



Uranium isotopes (^{234}U and ^{238}U) in *Perna viridis* from a titanium placer coastal zone in Vietnam: bioaccumulation patterns and radiological risk assessment

Van-Hao Duong¹ · Tien Chu Trung¹ · Khai M. Nguyen^{2,3} · Thi Thuy Huong Ngo⁴ · Marckasagayam Priyadharshini⁵ · Mohamed Saiyad Musthafa⁶ · Xuan-Quang Nguyen^{7,8} · Nga Phung Thi⁹ · Trinh Phan Trong¹⁰ · Duc-Thang Duong¹¹ · Thanh-Duong Nguyen¹² · Miklós Hegedűs¹³ · Thanh-Xuan Pham Thi¹ · Tibor Kovács¹⁴

Received: 7 February 2026 / Accepted: 27 March 2026
© The Author(s) 2026

Abstract

Activity concentrations of ^{234}U and ^{238}U as well as $^{234}\text{U}/^{238}\text{U}$ ratios were investigated in the muscle and digestive diverticulum organs of ten size group samples of Asian green mussel (*Perna viridis*) from Binh Thuan, Vietnam by alpha-spectrometry, and radiological risk assessment was carried out. The ^{234}U and ^{238}U activities in muscle tissues and digestive diverticulum ranged from 1.4 ± 0.1 to 53.2 ± 4.3 Bq.kg⁻¹, from 1.2 ± 0.2 to 57.2 ± 4.5 Bq.kg⁻¹, and from 3.8 ± 0.3 to 45.0 ± 7.5 Bq.kg⁻¹, from 3.1 ± 0.2 to 42.0 ± 6.6 Bq.kg⁻¹, respectively. Uranium activities showed a decreasing trend in groups with smaller shell lengths from 5 to 6.5 cm and stabilized in individuals larger than 7 cm. Bioaccumulation factors were higher in smaller mussels, demonstrating greater accumulation, indicating their suitability as sentinel organisms for further study and radioecological monitoring of uranium isotopes. The $^{234}\text{U}/^{238}\text{U}$ activity ratios in digestive diverticula were consistently higher than in muscle tissues, suggesting dual uranium uptake pathways: direct absorption from seawater and ingestion of contaminated foods. The average risk to the mussels from exposure to uranium alone is below the ERICA screening reference level of 10 $\mu\text{Gy.h}^{-1}$, but a single sample exceeded this level indicating further investigation is necessary. Annual committed effective doses from consuming mussels containing ^{234}U and ^{238}U ranged from 2.11 to 43.60 $\mu\text{Sv.y}^{-1}$, with a mean of 12.04 $\mu\text{Sv.y}^{-1}$. While doses from ^{234}U and ^{238}U are within UNSCEAR safety thresholds, other radionuclides (e.g., Po, Pb, and Ra isotopes) should be considered for a comprehensive assessment. Not consuming small mussels is recommended due to higher potential radionuclide accumulation.

Keywords ^{234}U · ^{238}U · Environmental radioactivity · Uranium uptake pathway · Asian green mussel · Titanium placer · ERICA

Introduction

The marine ecosystem covers more than 70% of the Earth's surface, and is crucial for numerous human activities and life. The marine ecosystem, as a sink, contains a variety of pollutant materials, including both manufactured and natural contaminants (from human activities, tectonics, numerous natural disasters including storms, coastal erosion, sea level rise, earthquakes, tsunamis, and environmental pollution) [34, 35, 76, 83]. Furthermore, heavy metals, including radionuclides and elements like Cd or Hg, pose serious toxicity problems in marine food webs and are primarily generated

by mining, industrial discharges, and agriculture [22, 55, 69, 75]. Thus, it is crucial to study and observe marine environments to identify any threats to human health through food chains as well as the direct effects of pollution on marine ecosystems.

In recent years, increasing attention has been directed toward monitoring marine environmental pollution and evaluating radiological safety, particularly with respect to seafood consumption [12, 41, 59, 66, 82, 89]. Previous research efforts have focused on the characterization of radionuclides, their interaction mechanisms, migration pathways, excretion processes, and accumulation in marine organisms [9, 21, 96, 111]. Research on the assessment of radiological risks to humans and marine organisms intended for consumption remains relatively scarce, may be region specific, and often

Extended author information available on the last page of the article

focuses on artificial contamination, like releases from a nuclear disaster. A fundamental reality of life on Earth is that all organisms are continuously exposed to ionizing radiation from natural background sources [10]. Protecting humans from excessive exposure simultaneously helps to ensure that ecosystems and non-human species are adequately safeguarded [51]. To inform environmental impact assessments and guide policy-making, numerous studies have sought to establish reliable and scientifically robust frameworks for evaluating the ecological consequences of ionizing radiation [6, 32, 39, 52, 65]. Some studies have examined the potential radiological risks associated with seafood consumption [2, 4, 45, 71, 95, 97, 101, 105]. Because of bioaccumulation, aquatic organisms may accumulate radionuclides in their tissues at levels considerably higher than those present in ambient waters, making them more susceptible to both internal and external exposure [79, 98]. To evaluate these risks, different analytical frameworks have been proposed. Therein, the ERICA tool (Environmental Risk from Ionizing Contaminants: Assessment and Management) being among the most widely applied. ERICA facilitates dose assessments for biota across terrestrial, freshwater, and marine systems, and can be tailored to both standard reference organisms and species of specific interest [7, 13–15, 42, 106]. Refining and applying such assessment frameworks will improve understanding of health risks from naturally occurring radionuclides in seafood and support stronger radiation protection for humans and marine ecosystems.

Vietnam's coastline features approximately 92 titanium placer deposits, distributed across various coastal provinces. Notably, Binh Thuan province accounts for over 90% of Vietnam's titanium reserves, estimated at around 600 million tons. The place was also selected for building two nuclear power plants, which will be operational in 2030. According to Nguyen et al., mining activities in these placer regions could introduce naturally occurring radioactive materials into coastal marine systems [82]. In addition, inland mining, agricultural activities, and residential activities also contribute to the release of radioactive isotopes into the marine environment in the region. Uranium was found to be at relatively high concentrations in seawater [1, 17, 31, 63]. The weathering and leaching of rocks, soils, sediments, and atmospheric deposition may be the primary sources of uranium in the marine ecosystem [94, 109]. The uranium concentration of seawater remains steady, oscillating around approximately $3.3 \mu\text{g}\cdot\text{L}^{-1}$ [3], making it useful for tracking and assessing variations in the radioactive content of the marine environment. ^{238}U and ^{234}U have been widely used in the investigation of oceanographic processes (dating many depositional processes, seafloor hydrothermal, and coral growth) [64]. Uranium's radioactivity is a secondary concern, the metal's chemical toxicity is the primary environmental

health danger [16]. When ^{238}U and ^{234}U enter the human body through the digestive tract, the body will absorb up to 5% of uranyl ions [11]. Upon entering the bloodstream, uranium tends to accumulate and persist for many years in bone cells [11] as well as deposit in the liver, kidneys, reproductive organs, and other tissues and organs [47], leading to chronic diseases in humans and significantly affecting health. Thus, uranium in the coastal marine environment is also a matter of concern and requires careful monitoring and risk assessment.

The green mussel (*Perna viridis*), a bivalve species of the Mytilidae family, is widely recognized for its filter-feeding habits and high capacity for bioaccumulating pollutants from the marine environment [12, 67, 88]. Regarding these capacities, the *Perna viridis* has been widely used as an indicator organism in marine pollution monitoring programs, primarily to assess the presence and behavior of both natural and artificial radionuclides [12, 23, 26, 72, 78, 82]. These findings highlight the species' suitability for evaluating radionuclide contamination and its ecological impacts in various coastal regions, including Malaysia, India, and Indonesia [61, 72]. Despite their proven usefulness, studies focusing on determining the accumulation and activity of natural uranium isotopes, such as ^{234}U and ^{238}U , in green mussels remains very limited globally. This represents a significant knowledge gap, particularly given the ecological relevance of uranium in coastal systems. Therefore, studies on the bioaccumulation potential and distribution patterns of these isotopes in this species are urgently needed, both to understand their environmental behavior better and to enhance the species' applicability in comprehensive marine radiological monitoring frameworks.

Asian green mussels are commonly found in the Asia-Pacific region, distributed along the coastal provinces of Vietnam from Hai Phong to Kien Giang [18]. So far, there are no study to investigate the radioecological characteristics and pollutant bioaccumulation potential as well as radiological risks to humans due to the consumption of mussels and to this marine organism in study region to establish monitoring data for future REE mineral processing and the planned nuclear power plants. Therefore, this study was aimed at: (1) to study the activity concentrations of ^{234}U and ^{238}U in the muscle tissue and digestive diverticulum organs of *Perna viridis* of selected size groups at the coastal region of Binh Thuan, which is known for its naturally radioactive titanium placers, and and establish baseline data on $^{234}\text{U}/^{238}\text{U}$ ratios, (2) to assess uranium bioaccumulation and the suitability of this species as a bioindicator of marine radioactivity at this specific location; (3) to evaluate the potential radiological risk to the mussel populations at the study area; and (4) to assess the radiological risks to people due to consumption of Asian green mussels containing ^{234}U and ^{238}U based on the annual committed effective dose (ACED).

Study area and methods

The study location and sampling

The study location was selected at Binh Thuan province, located along Vietnam's south-central coast, hosting the country's largest reserves of titanium placers and the place selected for building two nuclear power plants (Fig. 1). These deposits are rich in naturally radioactive minerals such as zircon and monazite, which contain elevated concentrations of thorium and uranium [93, 33]. Mining and refining activities in this region have the potential to release radionuclides, including uranium isotopes, into the marine environment through wastewater discharge. Binh Thuan is also one of Vietnam's top three marine fisheries regions, boasting strong economic potential, particularly in seafood production and tourism development [48].

For this investigation, Asian green mussels (*Perna viridis*) were gathered from the Binh Thuan coast by local fishermen, and were sorted into 10 groups by size, each group with 10 individuals. The groups varied in body weight and shell length and each group consisted of ten individuals. All samples were sent to the lab for additional processing after being placed in the refrigerator. In the laboratory, the soft tissues of the ten individuals within each size group were dissected to separate the muscle tissue and digestive diverticulum organs. The same organ from the ten individuals in each group were then pooled and homogenized separately to obtain representative composite samples for each tissue type. From these homogenized samples, approximately 3 g of muscle tissue and

1 g of digestive diverticulum were weighed for subsequent chemical separation and uranium isotope analysis. According to earlier studies, radionuclides typically build up in bivalves' muscle tissue and digestive diverticulum organs [12, 43, 44, 67, 77, 100, 112]. In addition, the whole mussel, including the digestive diverticulum organ of bivalve species are consumed as food in many countries depending on cooking method, and this is the typical case in Vietnam. Thereby, both muscle and digestive diverticula were selected for uranium isotope analysis and radiological risk estimation. To complement the biota data and evaluate the bioaccumulation potential of uranium isotopes (^{234}U and ^{238}U), three seawater samples were also collected from the sampling locations.

Methods

Analysis of ^{234}U and ^{238}U activity concentrations

The activities of ^{234}U and ^{238}U in Asian green mussel and seawater samples were determined using alpha spectrometry, following the procedure outlined by Van Duong et al. [103], Van Hao [104], and Nguyen Dinh et al. [80]. Each sample underwent a digestion process after the addition of a ^{232}U tracer (~ 50 mBq) to determine chemical recovery. Uranium was then separated via co-precipitation of ammonium diuranate $[(\text{NH}_4)_2\text{U}_2\text{O}_7]$ with manganese dioxide (MnO_2). The resulting precipitate was thoroughly washed with distilled water, dissolved in concentrated hydrochloric acid (HCl), and passed through a Dowex 1×8 anion exchange chromatography column (100–200 mesh) to isolate uranium. Eluted uranium fractions were collected using HNO_3 and

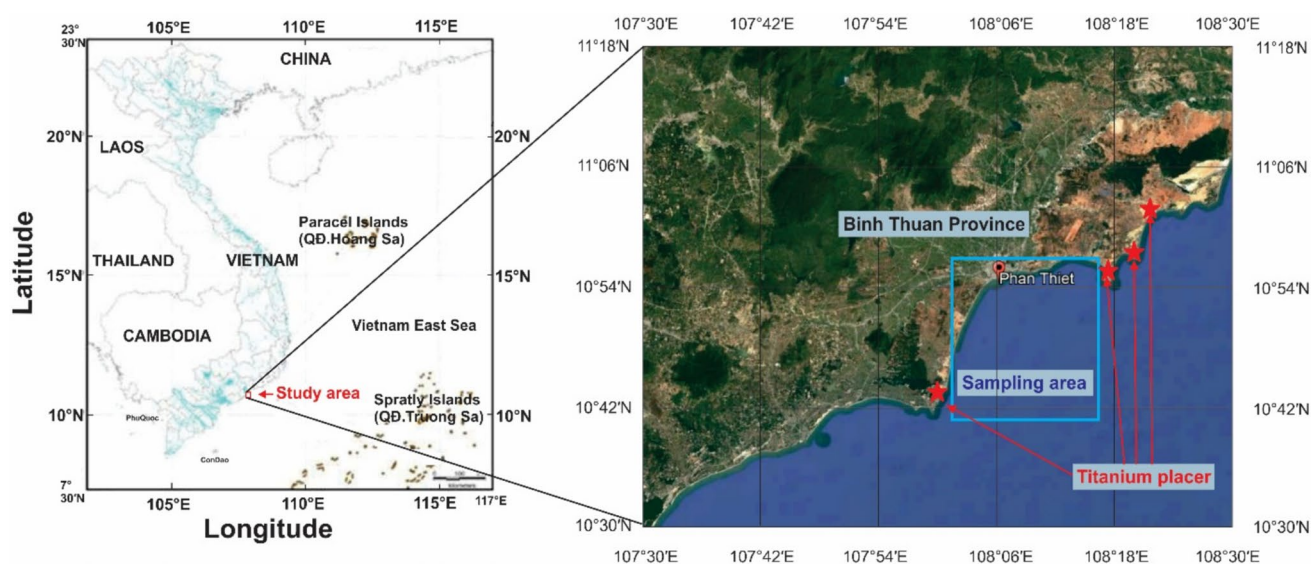


Fig. 1 Sampling area

distilled water, then evaporated to dryness. The residue was re-dissolved in diluted hydrochloric acid (HCl), and a mixture of Mohr salt, neodymium, and hydrofluoric acid (HF) was added to facilitate source preparation.

Subsequently, the solution was filtered through a 0.1 µm membrane and dried at room temperature. Alpha activity was measured using an ORTEC Alpha-Ensemble-4 spectrometer. Blank and quality control (QC) samples were processed identically to ensure analytical reliability. The minimum detectable activity (MDA) for both ^{234}U and ^{238}U was approximately 0.2 mBq.

Bioaccumulation

Bioconcentration is defined as the process by which aquatic organisms absorb chemical elements or radionuclides from the ambient environment [58]. In this study, the bioaccumulation factor (BCF) of uranium was calculated as the ratio between the activity concentration of uranium in Asian green mussel (A_{mussel}) and the activity concentration of uranium in ambient seawater (A_{water}) [84]:

$$\text{BCF} = \frac{A_{\text{mussel}}}{A_{\text{water}}} \quad (1)$$

The potential radiological risk by ERICA tool

To assess the dose rate of uranium to the Asian green mussel (*Perna viridis*) at study area, the ERICA Tool (version 2.0, Tier 2) was used [15, 73, 74]. The input parameters included the reference organism categorized as Mollusk—Bivalve; the average activity of ^{234}U and ^{238}U in seawater (Table 1), and the ecological occupancy factor for the reference organism set to “Water = 1” (indicating residence in the water, unaffected by tides).

Specifically, to estimate the external dose rate, the average activity of uranium in seawater was used. Meanwhile, the internal dose rate was derived from the activity of the two uranium isotopes measured in the study samples. A radiation weighting factor of 10 was applied for alpha radiation (ICRP, 2021). All other parameters were set to their default values as specified by the software.

Table 1 ^{234}U and ^{238}U activities in seawater, digestive diverticulum, and muscle tissue organs of each Asian green mussel samples

Sample names ($n=10$)	Shell length (cm)	Weight (g)	^{234}U (Bq.kg $^{-1}$ fresh weight)		^{238}U (Bq.kg $^{-1}$ fresh weight)		$^{234}\text{U}/^{238}\text{U}$	
			Muscle tissue	Digestive diverticulum	Muscle tissue	Digestive diverticulum	Muscle tissue	Digestive diverticulum
Mussel group 1	5.1	6.06	53.2 ± 4.3	45.0 ± 7.5	57.2 ± 4.5	42.0 ± 6.6	0.93	1.07
Mussel group 2	5.6	7.81	37.0 ± 2.1	13.9 ± 1.3	29.1 ± 1.8	8.3 ± 1.0	1.27	1.67
Mussel group 3	6.1	9.09	15.1 ± 1.1	13.9 ± 1.0	15.2 ± 1.1	7.8 ± 0.7	0.99	1.78
Mussel group 4	6.5	13.07	3.1 ± 0.3	7.2 ± 0.8	2.0 ± 0.2	4.3 ± 0.6	1.55	1.67
Mussel group 5	7.0	12.99	5.2 ± 0.4	6.4 ± 0.7	3.0 ± 0.3	3.6 ± 0.5	1.73	1.78
Mussel group 6	8.6	22.17	1.4 ± 0.1	3.8 ± 0.3	1.2 ± 0.2	3.1 ± 0.2	1.17	1.22
Mussel group 7	9.0	26.54	2.2 ± 0.2	9.4 ± 0.6	1.6 ± 0.2	5.5 ± 0.5	1.38	1.71
Mussel group 8	9.5	25.66	6.7 ± 0.5	22.5 ± 1.2	7.2 ± 0.5	7.1 ± 0.6	0.93	3.17
Mussel group 9	10	33.48	2.6 ± 0.2	32.0 ± 2.0	2.4 ± 0.2	29.0 ± 1.9	1.08	1.10
Mussel group 10	10.5	42.36	3.3 ± 0.2	13.9 ± 1.3	3.3 ± 0.3	11.9 ± 1.2	1.00	1.17
Average	13	16.8	12.2	12.3	1.20	1.63		
Min	1.4 ± 0.1	3.8 ± 0.3	1.2 ± 0.2	3.1 ± 0.2	0.93	1.07		
Max	53.2 ± 4.3	45.0 ± 7.5	57.2 ± 4.5	42.0 ± 6.6	1.73	3.17		
Sea water samples			^{234}U (mBq.L $^{-1}$)		^{238}U (mBq.L $^{-1}$)		$^{234}\text{U}/^{238}\text{U}$	
Seawater 1			39.6 ± 1.5		33.6 ± 1.3		1.18	
Seawater 2			40.0 ± 1.0		34.5 ± 1.2		1.16	
Seawater 3			39.0 ± 1.0		33.4 ± 1.0		1.17	
Average			39.5		33.8		1.17	
Min			39.0 ± 1.0		33.4 ± 1.0		1.16	
Max			40.0 ± 1.0		34.5 ± 1.2		1.18	

Annual committed effective dose (ACED)

The following formula is used to determine the ACED of ^{234}U and ^{238}U :

$$\text{ACED} = A \times F \times p \quad (2)$$

For each Asian green mussel sample, A_{mussel} is the mean concentration of ^{234}U or ^{238}U in edible tissues and digestive diverticulum organs (Bq.kg^{-1}), F is the dose conversion factor for adults (^{238}U is $4.5 \times 10^{-5} \text{ mSv.Bq}^{-1}$; ^{234}U is $4.9 \times 10^{-5} \text{ mSv.Bq}^{-1}$) [53, 107], p is the average annual consumption of green mussels by Vietnamese people (4.7 kg.y^{-1}) [81], and ACED is the annual committed effective dose (mSv.y^{-1}).

Results and discussions

The ^{234}U and ^{238}U activity concentration in the muscle tissue and digestive diverticulum organs of Asian green mussels related to different sizes (shell length) and weights

Table 1 presents the ^{234}U and ^{238}U activity concentrations in the digestive diverticulum and muscle tissue organs of Asian green mussels of varying weights and sizes (shell length). The minimum, maximum, and average values of ^{234}U and ^{238}U in muscle tissue and digestive diverticulum organs were 1.4 ± 0.1 , 53.2 ± 4.3 , and 13.0 Bq.kg^{-1} ; 1.2 ± 0.2 , 57.2 ± 4.5 and 12.2 Bq.kg^{-1} ; 3.8 ± 0.3 , 45.0 ± 7.5 and 16.8 Bq.kg^{-1} ; 3.1 ± 0.2 , 42.0 ± 6.6 and 12.3 Bq.kg^{-1} , respectively. The ^{234}U and ^{238}U activity in muscle tissue are little lower in the intestinal diverticulum organ (Table 1). According to Carvalho, uranium found in green mussels can originate from uranium dissolved in seawater. Still, it can also originate from the ingestion of suspended matter, specifically sediment particles and the ephemera of organisms [19]. Additionally, the ICRP (International Commission on Radiological Protection) has also recommended that digested food containing radionuclides is first absorbed into the digestive diverticular organs (stomach) and then into the intestine, with a total occupancy of 50% in activity. The radionuclides in the intestine pass into the blood and are distributed to muscles along with nutrients [50]. Thus, the greater amount of radioactive substances in the digestive diverticular organs could relate to the absorption of radionuclides from food, and a higher relative weight of this uptake pathway. This result was also observed in previous studies, attributed to the mussels filter-feeding mechanism [19, 25, 36, 91]. However, there was also an opinion that the main source of uranium in

mussels comes from seawater through the drinking reflex, which compensates for ion loss and maintains osmotic balance with the external environment [70]. The uranium in seawater is not only absorbed through branched absorption (transepithelial ion transport), but also through the absorption of uranium from seawater through the intestinal wall of green mussels [19]. This process has also been reported for other non-essential and high atomic number elements in fish, such as americium and plutonium [20, 86]. Thus, uranium in Asian green mussels could mainly come from two routes: (1) through the process of digesting foods containing uranium and (2) the process of absorbing uranium from seawater.

In addition, the $^{234}\text{U}/^{238}\text{U}$ ratio was also identified in the two organs (Table 1). The $^{234}\text{U}/^{238}\text{U}$ ratio in muscle tissue of this species (average 1.20) is approximately the same as the $^{234}\text{U}/^{238}\text{U}$ ratio in seawater (average 1.17). During the growth and development process, the muscle tissue and gills of green mussels open continuously to absorb seawater to filter food. This action results in most of the mussel's muscle tissue being in direct contact with seawater (the source of uranium). This suggests a high likelihood that the presence of uranium in this organ originates from uranium in seawater. While this ratio in the digestive diverticulum organs of green mussels is somewhat higher (average 1.63), this difference may be due to the uranium accumulation mechanism from food in this organ. This evidence confirms that the uptake pathways of uranium in green mussels involve two routes: through seawater and food digestion. It is important to highlight that the digestive diverticulum organs had a greater $^{234}\text{U}/^{238}\text{U}$ ratio than muscle tissue.

The ^{234}U and ^{238}U activities in muscle tissue in this study were compared with those of some previous studies worldwide on radionuclides in mollusks (Table 2). The uranium isotope activities in Asian green mussels in this study are significantly lower than those of other radionuclides that have been studied in mussels, such as ^{137}Cs , ^{210}Po , and ^{210}Pb . This discrepancy can be explained by the lower bioavailability and weaker affinity of uranium for plankton and soft tissues compared to the strong binding and bioaccumulation tendencies of ^{210}Po and ^{210}Pb [56, 27, 30]. Ecologically, the low uranium levels suggest that U isotopes contribute less to the overall radiological risk in mussels than ^{210}Po or ^{210}Pb , but still provide important baseline information for assessing long-term radiation exposure in marine ecosystems. Furthermore, the activity concentrations of ^{234}U and ^{238}U measured in Asian green mussels in this study were significantly higher than those reported for mollusks from the Ebro Delta area [40] and Bay of Bengal [5]. Specifically, in the study by Fonollosa et al. [40]: *Mytilus edulis* had ^{234}U and ^{238}U activities of 1.0 ± 0.3 and $0.9 \pm 0.2 \text{ Bq kg}^{-1}$ dry weight, respectively; Large oysters exhibited values of 2.9 ± 0.7 and $2.4 \pm 0.6 \text{ Bq kg}^{-1}$ dry weight; while clams presented

Table 2 Activity of some radionuclides in mollusks

Mollusks	Radionuclides	Activities (Bq.kg ⁻¹)	Region	References
<i>M. Galloprovincialis</i>	¹³⁷ Cs	30.5	Tohoku, Japan	[78]
Asian green mussels	²³⁸ U	2.8–3.6	Bay of Bengal	[5]
Mytilus edulis	²³⁴ U	1.0 ± 0.3	Ebro Delta	[40]
	²³⁸ U	0.9 ± 0.2		
Large oysters	²³⁴ U	2.9 ± 0.7		
	²³⁸ U	2.4 ± 0.6		
Clams	²³⁴ U	1.3 ± 0.3		
	²³⁸ U	1.1 ± 0.2		
<i>P. indica</i>	²¹⁰ Po	156 ± 30 to 928 ± 41	India	[62]
<i>P. viridis</i>	²¹⁰ Po	183 ± 18 to 1063 ± 30		
<i>P. indica</i>	²¹⁰ Po	242 ± 12.9	India	[61]
<i>M. galloprovincialis</i>	²¹⁰ Po	767 ± 283	Costa da Caparica beach	[23]
	²¹⁰ Pb	46 ± 20		
<i>M. galloprovincialis Lmk</i>	²¹⁰ Po	759 ± 277	Costa da Caparica	[26]
	²¹⁰ Pb	45 ± 19		
<i>P. viridis</i>	²³⁴ U	13.0	Binh Thuan, Viet Nam	This study
	²³⁸ U	12.2		

activities of 1.3 ± 0.3 and 1.1 ± 0.2 Bq kg⁻¹ dry weight for ²³⁴U and ²³⁸U, respectively. In the Bay of Bengal, the ²³⁸U activity found in Asian green mussels ranged from 2.8 to 3.6 Bq.kg⁻¹ for the whole soft tissue, especially for smaller specimens [5]. The relatively higher uranium activities in Asian green mussels in the present study may be related to local environmental conditions. In particular, the study area is influenced by the exploitation of nearby titanium placer deposits, which is suspected to increase uranium concentrations in seawater and may consequently enhance uranium accumulation in Asian green mussels.

In this study, shell length was used as an indirect indicator of the age for individuals in the same environment and living conditions. There is a decreasing trend of ²³⁴U and ²³⁸U activities in the four young groups with body sizes from 5 to 6.5 cm, and activities are relatively constant in groups exceeding 7 cm in body size. These relationships are not observed for the digestive diverticulum organ (Table 1). The result is consistent with previous studies on the correlation between radionuclide concentration and mussel weight and size [8, 29, 46, 68, 92]. The higher activities observed in younger mussels may be associated with higher metabolic and filtration rates relative to body mass during early growth stages [99], which can enhance radionuclide uptake. In addition, a growth dilution effect may occur as mussels increase in body size [28], resulting in relatively stable activity concentrations once individuals reach adult size (> 7 cm). When physiological and nutritional conditions become more stable, resulting in reduced variation in the uptake and accumulation of ²³⁴U and ²³⁸U. The sex and reproductive status of the mussels can be possible confounding factors [90], however this was not the focus of the current study.

The bioaccumulation of the ²³⁴U and ²³⁸U in Asian green mussels

Bioaccumulation of the ²³⁴U and ²³⁸U isotopes in Asian green mussels was also calculated (Table 3). The results showed that the ability of green mussels to accumulate uranium is relatively high, with average values of 328 and 425 for ²³⁴U and 361 and 362 for ²³⁸U. Among them, the smallest mussel samples had higher bioaccumulation rates, greater than 1000.

Compared to the bioaccumulation levels of other naturally occurring radionuclides reported in *Mytilus galloprovincialis* from Italy [57], the bioaccumulation of uranium isotopes in this study was lower than that of ²¹⁰Po ($(1.22 \pm 0.72) \times 10^4$), ²¹⁰Pb (517 ± 280), ²²⁸Th (480 ± 265); however, it was higher than that of ²²⁶Ra (33.3 ± 13.4), and ²²⁴Ra (100 ± 52), uranium exhibited significantly higher accumulation in our study. These differences may be attributed to the different chemical properties of uranium in seawater, its oxidation states, and possibly species-specific physiological mechanisms [49, 57]. However, comparisons between different mussel species and different regions must be treated with caution, as environmental differences and the biological capabilities of individual species and individuals can significantly influence radioactivity uptake and retention [37, 87, 105].

Environmental monitoring of natural and anthropogenic factors in seawater using mussels as sentinel organisms often evolves into pollution assessment through site-to-site comparisons. This procedure must consider the influence of body size on radionuclide concentration. Larger mussels exhibit lower soft tissue radioactivity concentrations than

Table 3 Bioaccumulation and annual committed effective dose contribution from ^{234}U , ^{238}U isotopes in Asian green mussels

Sample no	Bioaccumulation				ACED (μSv.y ⁻¹)				Total
	²³⁴ U		²³⁸ U		²³⁴ U		²³⁸ U		
	Muscle tissue	Digestive diverticu- lum	Muscle tissue	Digestive diverticu- lum	Muscle tissue	Digestive diver- ticulum	Muscle tissue	Digestive diverticu- lum	
Mussel group 1	1346	1138	1691	1241	12.25 ± 4.0	10.36 ± 6.9	12.1 ± 3.8	8.88 ± 5.6	43.60
Mussel group 2	936	352	860	245	8.52 ± 1.9	3.2 ± 1.2	6.15 ± 1.5	1.76 ± 0.8	19.63
Mussel group 3	382	352	449	231	3.48 ± 1.0	3.2 ± 0.9	3.21 ± 0.9	1.65 ± 0.6	11.54
Mussel group 4	78	182	59	127	0.71 ± 0.3	1.66 ± 0.7	0.42 ± 0.2	0.91 ± 0.5	3.70
Mussel group 5	132	162	89	106	1.2 ± 0.4	1.47 ± 0.6	0.63 ± 0.3	0.76 ± 0.4	4.07
Mussel group 6	35	96	35	92	0.32 ± 0.1	0.88 ± 0.3	0.25 ± 0.2	0.66 ± 0.2	2.11
Mussel group 7	56	238	47	163	0.51 ± 0.2	2.16 ± 0.6	0.34 ± 0.2	1.16 ± 0.4	4.17
Mussel group 8	169	569	213	210	1.54 ± 0.5	5.18 ± 1.1	1.52 ± 0.4	1.5 ± 0.5	9.75
Mussel group 9	66	809	71	857	0.6 ± 0.2	7.37 ± 1.8	0.51 ± 0.2	6.13 ± 1.6	14.61
Mussel group 10	83	352	98	352	0.76 ± 0.2	3.2 ± 1.2	0.7 ± 0.3	2.52 ± 1.0	7.18
Average	328	425	361	362	2.99	3.87	2.58	2.59	12.04
Min	35	96	35	92	0.32 ± 0.1	0.88 ± 0.3	0.25 ± 0.2	0.66 ± 0.2	2.11
Max	1346	1138	1691	1241	12.25 ± 4.0	10.36 ± 6.9	12.1 ± 3.8	8.88 ± 5.6	43.60

small-sized one. Using mussels to assess spatial and temporal trends in radionuclide concentrations requires sampling mussels of similar body size (i.e., within the same size class) and paying attention to condition indicators of the mussels to allow for comparison across different locations. Based on the initial results obtained, the authors recommend using small green mussels to facilitate environmental monitoring of uranium substances.

The potential radiological risk on Asian green mussels

The minimum, maximum, and average activity values of ^{234}U and ^{238}U in muscle tissue were used to calculate the activities in the whole body (not including the shells) of Asian green mussels (Table 4). The activities of ^{234}U and ^{238}U in the entire body of mussels were calculated according to the method of Yankovich et al., [110].

The exposure risks of ^{234}U and ^{238}U in Asian green mussels are shown in Table 4. The external radiation dose rates from both isotopes (^{234}U and ^{238}U) are within the reference

standard. Internal radiation dose rates are much higher than external radiation doses, particularly for ^{234}U . The average internal dose rate of ^{234}U is $1.53 \mu\text{Gy.h}^{-1}$, which is significantly higher than the external dose rate of ^{234}U ($1.61 \times 10^{-5} \mu\text{Gy.h}^{-1}$). The total dose rate from the two uranium isotopes is only dominated by internal exposure.

The total dose rate from the two uranium isotopes (the sum of internal and external doses) varies significantly from 0.107 to $20.7 \mu\text{Gy.h}^{-1}$, with an average of $2.8 \mu\text{Gy.h}^{-1}$. These values indicate that, while the mussels were receiving radiation, the total exposure was largely within the range considered non-hazardous according to the ERICA reference standard ($10 \mu\text{Gy.h}^{-1}$). Although the doses contributed by ^{234}U and ^{238}U are within safe limits, other radionuclides (e.g., Po, Pb, and Ra isotopes) may also contribute to the total radiation dose and should be considered for a more comprehensive assessment. However, since the dose exceeded the screening value for an individual green mussel (mussel sample group 1). This suggests that further assessment is needed to understand the potential radiation risk to mussels fully and to explore the possibility of modifying strategies to

Table 4 Radiation risk to Asian green mussels in the Binh Thuan area, Vietnam

	Whole body (Bq.kg^{-1})		External dose rate ($\mu\text{Gy.h}^{-1}$)		Internal dose rate ($\mu\text{Gy.h}^{-1}$)		Total dose rate ($\mu\text{Gy.h}^{-1}$)
	^{234}U	^{238}U	^{234}U	^{238}U	^{234}U	^{238}U	
Min	2.38	1.53	1.61×10^{-5}	2.25×10^{-3}	6.65×10^{-2}	3.82×10^{-2}	0.107
Max	377	406	1.61×10^{-5}	2.25×10^{-3}	10.6	10.1	20.7
Average	54.6	50.8	1.61×10^{-5}	2.25×10^{-3}	1.53	1.27	2.8

reduce or manage uranium exposure. In particular, in addition to the rivers carrying inland pollutants, this study area has large titanium placers that have been and are currently being exploited and there are two planned nuclear power plants that will operate in the future.

The radiological risks to people due to consumption of Asian green mussels based on the annual committed effective dose

The consumption of Asian green mussels (green mussel) by coastal residents of Vietnam has been surveyed: an average of 12.8 g/person/d⁻¹, equivalent to 4.7 kg/person/y⁻¹, out of a total mollusk consumption of 14.3 kg/person/y⁻¹ [81]. The value of 4.7 kg/person/y⁻¹ was used in this study as the average consumption to estimate the potential radiation dose contributed by ²³⁴U and ²³⁸U from green mussel consumption in adults. The ACED calculated for ²³⁴U and ²³⁸U, using green mussels as food, is shown in Table 3. According to the data, the average total dosage value is 12.04 μSv.y⁻¹, with a range of 2.11 to 43.60 μSv.y⁻¹.

The WHO (World Health Organization) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommended that the effective annual dose for food and water consumption range from 200 to 1000 μSv.y⁻¹ (0.2 to 1 mSv.y⁻¹) [102, 108]. Thus, the consumption of green mussels in this area is considered relatively safe in terms of radiation doses contributed by ²³⁴U and ²³⁸U. However, green mussels are a species that accumulate a significant amount of toxic substances and other radionuclides such as ²¹⁰Po, ²¹⁰Pb and ^{226,228}Ra that typically contribute more seafood ingestion dose than U isotopes [60, 85], especially in smaller mussels [66, 33, 38, 12, 88]. Therefore, we recommend limiting the consumption of green mussels, and if people do use them, they should opt for adult (large) mussels.

Conclusions

This study measured the activity concentrations of ²³⁴U and ²³⁸U, as well as the ²³⁴U/²³⁸U ratios, in the muscle and the digestive diverticulum organs of *Perna viridis* from the coastal region of Binh Thuan, Vietnam, the following conclusions are drawn:

The results provide evidence based on U isotopic ratios that uranium in green mussels originates from two primary pathways: (1) direct uptake from uranium-contaminated food and (2) absorption from surrounding seawater. The bioaccumulation analysis revealed a relatively low capacity of *Perna viridis* to accumulate uranium isotopes. Uranium accumulation decreased with increasing body size for the smaller individuals while the larger mussels, the

²³⁴U and ²³⁸U activity appeared to reach a state of stability. These findings suggest that smaller mussels may serve as more sensitive bioindicators for monitoring uranium in marine environments. Future studies should explore the application of young *Perna viridis* as biological sentinels in radioactivity environmental monitoring programs of uranium in Vietnam. Radiological dose assessment revealed that the total dose rates (two uranium isotopes only) for most mussel samples were below the ERICA screening reference level (10 μGy.h⁻¹), indicating minimal ecological risk. However, some of the smallest individuals exceeded the threshold, it is warranting additional investigation to clarify localized exposure risks and guide appropriate mitigation strategies as needed. This study also recommends that since the doses from U alone are substantive, that total dose from all radionuclides present, especially ²¹⁰Po, ²¹⁰Pb and ^{226,228}Ra (as well as ⁴⁰K) be evaluated. Lastly, although the study area has some titanium placer deposits that have been and are being exploited, the ACED to humans from the consumption of uranium-containing green mussels in this region remains well within the safety limits established by WHO and UNSCEAR. Nonetheless, considering the mussel's uranium bioaccumulate ability and previous findings for other pollutants, it is advisable to limit the consumption of small-sized individuals and prioritize larger specimens for safer dietary intake.

Authors contribution Conception: Thanh-Xuan Pham Thi, Van-Hao Duong. Study design methods: Van-Hao Duong, Thanh-Xuan Pham Thi. Acquisition and collation of data: Van-Hao Duong, Thanh-Xuan Pham Thi. Analysis and interpretation of data: Thanh-Xuan Pham Thi, Tien Chu Trung, Khai M. Nguyen, Thi Thuy Huong Ngo, Marckasagayam Priyadharshini, Mohamed Saiyad Musthafa, Xuan-Quang Nguyen, Nga Phung Thi, Trinh Phan Trong, Duc-Thang Duong, Thanh-Duong Nguyen, Miklós Hegedűs, Tibor Kovács, Van-Hao Duong. Writing the manuscript: Thanh-Xuan Pham Thi, Van-Hao Duong, Marckasagayam Priyadharshini, Mohamed Saiyad Musthafa. Critical revision of paper: Thanh-Xuan Pham Thi, Tien Chu Trung, Khai M. Nguyen, Thi Thuy Huong Ngo, Marckasagayam Priyadharshini, Mohamed Saiyad Musthafa, Xuan-Quang Nguyen, Nga Phung Thi, Trinh Phan Trong, Duc-Thang Duong, Thanh-Duong Nguyen, Miklós Hegedűs, Tibor Kovács, Van-Hao Duong.

Funding Open access funding provided by Semmelweis University. This research is funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number: 11/2022/TN.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Ethical approval No approval of research ethics committees was required to accomplish the goals of this study because experimental work was conducted with an unregulated invertebrate species.

Consent to participate Authors confirm that the named authors have read and approved the paper. The author confirms that the named authors have approved the order of authors listed in the manuscript.

Consent for publication Upon publication, the authors transfer all copyright ownership of the manuscript above to the JRNC.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abney CW, Mayes RT, Saito T, Dai S (2017) Materials for the recovery of uranium from seawater. *Chem Rev* 117(23):13935–14013. <https://doi.org/10.1021/acs.chemrev.7b00355>
- Aközcan S, Uğur A (2013) Activity levels of ^{210}Po and ^{210}Pb in some fish species of the Izmir Bay (Aegean Sea). *Mar Pollut Bull* 66(1–2):234–238
- Akyil S, Yusof A (2007) The distribution of uranium and thorium in samples taken from different polluted marine environment. *J Hazard Mater* 144(1–2):564–569. <https://doi.org/10.1016/j.jhazmat.2006.10.088>
- Al-Masri MS, Mamish S, Abdel-Haleem M, Durgham HH (2019) ^{210}Po and ^{210}Pb concentration in zooplankton of the Syrian coastal waters (Eastern Mediterranean Sea). *Mediterr Mar Sci* 20(2):320–325
- Alam MN, Chowdhury MI, Kamal M, Ghose S, Matin AKMA, Ferdousi GSM (2000) Radionuclide concentrations in mussels collected from the southern coast of Bangladesh. *J Environ Radioact* 47(2):201–212. [https://doi.org/10.1016/S0265-931X\(99\)00038-7](https://doi.org/10.1016/S0265-931X(99)00038-7)
- Andersson P, Garnier-Laplace J, Beresford NA, Copplestone D, Howard BJ, Howe P, Oughton D, Whitehouse P (2009) Protection of the environment from ionising radiation in a regulatory context (PROTECT): proposed numerical benchmark values. *J Environ Radioact* 100(12):1100–1108. <https://doi.org/10.1016/j.jenvrad.2009.05.010>
- Aryanti CA, Suseno H, Prihatiningsih WR (2022) Potential radiological dose of ^{210}Po to several marine organisms in coastal area of coal-fired power plant Tanjung Awar-Awar, Tuban. *ILMU KELAUT: Indones J Mar Sci*. <https://doi.org/10.14710/ik.ijms.27.1.73-82>
- Barescut J, i Batlle JV, Wilson R, Watts S, McDonald P, Craze A (2009) Derivation of allometric relationships for radionuclides in marine phyla. *Radioprotection* 44(5):47–52. <https://doi.org/10.1051/radiopro/20095015>
- Bell O (2024) Radionuclide bioaccumulation and transfer in aquatic food webs. *Aqua Introd Res Essay*. <https://doi.org/10.54612/a.2kv8e1185i>
- Belli M, Indovina L (2020) The response of living organisms to low radiation environment and its implications in radiation protection. *Front Public Health* 8:601711
- Bird GA (2012) Uranium in the environment: behavior and toxicity. *Encyclopedia of sustainability science and technology*. Springer, Cham, pp 11220–11262
- Biswas KP, Hossain S, Deb N, Bhuian ASI, Gonçalves SC, Hossain S, Hossen MB (2021) Assessment of the levels of pollution and of their risks by radioactivity and trace metals on marine edible fish and crustaceans at the Bay of Bengal (Chattogram, Bangladesh). *Environments* 8(2):13. <https://doi.org/10.3390/environments8020013>
- Brown J, Alfonso B, Avila R, Beresford NA, Copplestone D, Pröhl G, Ulanovsky A (2008) The ERICA tool. *J Environ Radioact* 99(9):1371–1383
- Brown J, Jones S, Saxén R, Thørring H, i Batlle JV (2004) Radiation doses to aquatic organisms from natural radionuclides. *J Radiol Prot* 24(4A):A63
- Brown JE, Alfonso B, Avila R, Beresford NA, Copplestone D, Hosseini A (2016) A new version of the ERICA tool to facilitate impact assessments of radioactivity on wild plants and animals. *J Environ Radioact* 153:141–148
- Brugge D, Buchner V (2011) Health effects of uranium: new research findings. *Rev Environ Health* 26(231):249
- Bui Chi T, Nguyen Tien T, Duong V-H (2024) Concentrations of ^{238}U , ^{234}U , ^{226}Ra , ^{210}Pb , and ^{210}Po in seawater at Thanh Hoa coastal area, Vietnam. *J Radioanal Nucl Chem* 333(4):1769–1777. <https://doi.org/10.1007/s10967-024-09455-0>
- Bui QN (2006) Biological characteristics of the reproduction of Green Mussel *Perna viridis* (Linnaeus, 1758) in area of lobster culture. In: Xuan T, Ninh V, Hoa K (eds) Collection of marine research works XV. Science and Technics Publishing House, Hanoi, pp 223–230
- Carvalho F, Fesenko S, Harbottle A, Lavrova T, Mitchell N, Payne T, Rigol A, Thorne M, Ulanowski A, Vidal M (2023) The environmental behaviour of uranium. <https://www.iaea.org/publications/14688/the-environmental-behaviour-of-uranium>
- Carvalho F, Fowler S, La Rosa J (1983) Assimilation, inter-organ transfer and excretion of americium in two teleost fish. *Mar Biol* 77(1):59–66. <https://doi.org/10.1007/BF00393210>
- Carvalho FP (2018) Radionuclide concentration processes in marine organisms: a comprehensive review. *J Environ Radioact* 186:124–130. <https://doi.org/10.1016/j.jenvrad.2017.11.002>
- Carvalho FP, Nhan DD, Oliveira JM, Long NQ, Thuan DD, Malta M, Santos M (2021) Environmental radioactivity in the marine environment of Ha Long Bay, North Vietnam, and bio-magnification of polonium. *Environ Process* 8(4):1359–1378
- Carvalho FP, Oliveira JM (2008) Accumulation of ^{210}Po and ^{210}Pb in mussels: implications for environmental bio monitoring programmes. In: Proceedings of the international conference radioecology and environmental radioactivity.
- Carvalho FP, Oliveira JM, Alberto G, i Batlle JV (2010) Allometric relationships of ^{210}Po and ^{210}Pb in mussels and their application to environmental monitoring. *Mar Pollut Bull* 60(10):1734–1742. <https://doi.org/10.1016/j.marpolbul.2010.06.025>
- Carvalho FP, Oliveira JM, Alberto G (2011) Factors affecting ^{210}Po and ^{210}Pb activity concentrations in mussels and implications for environmental bio-monitoring programmes. *J Environ Radioact* 102(2):128–137. <https://doi.org/10.1016/j.jenvrad.2010.11.003>
- Carvalho FP, Oliveira JM, Malta M (2011) Radionuclides in deep-sea fish and other organisms from the North Atlantic

- Ocean. ICES J Mar Sci 68(2):333–340. <https://doi.org/10.1093/icesjms/fsq088>
27. Carvalho FP (2011) Polonium (210Po) and lead (210Pb) in marine organisms and their transfer in marine food chains. J Environ Radioact 102(5):462–472. <https://doi.org/10.1016/j.jenvrad.2010.10.011>
 28. Carvalho F, Fernandes S, Fesenko S, Holm E, Howard B, Martin P, Twining J (2017) The environmental behaviour of polonium, vol 484. International Atomic Energy Agency, Vienna, Austria, p 255
 29. Cherry R, Heyraud M (1991) Polonium-210 and lead-210 in marine organisms: allometric relationships and their significance. Radionuclides in the study of marine processes. Springer, Dordrecht, pp 309–318. https://doi.org/10.1007/978-94-011-3686-0_33
 30. Cherry RD, Heyraud M (1981) Polonium-210 content of marine shrimp: variation with biological and environmental factors. Mar Biol 65:165–175. <https://doi.org/10.1007/BF00397082>
 31. Chi F, Zhang S, Wen J, Xiong J, Hu S (2018) Highly efficient recovery of uranium from seawater using an electrochemical approach. Ind Eng Chem Res 57(23):8078–8084. <https://doi.org/10.1021/acs.iecr.8b01063>
 32. Copplestone D, Bielby S, Jones S (2001) Impact assessment of ionising radiation on wildlife. Environment Agency, London
 33. Cuney M (2012) Uranium and thorium: the extreme diversity of the resources of the world's energy minerals. Non-Renewable Resource Issues: Geosci Soc Ch Hall 91–129. https://doi.org/10.1007/978-90-481-8679-2_6
 34. Da Le N, Hoang TTH, Duong TT, Phuong NN, Le PT, Nguyen TD, Phung TXB, Le TMH, Le TL, Vu TH (2023) Microplastics in the surface sediment of the main Red River Estuary. Vietnam J Earth Sci 45(1):19–32
 35. De Carvalho FG, Loyau A, Kelly-Irving M, Schmeller DS (2025) Aquatic ecosystem indices, linking ecosystem health to human health risks. Biodivers Conserv 34(3):723–767
 36. Desideri D, Meli M, Roselli C, Feduzi L (2009) A biomonitoring study: 210 Po and heavy metals in mussels. J Radioanal Nucl Chem 279(2):591–600. <https://doi.org/10.1007/s10967-008-7334-0>
 37. Duong V-H, Pham-Thi T-X, Nguyen T-T, Luu V-D, Tran D-Q, Nguyen T-M, Tran T-T, Nguyen T-N (2023) Characteristics of 210Po in Asian overbite clam (*Potamocorbula laevis*) from the coastal area at Thai Binh province, Vietnam. Mar Pollut Bull 194:115425. <https://doi.org/10.1016/j.marpolbul.2023.115425>
 38. Duong VH, Pham-Thi TX, Chu TT, Nguyen TN, Tai TN, Viet DL et al (2025) High accumulation of 210Po 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. Mar Pollut Bull 219:118348. <https://doi.org/10.1016/j.marpolbul.2025.118348>
 39. Energy UDo (2002) Occupational radiation exposure report 2002. <https://www.energy.gov/sites/prod/files/2014/06/f16/2002report.pdf>
 40. Fonollosa E, Peñalver A, Aguilar C, Borrull F (2017) Bioaccumulation of natural radionuclides in molluscs from the Ebro Delta area. Environ Sci Pollut Res 24(1):208–214
 41. Fisher NS, Beaugelin-Seiller K, Hinton TG, Baumann Z, Madigan DJ, Garnier-Laplace J (2013) Evaluation of radiation doses and associated risk from the Fukushima nuclear accident to marine biota and human consumers of seafood. Proc Natl Acad Sci U S A 110(26):10670–10675. <https://doi.org/10.1073/pnas.1221834110>
 42. Gjelsvik R, Brown J, Holm E, Roos P, Saxen R, Outola I (2012) Polonium-210 and other radionuclides in terrestrial, freshwater and brackish environments Results from the NKS project GAPRAD (Filling knowledge gaps in radiation protection methodologies for non-human biota).
 43. Goldberg ED, Bertine KK (2000) Beyond the mussel watch—new directions for monitoring marine pollution. Sci Total Environ 247(2–3):165–174. <https://doi.org/10.1016/j.jenvrad.2007.09.003>
 44. Hameed MS, Bukhari S, Hameed S (2004) Study on the bioaccumulation of polonium-210 and lead-210 in the abiotic and biotic components of Palk Strait, south east coast of India. In: 11th international congress of the international radiological protection association. Madrid, Spain.
 45. Hassona RK, Sam A, Osman O, Sirelkhatim D, LaRosa J (2008) Assessment of committed effective dose due to consumption of Red Sea coral reef fishes collected from the local market (Sudan). Sci Total Environ 393(2–3):214–218. <https://doi.org/10.1016/j.scitotenv.2007.12.014>
 46. Heyraud M, Cherry R, Oschadleus H-D, Augustyn C, Cherry M, Sealy J (1994) Polonium-210 and Lead-210 in edible molluscs from near the Cape of Good Hope: sources of variability in polonium-210 concentrations. J Environ Radioact 24(3):253–272. [https://doi.org/10.1016/0265-931X\(94\)90043-4](https://doi.org/10.1016/0265-931X(94)90043-4)
 47. Hindin R, Brugge D, Panikar B (2005) Teratogenicity of depleted uranium aerosols: a review from an epidemiological perspective. Environ Health 4(1):17
 48. Hoang H, Dang KB, Van Rompaey A (2022) Comprehensive assessment of coastal tourism potential in Vietnam. Sci Earth. <https://doi.org/10.15625/2615-9783/17374>
 49. Hodge HC, Stannard JN, Hursh JB (2013) Uranium Plutonium transplutonic elements, vol 36. Springer Science & Business Media, Berlin
 50. ICRP (1979) Limits for intakes of radionuclides by workers, vol 30. ICRP Publication, London
 51. ICRP (1991) Recommendations of the international commission on radiological protection (Publication No. 60), vol 21. Annals of the ICRP, London
 52. ICRP (2003) A framework for assessing the impact of ionising radiation on non-human species (Publication No. 91), vol 33. Annals of the ICRP, London
 53. ICRP (2012) Compendium of dose coefficients based on ICRP Publication 60, vol 119. International Commission on Radiological Protection Publication, London
 54. ICRP (2021) Radiation weighting for Reference Animals and Plants. ICRP Publication 148. Ann. ICRP 50(2)
 55. Iryna P (2017) Toxicity of radionuclides in determining harmful effects on humans and environment. J Environ Sci China 1(2):115–119. <https://doi.org/10.26502/JESPH.011>
 56. Issifu I, Deffor EW, Deyshappriya NPR, Dahmouni I, Sumaila UR (2022) Drivers of seafood consumption at different geographical scales. J Sustain Res. <https://doi.org/10.20900/jsr20220012>
 57. Jia G, Torri G, Magro L (2020) The fate of the main naturally occurring radionuclides in mussels (*Mytilus edulis*) and their radiological impact on human beings. Environ Monit Assess 192(4):217. <https://doi.org/10.1007/s10661-020-8137-1>
 58. Jin Y, Fu B, Wang X (2024) Quantifying heavy metal and radionuclide contamination in fish and water proximal to a uranium tailings facility: a Linshui River basin investigation, China. J Trace Elem Med Biol 85:127485. <https://doi.org/10.1016/j.jtemb.2024.127485>
 59. Johansen MP, Gwynn JP, Carpenter JG, Charmasson S, McGinnity P, Mori A, Orr B, Simon-Cornu M, Osvath I (2025) Radiological dose from seafood ingestion; a global summary from 40 years of study. Crit Rev Environ Sci Technol 55(6):422–445. <https://doi.org/10.1080/10643389.2024.2413202>
 60. Johansen MP, Gwynn JP, Carpenter JG, Charmasson S, Mori A, Orr B, Simon-Cornu M, Osvath I, McGinnity P (2025) Which radionuclides contribute most to seafood ingestion dose? J Environ Radioact 287:107706
 61. Khan MF, Wesley SG (2012) Radionuclide monitoring in molluscs inhabiting intertidal region near a nuclear installation, Gulf

- of Mannar, India. *Mar Pollut Bull* 64(2):436–444. <https://doi.org/10.1016/j.marpolbul.2011.11.010>
62. Khan MF, Wesley SG, Rajan M (2014) Polonium-210 in marine mussels (bivalve molluscs) inhabiting the southern coast of India. *J Environ Radioact* 138:410–416. <https://doi.org/10.1016/j.jenvrad.2014.06.023>
 63. Kim J, Tsouris C, Mayes RT, Oyola Y, Saito T, Janke CJ, Dai S, Schneider E, Sachde D (2013) Recovery of uranium from seawater: a review of current status and future research needs. *Sep Sci Technol* 48(3):367–387. <https://doi.org/10.1080/01496395.2012.712599>
 64. Klinkhammer G, Palmer M (1991) Uranium in the oceans: where it goes and why. *Geochim Cosmochim Acta* 55(7):1799–1806. [https://doi.org/10.1016/0016-7037\(91\)90024-Y](https://doi.org/10.1016/0016-7037(91)90024-Y)
 65. Larsson C-M (2008) An overview of the ERICA integrated approach to the assessment and management of environmental risks from ionising contaminants. *J Environ Radioact* 99(9):1364–1370. <https://doi.org/10.1016/j.jenvrad.2007.11.019>
 66. Lim MP, Mohamed CAR (2019) Radioactivity of ^{210}Po in green mussels (*Perna viridis*) at the west coast of Johore straits, Malaysia. *Malays J Anal Sci* 23(6):980–990. <https://doi.org/10.17576/mjas-2019-2306-06>
 67. Makmur M, Prihatiningsih W, Yahya M (2020) Baseline concentration of polonium-210 (^{210}Po) in several biota from Jakarta Bay. *IOP Conf Ser Earth Environ Sci*. <https://doi.org/10.1088/1755-1315/429/1/012061>
 68. Mamish S, Al-Masri M, Durgham H (2015) Radioactivity in three species of Eastern Mediterranean jellyfish. *J Environ Radioact* 149:1–7. <https://doi.org/10.1016/j.jenvrad.2015.07.004>
 69. Maqsood Q, Waseem R, Sumrin A, Wajid A, Tariq MR, Ali SW, Mahnoor M (2024) Recent trends in bioremediation and bioaugmentation strategies for mitigation of marine based pollutants: current perspectives and future outlook. *Discov Sustain* 5(1):524
 70. Markich SJ (2003) Influence of body size and gender on valve movement responses of a freshwater bivalve to uranium. *Environ Toxicol* 18(2):126–136. <https://doi.org/10.1002/tox.10109>
 71. Marsico E, Ferreira M, São Clemente S, Gouvea R, Jesus E, Conti C, Junior CC, Kelecom A (2014) Distribution of Po-210 in two species of predatory marine fish from the Brazilian coast. *J Environ Radioact* 128:91–96. <https://doi.org/10.1016/j.jenvrad.2013.10.026>
 72. Mashiatullah A, Khan M, Javed T, Chaudhary M, Qureshi R, Chughtai F (2010) Influence of pH on uptake and bioaccumulation of radiocesium (^{137}Cs) in the green mussels *Perna viridis*. *Nucleus* 47(1):31–34. <https://doi.org/10.71330/thenucleus.2010.907>
 73. Men W, Wang F, Yu W, He J, Lin F, Deng F (2020) Impact of the Fukushima Dai-ichi nuclear power plant accident on the neon flying squids in the Northwest Pacific from 2011 to 2018. *Environ Pollut* 264:114647. <https://doi.org/10.1016/j.envpol.2020.114647>
 74. Men W, Wang F, Yu W, He J, Lin F, Deng F, Ma H, Zeng Z (2020) Impact of the Fukushima Dai-ichi nuclear power plant accident on dolphin fishes in the Northwest Pacific. *Chemosphere* 257:127267. <https://doi.org/10.1016/j.chemosphere.2020.127267>
 75. Milenkovic B, Stajic JM, Stojic N, Pucarevic M, Strbac S (2019) Evaluation of heavy metals and radionuclides in fish and seafood products. *Chemosphere* 229:324–331. <https://doi.org/10.1016/j.chemosphere.2019.04.189>
 76. Minh QN, Van HV, Thi MN, Thi DN, Thu CNT, Minh TD, Xuan TD, Thi MT, Thi TN (2023) Holocene sedimentary facies in the incised valley of Ma River Delta, Vietnam. *Vietnam J Earth Sci* 45(4):497–516
 77. Monirith I, Ueno D, Takahashi S, Nakata H, Sudaryanto A, Subramanian A, Karuppiiah S, Ismail A, Muchtar M, Zheng J (2003) Asia-Pacific mussel watch: monitoring contamination of persistent organochlorine compounds in coastal waters of Asian countries. *Mar Pollut Bull* 46(3):281–300. [https://doi.org/10.1016/S0025-326X\(02\)00400-9](https://doi.org/10.1016/S0025-326X(02)00400-9)
 78. Murakami-Sugihara N, Shirai K, Tazoe H, Mizukawa K, Takada H, Yamagata T, Ootosaka S, Ogawa H (2021) Spatiotemporal change of cesium-137 in the Pacific coast of Tohoku, Japan: the mussel watch approach. *Mar Pollut Bull* 168:112413. <https://doi.org/10.1016/j.marpolbul.2021.112413>
 79. Musthafa MS, Krishnamoorthy R (2012) Estimation of ^{210}Po and ^{210}Pb and its dose to human beings due to consumption of marine species of Ennore Creek, South India. *Environ Monit Assess* 184(10):6253–6260. <https://doi.org/10.1007/s10661-011-2417-8>
 80. Nguyen Dinh C, Duong V-H, Chu Trung T, Pham Thi T-X, Nguyen Ngoc T, Nguyen Thi HH, Hoang Dinh Q, Tran Danh H, Musthafa MS, Nguyen T-M (2024) Uranium isotopes and several heavy elements in selected waters in Quang Nam-Da Nang provinces, Central Vietnam. *J Radioanal Nucl Chem* 333(11):5687–5699. <https://doi.org/10.1007/s10967-024-09733-x>
 81. Nguyen TA, Picot C, Tran TL, Carpentier FG, Roudot AC, Parent-Massin D (2012) Evaluation of shellfish consumption in Nha Trang City, Southern coastal Vietnam. *Malays J Nutr* 18(1):37–45
 82. Nguyen T-N, Nguyen T-D, Duong V-H, Nguyen T-T (2021) Distribution and annual committed effective dose assessment of ^{210}Po in popular marine species at the near-shore Binh Thuan province, Vietnam. *Mar Pollut Bull* 165:112073. <https://doi.org/10.1016/j.marpolbul.2021.112073>
 83. Nhi TB, Van PT, Van DN, Trong TP (2024) The present strain rate of Quang Nam-Quang Ngai and the surrounding region. *Vietnam J Earth Sci* 46(3):303–321
 84. OECD. (2012). OECD GUIDELINES FOR TESTING OF CHEMICALS. Test No. 305: Bioaccumulation in Fish: Aqueous and Dietary Exposure
 85. Ota T, Sanada T, Kashiwara Y, Morimoto T, Sato K (2009) Evaluation for committed effective dose due to dietary foods by the intake for Japanese adults. *Jpn J Health Phys* 44:80–88
 86. Pentreath R (1978) ^{237}Pu experiments with the plaice *Pleuronectes platessa*. *Mar Biol* 48(4):327–335. <https://doi.org/10.1007/BF00391636>
 87. Piñero-García F, Thomas R, Mantero J, Forssell-Aronsson E, Isaksson M (2023) Biodistribution of ^{210}Po in seafood and risk assessment for consumers in Sweden. *Food Control* 151:109789. <https://doi.org/10.1016/j.foodcont.2023.109789>
 88. Rahim AR, Utami DR (2025) Density of green mussels (*Perna viridis*) and its impact on growth and lead accumulation in polyculture systems in tropical waters. *Asian J Fish Aquat Res* 27(1):79–89. <https://doi.org/10.9734/ajfar/2025/v27i1865>
 89. Rathnayake RP, Rajapaksha D (2025) Nuclear and radioactive marine pollution and monitoring of radioactivity in oceans. *Coast Mar Pollut Source Sink Mitig Manag*. <https://doi.org/10.1002/9781394237029.ch10>
 90. Richir J, Gobert S (2014) The effect of size, weight, body compartment, sex and reproductive status on the bioaccumulation of 19 trace elements in rope-grown *Mytilus galloprovincialis*. *Ecol Indic* 36:33–47. <https://doi.org/10.1016/j.ecolind.2013.06.021>
 91. Ryan B, Bollhöfer A, Martin P (2008) Radionuclides and metals in freshwater mussels of the upper South Alligator River, Australia. *J Environ Radioact* 99(3):509–526. <https://doi.org/10.1016/j.jenvrad.2007.08.019>
 92. Ryan T, Dowdall A, McGarry A, Pollard D, Cunningham J (1999) ^{210}Po in *Mytilus edulis* in the Irish marine environment. *J Environ Radioact* 43(3):325–342. [https://doi.org/10.1016/S0265-931X\(98\)00062-9](https://doi.org/10.1016/S0265-931X(98)00062-9)
 93. Sengupta D, Van Gosen B (2016) Placer-type rare earth element deposits. *Rev Econ Geol* 18:81–100. <https://doi.org/10.1130/abs/2016AM-279551>
 94. Skwarzec B, Strumińska-Parulska DI, Boryło A, Kabat K (2012) Polonium, uranium and plutonium radionuclides in aquatic and land ecosystem of Poland. *J Environ Sci Health A* 47(3):479–496. <https://doi.org/10.1080/10934529.2012.646153>

95. Srilerd A, Kungskulniti N, Tumnoi Y, Charoenca N (2024) Radiological risk assessment in the Asian green mussel (*Perna viridis*) and the Thai seafood consumers. *Environ Adv* 15:100487. <https://doi.org/10.1016/j.envadv.2024.100487>
96. Stewart GM, Fowler SW, Fisher NS (2008) The bioaccumulation of U-and Th-series radionuclides in marine organisms. *Radioact Environ* 13:269–305. [https://doi.org/10.1016/S1569-4860\(07\)00008-3](https://doi.org/10.1016/S1569-4860(07)00008-3)
97. Štok M, Smodiš B (2011) Levels of ²¹⁰Po and ²¹⁰Pb in fish and molluscs in Slovenia and the related dose assessment to the population. *Chemosphere* 82(7):970–976. <https://doi.org/10.1016/j.chemosphere.2010.10.075>
98. Suseno H, Prihatiningsih WR (2014) Monitoring ¹³⁷Cs and ¹³⁴Cs at marine coasts in Indonesia between 2011 and 2013. *Mar Pollut Bull* 88(1–2):319–324. <https://doi.org/10.1016/j.marpolbul.2014.08.024>
99. Tantanararit C, Babel S, Englande AJ, Meksumpun S (2013) Influence of size and density on filtration rate modeling and nutrient uptake by green mussel (*Perna viridis*). *Mar Pollut Bull* 68(1–2):38–45. <https://doi.org/10.1016/j.marpolbul.2012.12.027>
100. Thebault H, Y Baena AMR (2007) Mediterranean mussel watch: a regional program for detecting radionuclides, trace-and emerging-contaminants. *Rapp de la Comm Int de la Mer Méditerranée* 38:41
101. Uddin S, Al-Ghadban A, Behbehani M, Aba A, Al Mutairi A, Karam Q (2012) Baseline concentration of ²¹⁰Po in Kuwait's commercial fish species. *Mar Pollut Bull* 64(11):2599–2602
102. UNSCEAR (2000) Sources and effects of ionizing radiation, ANNEX B, Exposures from natural radiation sources. *Unsclear 2000 Rep N Y* 1:97–99
103. Van Duong H, Nguyen CD, Nowak J, Kovacs T, Hoang QA (2019) Uranium and radium isotopes in some selected thermal, surface and bottled waters in Vietnam. *J Radioanal Nucl Chem* 319(3):1345–1349. <https://doi.org/10.1007/s10967-018-6317-z>
104. Van Hao D (2019) Quantitative methods of ²³⁸U, ²³⁴U, ²²⁸RA, ²²⁶RA radioisotopes in groundwater samples. <https://doi.org/10.15625/vap.2019.000212>
105. Van HD (2020) Assessment of the annual committed effective dose due to the ²¹⁰Po ingestion from selected sea-food species in Vietnam. *Chemosphere* 252:126519. <https://doi.org/10.1016/j.chemosphere.2020.126519>
106. Vetikko V, Saxén R (2010) Application of the ERICA assessment tool to freshwater biota in Finland. *J Environ Radioact* 101(1):82–87. <https://doi.org/10.1016/j.jenvrad.2009.09.001>
107. WHO (2004) Guidelines for drinking-water quality.
108. WHO (2011) Guidelines for drinking-water quality. *WHO Chron* 38(4):104–108
109. Yadav M, Kumar P, David A, Jindal MK (2025) Transportation of radioactivity in the marine world. *Radiation status in the marine world*. Springer, Cham, pp 95–131. https://doi.org/10.1007/978-3-031-82403-6_3
110. Yankovich TL, Beresford NA, Wood MD, Aono T, Andersson P, Barnett CL, Bennett P, Brown JE, Fesenko S, Fesenko J (2010) Whole-body to tissue concentration ratios for use in biota dose assessments for animals. *Radiat Environ Biophys* 49(4):549–565. <https://doi.org/10.1007/s00411-010-0323-z>
111. Zerbini M (2025) The impact of radioactive metals on marine ecosystems: in vivo speciation and molecular mechanisms of the uptake by brown algae Université Côte d'Azur]. <https://theses.hal.science/tel-05079610v1>
112. Zorita I, Apraiz I, Ortiz-Zarragoitia M, Orbea A, Cancio I, Soto M, Marigómez I, Cajaraville MP (2007) Assessment of biological effects of environmental pollution along the NW Mediterranean Sea using mussels as sentinel organisms. *Environ Pollut* 148(1):236–250. <https://doi.org/10.1016/j.envpol.2006.10.022>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Van-Hao Duong¹ · Tien Chu Trung¹ · Khai M. Nguyen^{2,3} · Thi Thuy Huong Ngo⁴ · Marckasagayam Priyadharshini⁵ · Mohamed Saiyad Musthafa⁶ · Xuan-Quang Nguyen^{7,8} · Nga Phung Thi⁹ · Trinh Phan Trong¹⁰ · Duc-Thang Duong¹¹ · Thanh-Duong Nguyen¹² · Miklós Hegedűs¹³ · Thanh-Xuan Pham Thi¹ · Tibor Kovács¹⁴

✉ Thanh-Xuan Pham Thi

✉ Tibor Kovács
kovacstiborjanos@gmail.com

¹ VNU School of Interdisciplinary Studies, Vietnam National University, 144 Xuan Thuy, Cau Giay, Hanoi 10000, Vietnam

² Faculty of Environmental Science, University of Science, Vietnam National University, Hanoi, Vietnam

³ VNU Key Laboratory of Green Environment, Technology and Waste Utilization (GreenLab), University of Science, Vietnam National University, Hanoi, Vietnam

⁴ Faculty of Biotechnology, Chemistry and Environmental Engineering, Phenikaa University, Hanoi 12116, Vietnam

⁵ Saveetha Institute of Basic Medical Sciences (SIBMS), Saveetha University, Tamil Nadu, India

⁶ Unit of Research in Radiation Biology & Environmental Radioactivity (URRBER), P.G. & Research Department

of Zoology, The New College (Autonomous), Affiliated to University of Madras, Chennai, Tamil Nadu 600 014, India

⁷ Environment and Sustainable Development Research Group, Dong Nai Technology University, Bien Hoa City, Vietnam

⁸ Faculty of Technology, Dong Nai Technology University, Bien Hoa City, Vietnam

⁹ Thanh Do University, Hanoi, Vietnam

¹⁰ Institute of Earth Sciences, Vietnam Academy of Science and Technology, Hanoi, Vietnam

¹¹ Institute for Nuclear Science and Technology, Vinatom, 179 Hoang Quoc Viet, Cau Giay, Hanoi, Vietnam

¹² Hanoi University of Mining and Geology (HUMG), 18 Vien, Dong Ngac, Hanoi, Vietnam

¹³ Department of Radiochemistry and Radioecology, University of Pannonia, Veszprem, Hungary

¹⁴ Department of Biophysics and Radiation Biology, Semmelweis University, Budapest, Hungary