the distribution of ^{210}Po in coastal organisms showed that the green mussel has a significantly higher accumulation capacity than other groups of organisms, reflecting the sensitivity of this species to radionuclide contamination (Nguyen et al., 2021). More recently, the study by Duong et al. (2025) on the Asian green mussel (*Perna viridis*) yielded alarming findings, showing that the effective dose from consuming this species exceeded the reference level of 1 mSv/year in most cases, particularly for children and infants (Duong et al., 2025). In this context, high seafood consumption, combined with the risk of radionuclide contamination from mining activities, underscores the urgent need to conduct research in the study's coastal region to provide baseline data for environmental monitoring and human health risk assessment. In addition, there is a lack of environmental radioactivity data globally in tropical monsoon coastal regions compared to temperate areas. Therein, the understanding of uranium distribution and accumulation in bivalve mollusks within tropical marine ecosystems, with potential emissions from mining activities such as those in Lam Dong province, remains limited. Previous studies were localized, focused on a few individual species and were insufficient to build a baseline database for environmental monitoring and health risk assessment (Assunta Meli et al., 2008; Duong et al., 2026; Fonollosa et al., 2017; Simon et al., 2011; Stefanelli et al., 2024). The bivalve mollusks were underexploited as a biomonitoring tool for uranium in those areas. To address these critical knowledge gaps and meet the urgent need for baseline database and risk assessment in the study region, the present study was conducted with the following aims: (i) to determine uranium concentrations (^{238}U and ^{234}U) in the muscle and hepatopancreatic tissues of 12 ecologically and commercially bivalve mollusk species collected from the coastal of Lam Dong province; (ii) to clarify the distribution and accumulation characteristics of uranium among species and organs, as well as the morphological factors; (iii) to assess radiation risk of uranium to humans by calculating annual effective doses (AED) from the consumption of these bivalve mollusks across different age groups (adults, children, and infants); and (iv) to evaluate the ionizing radiation risk of uranium to bivalve mollusks using the ERICA tool to determine potential population-level impact.

2. Materials and methods

2.1. Sampling

Twelve ecologically, commercially important, and commonly consumed bivalve mollusk species were collected by local men from the coastal area of Lam Dong province (Vietnam) in December 2024. For each species, five commercially sized individuals were selected. After collection, all specimens were immediately put in a box and transported to the laboratory. Three water samples were also collected to determine uranium concentrations, thereby supporting the assessment of uranium accumulation potential in bivalve species. In the laboratory, surface debris, sediments, and epibionts were removed by thorough washing with deionized water. Shell length and weight for each species were recorded to characterize bivalve morphology. The soft tissues were

separated into two parts: muscle tissue and digestive glands (hepatopancreas) to examine characteristic uranium distribution.

2.2. Method

2.2.1. Determination of ^{234}U and ^{238}U activities by alpha spectrometry

In the laboratory, the ^{234}U and ^{238}U activities in the muscle tissue and hepatopancreas of bivalve species were determined using alpha spectrometry, with ^{232}U employed as a tracer. The analytical procedure followed the method described by Chau et al. (2022) (Chau et al., 2022). The samples were decomposed in a microwave oven using a concentrated acid mixture (HCl and HNO_3 with a 3:1 ratio), with H_2O_2 added as an oxidizing agent, until complete dissolution was achieved. Uranium in biological and water samples was subsequently co-precipitated as $(\text{NH}_4)_2\text{U}_2\text{O}_7$ together with MnO_2 . The resulting precipitate was dissolved in concentrated HCl, and uranium was purified by adsorption onto a Dowex ion-exchange resin column with inner diameter of 1 cm and a resin height of 15 cm, the particle size of resins was 100-200 mesh and H^+ form (Rosenberg et al., 1991). Uranium fractions were then eluted using HNO_3 and distilled water. The obtained sample was evaporated to dryness and redissolved in 1M HCl. The solution was further treated with neodymium, Mohr's salt, and HF acid to convert uranium into a form suitable for alpha spectrometric measurement. The final mixture was filtered through a 0.1 μm membrane and dried at room temperature. Activities of ^{232}U , ^{234}U , and ^{238}U were measured using an ORTEC Alpha Ensemble-4 alpha spectrometer. Blank and standard samples were processed using the same procedure to ensure analytical accuracy and reliability for quality control (QA).

2.2.2. Estimate of the annual effective dose

The radiation risk from consuming bivalve mollusks containing ^{234}U and ^{238}U is determined by the annual effective dose (AED), which is calculated using the following formula (1):

$$\text{AED} = C_U \times C_f \times C_m \quad (1)$$

In which,

AED is the annual effective dose (mSv/y),

C_U is the activity concentrations of ^{234}U and ^{238}U measured in bivalve tissues (Bq/kg),

C_f is the uranium conversion factor for adults, children, and infants, with values of 45×10^{-6} , 68×10^{-6} and 1.2×10^{-5} mSv/Bq for ^{238}U and 49×10^{-6} , 74×10^{-6} and 1.3×10^{-5} mSv/Bq for ^{234}U , respectively (UNSCEAR, 2000).

C_m is the average annual bivalve consumption mass of a person (28.6 g/d $\sim$ 10.439 kg/y) (Stankovic and Jovic, 2012). Due to a lack of data on the recommended intakes for different age groups, this value is applied to the general population (Duong et al., 2025).

2.2.3. Estimation of ionizing radiation risk to bivalves using ERICA

In this study, uranium radiation doses to bivalve mollusks were estimated using the ERICA (Environmental Risk from Ionizing Contaminants: Assessment and Management) tool, version 2.0, released in June 2023. ERICA enables the conversion of measured environmental radioactivity values into absorbed doses for target organisms through a three-tier assessment framework (Brown et al., 2008). In this study, the Tier 2 assessment was selected to evaluate external, internal, and total irradiation doses for bivalve species. The assessment is based directly on the screening dose rate generated for each selected reference organism. Input parameters are presented in Table 4, with assumed occupancy factors for each species determined by its living habits. Sand and mud-dwelling species were assumed to spend 50% of their time on the sediment surface and 50% within the sediment. In contrast, rocky cliff species were assigned a 5:3:2 occupancy ratio for water, sediment surface, and sediment, respectively. The CR is defined as the ratio between the uranium activity in the whole body of the organism (Bq/kg fresh

weight) and filtered seawater (Bq/L) (Brown et al., 2008). In this study, the uranium activity of bivalve mollusks was determined by the mass balance method (Yankovich et al., 2010).

2.3. Statistical analysis

Statistical analyses were performed with a 95% confidence level using SPSS 2020 (Statistical Package for the Social Sciences) software, where p-values < 0.05 were considered statistically significant. The relationship between uranium concentration in tissue types and morphological parameters of bivalve mollusks, including shell length and weight, was assessed using Pearson correlation coefficients. Differences in uranium concentration between muscle tissue and hepatopancreatic tissue were tested using the T-test. In addition, descriptive statistics and illustrative graphs were constructed using OriginPro 2023 software (OriginLab Corporation, Northampton, MA, USA).

3. Results and discussion

3.1. Uranium activity and $^{234}\text{U}/^{238}\text{U}$ activity ratio in bivalve mollusks and seawater

The uranium concentrations and $^{234}\text{U}/^{238}\text{U}$ activity ratios in bivalve mollusk species are presented in Appendix I. The results indicate considerable variability among species and organs. In muscle tissue, ^{238}U activity concentrations ranged from 0.24 ± 0.02 Bq/kg (Pacific oyster) to 13.1 ± 0.35 Bq/kg (Half-propeller ark) with an average value of 3.4 Bq/kg, while ^{234}U activity concentration varied from 0.25 ± 0.03 Bq/kg (Pacific oyster) to 15.5 ± 1.6 Bq/kg (Half-propeller ark) with an average value of 4.6 Bq/kg. Uranium concentrations in the hepatopancreas were significantly higher, with the minimum, maximum, and average values of ^{238}U being 0.32 ± 0.03 Bq/kg (Pacific oyster), 25.0 ± 2.1 Bq/kg (Indo-Pacific ark), and 12 Bq/kg, respectively, and corresponding values of ^{234}U of 0.61 ± 0.06 Bq/kg (Pacific oyster), 94.7 ± 9.47 Bq/kg (Undulate venus), and 20.9 Bq/kg. The $^{234}\text{U}/^{238}\text{U}$ activity ratios in the samples exceed unity, indicating disequilibrium between ^{234}U and ^{238}U within the uranium series in the bivalves. In muscle tissue, this ratio ranged from 1.04 to 2.60, with a mean value of 1.5, whereas in the hepatopancreas it ranged from 1.0 to 3.89, with an average of 1.7.

Uranium-isotope activity concentration and $^{234}\text{U}/^{238}\text{U}$ activity ratio in seawater (three sample sites) are presented in Table 1, Fig. 1. The results show that activity concentrations of U-isotopes were similar for the whole samples. ^{238}U activity concentrations ranged from 48.9 ± 3.5 to 51.3 ± 4.1 with an average value of 49.8 mBq/L, while ^{234}U activity concentration varied from 51.5 ± 3.6 to 57.6 ± 4.6 with an average of 54.9 mBq/L. These values are significantly higher than those reported for many seas and oceans worldwide, such as the Black Sea, the Irish Sea, and the Pacific Ocean, where ^{238}U activity typically ranges from 22.8 to 35.5 mBq/L and ^{234}U from 26.5 to 37.3 mBq/L (Eigl et al., 2013). This higher uranium concentration could be attributed to the characteristic climate and geology of the Lam Dong coastal area, where titanium placer deposits containing ilmenite, monazite, and zircon are widely distributed among which monazite and zircon are uranium-rich mineral

Table 1

Uranium-isotopes activity concentration and $^{234}\text{U}/^{238}\text{U}$ activity ratio in seawater samples collected from the study area.

Sample	Uranium concentration in water (mBq/L)		$^{234}\text{U}/^{238}\text{U}$
	^{238}U	^{234}U	
1	51.3 ± 4.1	57.6 ± 4.6	1.12 ± 0.13
2	49.3 ± 3.5	51.5 ± 3.6	1.04 ± 0.10
3	48.9 ± 3.9	55.6 ± 4.4	1.14 ± 0.13
Average	49.8 ± 3.8	54.9 ± 4.2	1.10 ± 0.12
Min	48.9 ± 3.5	51.5 ± 3.6	1.04 ± 0.10
Max	51.3 ± 4.1	57.6 ± 4.6	1.14 ± 0.13

phases. The $^{234}\text{U}/^{238}\text{U}$ activity ratio in seawater samples ranged from 1.04 ± 0.1 to 1.14 ± 0.13 , with a mean value of 1.10 ± 0.12 , consistent with the range of 1.14 to 1.17 generally observed in marine environments (Chi et al., 2024; Krishnaswami and Cochran, 2016; Skwarzec et al., 2004). These values are close to unity within analytical uncertainty, indicating near-equilibrium conditions. The $^{234}\text{U}/^{238}\text{U}$ activity ratio of approximately 1 in seawater indicates that alpha-recoil effects are negligible compared to other mobilization processes. In the coastal area of Lam Dong, strong chemical weathering processes under tropical monsoon climate conditions can promote the release of uranium from sediments and minerals into the marine environment. The dissolved uranium is subsequently transported and dispersed within the water column, providing a source for uptake and accumulation by bivalve mollusks in the study area.

3.2. Distribution, bioaccumulation of uranium among species, between organs and morphological factors

There are significant differences in uranium concentrations (^{234}U and ^{238}U) among species and between organs of bivalve mollusks. Therein, uranium concentrations in Indo-Pacific ark, Half-propeller ark, and Lyrate hard clam were recorded 2–3 times higher than the average value, whereas Pacific oyster and Antique had approximately 10–12 times lower uranium concentrations in both muscle tissue and hepatopancreas. Notably, the ^{238}U activity concentration in the muscle tissue of Half-propeller ark and Indo-Pacific was 54 and 78 times higher than that of the Pacific oyster, while this difference was even greater in the hepatopancreas. Previous studies had shown that substantial variability in heavy metal concentrations in bivalve mollusks can be attributed to a combination of biological and physiological factors, particularly feeding habits, food quality and quantity, and metabolic rate of each species (Hédouin et al., 2010; Liu et al., 2017; Morankar and Kurhe, 2023; Pavón et al., 2022). These factors interact with environmental

conditions to form accumulation patterns of each species (Indra Januar et al., 2019). The species' high capacity for uranium concentration accumulation is confirmed by the concentration factor (CF) coefficient. Therein, the concentration factor (CF) values for Indo-Pacific ark, Half-propeller ark, and Lyrate hard clam exceed the IAEA recommendations by 4–9 times in muscle tissue and 9–17 times in the hepatopancreas (IAEA, 2004). Conversely, species with low uranium concentrations, such as Pacific oyster and Antique ark showed significantly lower concentration factor (CF) coefficients, ranging from only 4.7 to 21.7, indicating limited uranium accumulation capacity.

The distribution of uranium among the organs of bivalve mollusks

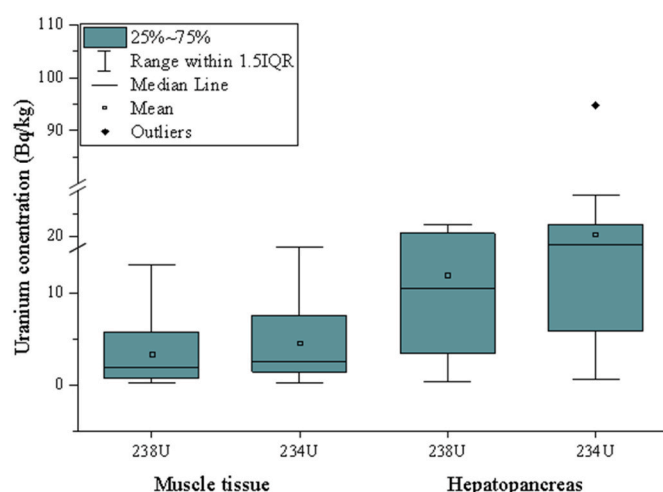


Fig. 2. Distribution of ^{234}U and ^{238}U activity concentration in muscle tissue and hepatopancreatic of bivalve species.

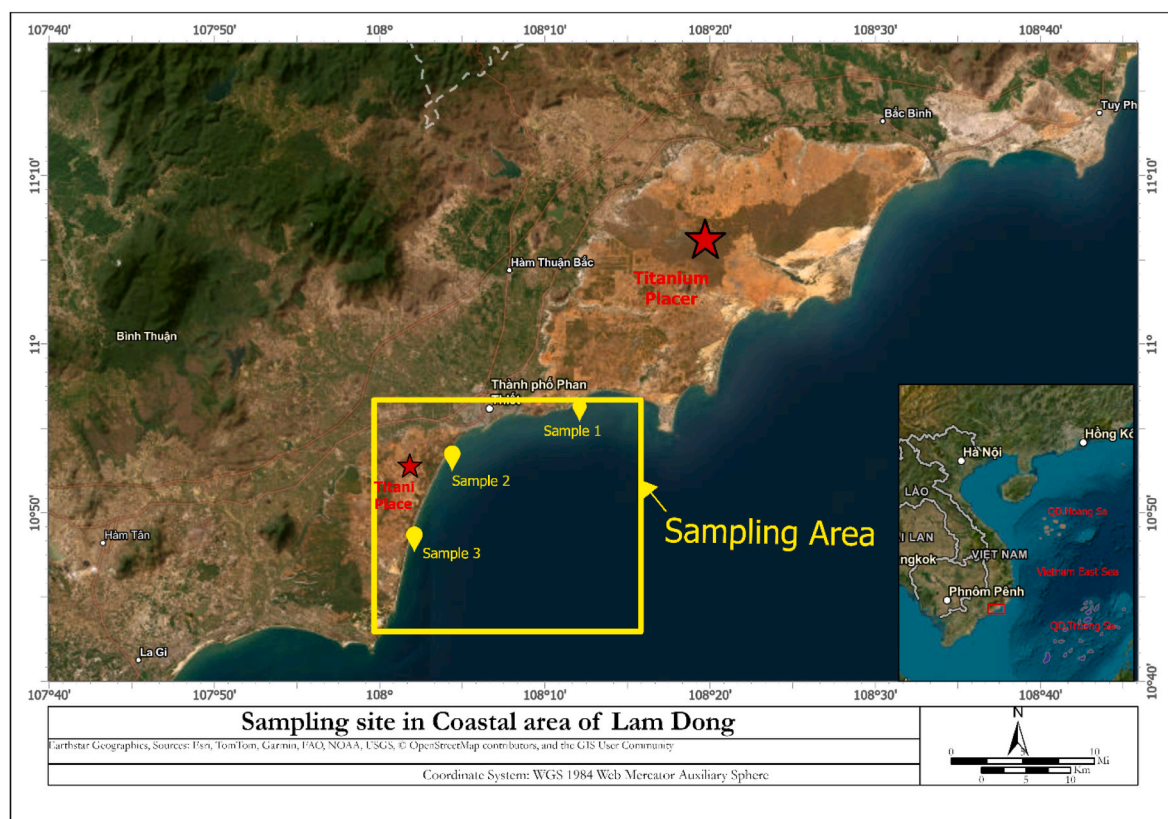


Fig. 1. The location of sampling site in the coastal area of Lam Dong province (Vietnam).

Table 2
Correlation between weight and shell length of bivalve species and ^{234}U , ^{238}U activity in muscle tissue and hepatopancreas.

		Weight	Shell length	Muscle tissue		Hepatopancreas	
				^{238}U	^{234}U	^{238}U	^{234}U
Muscle tissue	Weight	1					
	Shell length	0.78 ^a	1				
	^{238}U	−0.28	−0.27	1			
Hepatopancreas	^{234}U	−0.36	−0.28	0.97 ^a	1		
	^{238}U	−0.67 ^b	−0.59 ^b	0.42	0.46	1	
	^{234}U	−0.5	−0.48	0.08	0.12	0.76 ^a	1

^a Correlation is significant at the 0.01 level (2-tailed).

^b Correlation is significant at the 0.05 level (2-tailed).

showed distinct differences (Fig. 2), with the hepatopancreas recording uranium concentrations were approximately 3–5 times higher than those in muscle tissue in most of the surveyed species (see Fig. 1). Similarly, the concentration factor (CF) of uranium in the hepatopancreas surpassed that in muscle tissue by 3–5 times, reflecting the preferential accumulation in this organ. The preferential accumulation of uranium in the hepatopancreas was found to be similar to that reported for other transition metals such as Cd and Zn or radionuclide (^{210}Po) (Li et al., 2015; Romain Stefanelli et al., 2024a,b). High accumulation in visceral organs such as the hepatopancreas can be explained by the organ's unique physiological role, particularly its ability to complex biological molecules, including heavy metal-binding proteins such as metallothionein (Simon and Garnier-Laplace, 2004; Romain Stefanelli et al., 2024a,b).

The uranium bioaccumulation in bivalve mollusks is governed by a complex sequence of physicochemical and biological processes, including adsorption, inter-organ transport, storage, and excretion (Simon and Garnier-Laplace, 2004). While earlier studies identified uptake from seawater through the gill system as the dominant pathway of uranium accumulation in certain bivalve species (Simon et al., 2011; Simon and Garnier-Laplace, 2004). The present results indicate that this mechanism cannot fully explain the observed uranium distribution patterns. In particular, the $^{234}\text{U}/^{238}\text{U}$ activity ratios between two tissue organs and those measured in seawater strongly suggest the involvement of additional uptake pathways. Although the gills are thought to act as the first point of contact and have a high accumulation capacity from high exposure levels in the surrounding environment. Due to the lack of metallothionein (MT) in the gills, most uranium accumulates in the non-cytoplasmic portion of the gills, demonstrating a deficiency of cytoplasmic proteins for binding this metal (Cooley et al., 2000; Simon and Garnier-Laplace, 2004). This constraint reduces the long-term retention efficiency of gill tissues, necessitating redistribution to other organs.

In contrast, the hepatopancreas plays a more dynamic role in uranium uptake and processing. Experimental studies have demonstrated that this organ not only receives uranium transported from the gills via hemolymph circulation but also directly assimilates particulate-bound uranium through dietary intake (Marigómez et al., 2002; Simon and Garnier-Laplace, 2004), then transfers it to lysosomes and other structures for isolation and detoxification (Le Pennec and Le Pennec, 2001; Marigómez et al., 2002). Therefore, in this study, uranium accumulation in mollusks could be suggest the simultaneous contribution of two sources with different isotopic characteristics: (i) seawater-soluble uranium absorbed directly through the gills surface, with a $^{234}\text{U}/^{238}\text{U}$ activity ratio approximately equal to that in seawater, and (ii) uranium bound to sediment particles or suspended matter absorbed through the

digestive tract, often with a higher $^{234}\text{U}/^{238}\text{U}$ activity ratio due to ^{234}U enrichment on the particle surface. The $^{234}\text{U}/^{238}\text{U}$ activity ratio recorded in each tissue reflects the relative contribution of these two absorption pathways, consistent with previously reported results (Romain Stefanelli et al., 2024a,b). Therefore, the hepatopancreas is not only an input tissue but also a final distribution and reservoir, accounting for the majority of the measured uranium concentration in the body due to its high contribution to total body mass and its crucial role in metal absorption and metabolism.

Correlation analysis indicates that morphological factors significantly influenced uranium accumulation in bivalve tissues (Table 2). In muscle tissue, correlations between morphological factors (weight and shell length) and uranium concentration were not statistically significant ($p > 0.05$), indicating an unclear influence of morphological factors on uranium accumulation in this tissue. Conversely, a significant negative correlation between morphological factors and ^{238}U was observed in the hepatopancreas with correlation coefficients $r = -0.67$ for weight and $r = -0.59$ for shell length ($p < 0.05$). This trend suggests that smaller individuals are more likely to accumulate uranium in the hepatopancreas than larger individuals. Differences in uranium accumulation rates with size can be explained by changes in the physiological and morphological characteristics of organisms at different developmental stages. Younger individuals generally have higher metabolic activity, increased sensitivity, and a larger surface area-to-volume ratio, leading to faster metal absorption. Conversely, larger individuals have lower water filtration rates per unit body mass and a reduced surface area-to-volume ratio, thereby decreasing metal absorption capacity (Ansari et al., 2004; Azizi et al., 2018). The apparent correlation between morphological features and uranium concentration in the hepatopancreas reflects its specialized role in the absorption and accumulation of heavy metals, making this organ more sensitive to physiological changes associated with organism size.

Regarding habitat effects, the study does not find statistically significant differences in uranium concentration between species living on rocky cliffs and those living on sand and mud. This suggests that living habits are not the primary issues of uranium accumulation in bivalve mollusks in the study area, although they are often considered influential factors. The food type similarity in the environment and the uranium concentration in seawater could explain this result. Based on the above findings, it can be seen that the hepatopancreas of bivalve mollusks has significant potential as a sensitive biomarker in marine radioactivity monitoring programs. Furthermore, higher uranium concentrations in the hepatopancreas more accurately reflect environmental pollution levels (Simon and Garnier-Laplace, 2004; Stefanelli et al., 2024), supporting the suitability of this organ for bivalve-specific applications in marine environmental monitoring. In addition, the strong correlation

between morphological factors and uranium concentration in the hepatopancreas could provide a useful additional parameter for estimating actual environmental exposure concentrations in further studies. Notably, because the hepatopancreas typically contains higher uranium concentrations, the sample volume for analysis can be significantly reduced while maintaining reliability, thus improving analytical efficiency, reducing errors, and lowering costs in long-term monitoring programs.

3.3. Radiation risk assessment of uranium to humans due to consumption of bivalve mollusks

Annual effective dose (AED) due to consumption of uranium-containing bivalve mollusks is shown in Table 3. The results showed that AEDs calculated from muscle tissue and hepatopancreas consumption vary considerably among species and age groups. For muscle tissue, the mean AED for adults, children, and infants was 1.59, 2.4, and 4.24 $\mu\text{Sv}/\text{year}$ for ^{238}U , and 2.36, 3.56, and 6.25 $\mu\text{Sv}/\text{year}$ for ^{234}U , respectively. The AEDs calculation for the hepatopancreas showed significantly higher values than those in muscle tissue due to the higher uranium concentrations in this organ. Specifically, the AEDs for ^{238}U in the hepatopancreas were 6.12, 8.49, and 15 $\mu\text{Sv}/\text{year}$ for adults, children, and infants, respectively, while the corresponding values for ^{234}U were 10.7, 16.1, and 28.3 $\mu\text{Sv}/\text{year}$. When considering the total AED from both tissues and uranium isotopes, values ranged from 0.71 to 63.3 $\mu\text{Sv}/\text{year}$ for adults, from 1.05 to 94 $\mu\text{Sv}/\text{year}$ for children, and from 1.85 to 165 $\mu\text{Sv}/\text{year}$ for infants, with mean values of 20.7, 30.5, and 53.7 $\mu\text{Sv}/\text{year}$, respectively. The total AED clearly increased with decreasing age, indicating greater radiological sensitivity in children and infants. The difference in AED with age is associated with changes in dose conversion factors, reflecting the smaller body mass and higher metabolic rates of children and infants, which result is higher effective radiation doses for the same level of food consumption.

The AED limit of 1 mSv (1000 μSv) is recommended by the WHO (2011) and UNSCEAR (2000). All the AED values recorded in this study were significantly lower than the recommended level. This suggests that the radiation risk from consuming uranium-containing bivalve mollusks in the study area is negligible. It should be emphasized that this assessment considers only uranium exposure from bivalve mollusk consumption and is based on assumed consumption rates. The total radiation dose received by an individual includes other natural radionuclide sources, other foods, and man-made sources; therefore, a further comprehensive study is needed to assess the overall radiation risk to human health.

3.4. Ionizing radiation risk evaluation of uranium to bivalve mollusks using the ERICA tool

Assessing the risk of ionizing radiation exposure to bivalve mollusks due to uranium contamination is a crucial aspect of protecting marine ecosystems and maintaining biodiversity. The results showed significant variability in total dose among species, ranging from 0.06 to 3.2 $\mu\text{Gy}/\text{h}$, with an average value of 0.9 $\mu\text{Gy}/\text{h}$ (Table 4). Compared to the screening dose rate threshold of 10 $\mu\text{Gy}/\text{h}$ recommended by the ERICA, all values recorded in this study are significantly lower. This indicates that the risk of ionizing radiation from uranium to bivalve mollusks in the study area is negligible and has insignificant ecological impacts. Although current dose rates are within safe limits, this assessment considers only radiation from uranium and does not include other radionuclide substances that may be present in the environment, such as polonium or artificial isotopes. The total radiation dose actually received by organisms may be higher due to the cumulative effects from multiple sources. Furthermore, the biological impact of ionizing radiation depends not only on the dose rate but also on the exposure time, the organism's developmental stage, and the recovery capacity of each species. Therefore, further comprehensive, long-term studies are required to fully assess the

Table 3
Annual effective dose (AED) from consumption of bivalve species.

English name	Annual effective dose ($\mu\text{Sv}/\text{year}$)											
	Muscle tissue						Hepatopancreas					
	^{238}U			^{234}U			^{238}U			^{234}U		
	Adults	Children	Infants	Adults	Children	Infants	Adults	Children	Infants	Adults	Children	Infants
Pacific oyster	0.11	0.17	0.29	0.12	0.19	0.33	0.16	0.23	0.40	0.31	0.47	0.83
Senatorial scallop	0.94	1.41	2.50	2.65	4.00	7.03	4.04	5.61	9.91	4.98	7.52	13.2
Glottosa scallop	0.66	1.00	1.76	0.73	1.11	1.95	5.36	7.44	13.1	8.37	12.6	22.2
Indo - Pacific ark	3.19	4.83	8.52	3.89	5.87	10.3	12.8	17.7	31.2	12.8	19.4	34.0
Philippine horse mussel	0.71	1.07	1.88	1.27	1.92	3.38	2.52	3.50	6.18	3.02	4.56	8.01
Asian Green mussel	2.71	4.10	7.24	4.95	7.48	13.1	8.92	12.4	21.8	11.1	16.8	29.5
Comb pen shell	0.33	0.49	0.87	0.63	0.95	1.68	1.75	2.43	4.28	1.92	2.90	5.09
Antique ark	0.12	0.18	0.32	0.14	0.22	0.38	0.44	0.61	1.08	0.61	0.92	1.61
Windowpane oyster	1.21	1.82	3.22	1.33	2.01	3.52	1.05	1.46	2.57	0.61	0.92	1.61
Undulate venus	0.89	1.35	2.38	1.65	2.49	4.37	12.4	17.3	30.5	48.3	72.9	128
Asiatic hard clam	0.35	0.53	0.93	0.97	1.46	2.57	12.3	17.0	30.0	19.4	29.2	51.4
Half-protellor ark	6.12	9.25	16.3	7.92	12.0	21.0	6.98	9.68	17.1	8.44	12.7	22.4
Lyrate hard clam	3.33	5.03	8.87	4.37	6.60	11.6	10.8	15.0	26.5	15.8	23.8	41.8
Average	1.59	2.40	4.24	2.36	3.56	6.25	6.12	8.49	15.0	10.7	16.1	28.3
Min	0.11	0.17	0.29	0.12	0.19	0.33	0.16	0.23	0.40	0.31	0.47	0.83
Max	6.12	9.25	16.3	7.92	12.0	21.0	12.8	17.7	31.2	48.3	72.9	128
Total												
	Adults	Children	Infants	Adults	Children	Infants	Adults	Children	Infants	Adults	Children	Infants
	0.71	1.05	1.85	12.6	18.5	32.6	12.6	18.5	32.6	12.6	18.5	32.6
	15.1	22.2	39.0	32.6	47.7	84.1	32.6	47.7	84.1	32.6	47.7	84.1
	11.1	19.5	33.7	27.7	40.7	71.7	27.7	40.7	71.7	27.7	40.7	71.7
	4.62	6.77	11.9	4.62	6.77	11.9	4.62	6.77	11.9	4.62	6.77	11.9
	1.31	1.93	3.39	1.31	1.93	3.39	1.31	1.93	3.39	1.31	1.93	3.39
	7.07	10.6	18.6	7.07	10.6	18.6	7.07	10.6	18.6	7.07	10.6	18.6
	63.3	94.0	165	63.3	94.0	165	63.3	94.0	165	63.3	94.0	165
	32.9	48.2	84.9	32.9	48.2	84.9	32.9	48.2	84.9	32.9	48.2	84.9
	29.5	43.6	76.8	29.5	43.6	76.8	29.5	43.6	76.8	29.5	43.6	76.8
	34.3	50.5	88.8	34.3	50.5	88.8	34.3	50.5	88.8	34.3	50.5	88.8
	20.7	30.5	53.7	20.7	30.5	53.7	20.7	30.5	53.7	20.7	30.5	53.7
	0.71	1.05	1.85	0.71	1.05	1.85	0.71	1.05	1.85	0.71	1.05	1.85
	63.3	94.0	165	63.3	94.0	165	63.3	94.0	165	63.3	94.0	165

Table 4

Ionizing radiation risk for bivalve species calculated using the Erica tool.

English name	Living habits	Occupancy factor	Uranium concentration (Bq/kg ^a)		CR		Dose rate (μGy/h)		
			²³⁸ U	²³⁴ U	²³⁸ U	²³⁴ U	²³⁸ U	²³⁴ U	Total
Pacific oyster	Rocky cliffs	Water = 0.5, sediment - surface = 0.3, sediment = 0.2	0.99	1.03	19.8	18.8	0.03	0.03	0.06
Senatorial scallop	Rocky cliffs		8.40	21.8	169	398	0.21	0.61	0.82
Gloriosa scallop	Rocky cliffs		5.91	6.04	119	110	0.15	0.17	0.32
Indo - Pacific ark	Rocky cliffs		28.7	32.1	576	584	0.72	0.90	1.62
Philippine horse mussel	Rocky cliffs		6.34	10.5	127	191	0.16	0.29	0.45
Asian Green mussel	Rocky cliffs	Sediment-surface = 0.5, sediment = 0.5	24.4	40.8	489	744	0.61	1.14	1.75
Comb pen shell	Sand and mud		2.93	5.21	58.8	94.9	0.08	0.15	0.22
Antique ark	Sand and mud		1.09	1.18	21.9	21.6	0.03	0.03	0.07
Windowpane oyster	Sand and mud		10.8	10.9	217	199	0.28	0.30	0.58
Undulate venus	Sand and mud		8.00	13.6	161	247	0.21	0.38	0.59
Asiatic hard clam	Sand and mud		3.13	7.98	62.8	145	0.08	0.22	0.31
Half-propellor ark	Sand and mud		55.0	65.2	1104	1188	1.38	1.82	3.20
Lyrate hard clam	Sand and mud		29.9	36.0	600	656	0.75	1.01	1.76
Average			14.3	19.4	286	354	0.36	0.54	0.90
Min			0.99	1.03	19.8	18.8	0.03	0.03	0.06
Max			55.0	65.2	1104	1188	1.38	1.82	3.20

^a (fresh weight) (whole body).

effects of ionizing radiation on the health of bivalve mollusk populations, particularly in species with high uranium accumulation capacity and significant ecological value in coastal ecosystems.

4. Conclusion

This paper studied the distribution, accumulation, and radiological risks of ²³⁴U and ²³⁸U activity concentrations in twelve ecologically and commercially important bivalve mollusk species from a rich titanium placer area along Lam Dong's coast. Results showed uranium distribution varies among species, influenced by species' biological factors. The hepatopancreas dominated uranium accumulation over muscle, consistent with its role in binding heavy metals via metallothionein. The ²³⁴U/²³⁸U ratio differences between organs and seawater indicated absorption pathways from gills and digestion. The significant negative correlation between uranium concentration in the hepatopancreas and both body weight and shell length indicated that morphological factors influence heavy metal absorption and accumulation, whereas habitat type exerts negligible effects. Findings suggest the hepatopancreas could be a sensitive biomarker for marine radioactivity monitoring, accurately reflecting environmental pollution levels for reducing sample volume, costs, and uncertainties, more reliably, supporting future bio-surveys.

From a human health perspective, the annual effective dose from consuming these uranium-containing bivalve mollusks in the coastal waters of Lam Dong does not pose a significant impact on consumers under normal consumption conditions. Ecological risk assessment using the ERICA tool showed that the total uranium-attributable radiation doses to bivalve mollusk populations remained significantly below the screening threshold of 10 μGy/h across all species examined, indicating negligible ecological risk under prevailing environmental conditions.

This study provided a reliable scientific database on the distribution and accumulation of ²³⁴U and ²³⁸U in bivalve mollusk species, forming the basis for food safety management, marine environmental monitoring, and biodiversity conservation in tropical monsoon coastal areas. The results obtained allow for the assessment of radiological risks to public health through seafood consumption and support the development and optimization of biomonitoring programs based on indicator organisms and organs.

CRediT authorship contribution statement

Van-Hao Duong: Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Trung-Tien Chu:** Investigation, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. **Thanh-Xuan Pham Thi:** Conceptualization, Investigation, Resources, Software, Validation, Visualization, Writing – review & editing. **Khai M. Nguyen:** Data curation, Formal analysis, Investigation, Resources, Software, Writing – review & editing. **Marckasagayam Priyadharshini:** Conceptualization, Validation, Writing – original draft, Writing – review & editing. **Mohamed Saiyad Musthafa:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Trinh Phan Trong:** Data curation, Investigation, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Duc-Thang Duong:** Conceptualization, Formal analysis, Investigation, Resources, Validation, Writing – original draft, Writing – review & editing. **Thanh-Duong Nguyen:** Conceptualization, Data curation, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing. **Hue Nguyen Thanh Kim:** Conceptualization, Data curation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

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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Appendix I

Sample	Local name	English name	Scientific name	Living habits	Weight (g)	Shell length (cm)	Uranium concentration (Bq/kg)				Concentration factor				²³⁴ U/ ²³⁸ U	
							Mus		Hep		Mus		Hep		Mus	Hep
							²³⁸ U	²³⁴ U	²³⁸ U	²³⁴ U	²³⁸ U	²³⁴ U	²³⁸ U	²³⁴ U		
1	Hàu	Pacific oyster	<i>Magallana gigas</i> (Thunberg, 1793)	Rocky cliffs	89.4	10.6	0.24 ± 0.02	0.25 ± 0.03	0.32 ± 0.03	0.61 ± 0.06	4.72	4.47	6.48	11.1	1.04	1.89
2	Sò điệp	Senatorial scallop	<i>Mimachlamys sanguinea</i> (Linnaeus, 1758)		23.7	7.86	2.00 ± 0.20	5.20 ± 0.53	7.94 ± 0.75	9.77 ± 0.93	40.2	94.7	159	178	2.60	1.23
3	Điệp Glori	Gloriosa scallop	<i>Mimachlamys gloriosa</i> (Reeve, 1852-1853)		16.8	4.80	1.41 ± 0.14	1.44 ± 0.14	10.5 ± 1.0	16.4 ± 1.6	28.3	26.2	211	299	1.02	1.56
4	Sò navi	Indo - Pacific ark	<i>Arca navicularis</i> Bruguière, 1789		19.4	6.03	6.83 ± 0.68	7.63 ± 0.76	25.0 ± 2.1	25.1 ± 2.1	137	139	502	458	1.12	1.00
5	Vẹm đỏ	Philippine horse mussel	<i>Modiolus philippinarum</i> (Hanley, 1842-1846)	Sand and mud	39.2	9.94	1.51 ± 0.15	2.50 ± 0.25	4.95 ± 0.42	5.92 ± 0.49	30.3	45.5	99.5	108	1.66	1.20
6	Vẹm xanh	Asian Green mussel	<i>Perna viridis</i> (Linnaeus, 1758)		10.3	6.3	5.80 ± 0.59	9.72 ± 1.0	17.5 ± 1.7	21.8 ± 2.1	116	177	351	397	1.68	1.25
7	Sò mai	Comb pen shell	<i>Atrina pectinata</i> (Linnaeus, 1767)		109	18.4	0.70 ± 0.07	1.24 ± 0.12	3.43 ± 0.32	3.76 ± 0.35	14.0	22.6	68.9	68.6	1.78	1.10
8	Sò lông	Antique ark	<i>Anadara antiquata</i> (Linnaeus, 1758)		21.7	4.50	0.26 ± 0.03	0.28 ± 0.03	0.86 ± 0.08	1.19 ± 0.11	5.20	5.14	17.3	21.7	1.09	1.38
9	Sò giấy	Windowpane oyster	<i>Placuna placenta</i> (Linnaeus, 1758)		128	9.43	2.58 ± 0.26	2.61 ± 0.26	2.06 ± 0.19	6.84 ± 0.64	51.8	47.5	41.4	125	1.01	3.32
10	Sò lụa	Undulate venus	<i>Paratapes undulatus</i> (Born, 1778)		4.90	4.21	1.90 ± 0.19	3.2 ± 0.32	24.4 ± 2.4	94.7 ± 9.5	38.2	58.9	490	1726	1.70	3.88
11	Sò nâu	Asiatic hard clam	<i>Meretrix meretrix</i> (Linnaeus, 1758)		15.0	4.08	0.74 ± 0.08	1.90 ± 0.19	24.0 ± 2.4	38.0 ± 3.9	15.0	34.6	483	692	2.55	1.58
12	Sò vỏ lệch	Half-propellor ark	<i>Trisidos semitorta</i> (Lamarck, 1819)		26.5	6.17	13.1 ± 0.36	15.5 ± 1.59	13.7 ± 1.3	16.6 ± 1.6	263	283	275	302	1.19	1.21
13	Sò trắng	Lyrate hard clam	<i>Meretrix lyrata</i> (Sowerby, 1851)		20.5	4.40	7.11 ± 0.71	8.58 ± 0.86	21.3 ± 2.2	30.9 ± 3.2	143	156	427	564	1.21	1.45
Average		Average					3.4	4.6	12.0	20.9	68.2	84.2	241	381	1.5	1.7
Min		Min					0.24 ± 0.02	0.25 ± 0.03	0.32 ± 0.03	0.61 ± 0.06	4.7	4.5	6.5	11.1	1.0	1.0
Max		Max					13.1 ± 0.35	15.5 ± 1.6	25.0 ± 2.1	94.7 ± 9.5	263	283	502	1726	2.6	3.9

Mus: Muscle tissue.

Hep: Hepatopancreas.

Data availability

No data was used for the research described in the article.

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