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Distribution and annual committed effective dose assessment of ^{210}Po in popular marine species at the near-shore Binh Thuan province, Vietnam

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ABSTRACT

^{210}Po concentration in thirty popular marine species (twenty five fishes, four bivalves and one crab) with different habitats, feeding types, and trophic levels at the near-shore Binh Thuan, Vietnam was analyzed using the alpha detectors. The ^{210}Po activities were widely ranged from 3.07 ± 0.18 in a fish species (Bumpnose trevally) to 78.6 ± 5.3 Bq/kg w.w in a bivalve species (Green mussel) with the average value of 16.6 Bq/kg w.w. The results showed that the species with lower trophic level value have higher ^{210}Po concentration. Regarding the feeding types, the ^{210}Po concentration in the omnivorous species is about 2.9 times higher than in the carnivorous species. The species living in demersal zone accumulated a high ^{210}Po in comparison with species living in reef-associated and pelagic-neritic zones. The calculated annual committed effective dose from ^{210}Po due to the ingestion of seafood from demersal zone and bivalve species of the area was significant high.

1. Introduction

In marine environment, the concentration of radionuclides in the marine species can be higher than that in sea water due to their biological accumulation capacity (Khan and Wesley, 2011). The ingestion of seafood is a common routine, especially for residents in coastal area. Consumption of seafood containing radionuclides is one of major sources of natural radiation exposure (Mishra et al., 2009). Thus, measurement of radionuclide concentration in marine species is necessary, especially regarding the human health safety. The high toxicity of ^{210}Po is attributed to the high linear energy transfer of its alpha particles and its high specific activity (UNSCEAR, 2000). Among natural radionuclides in marine environment, ^{210}Po is of the most radiotoxic natural radionuclides which mainly comes from Uranium ^{238}U decay series. The presence of ^{210}Po in the marine environment is attributed to the direct deposition of ^{210}Po itself and indirect deposition of the decay of its grandparent ^{210}Pb which could come from the atmosphere, seawater, and seabed sedimentary materials (Fowler, 2011; Sirelkhatim et al., 2008; Skwarzec and Bojanowski, 1988; Saçan et al., 2010; Carvalho, 2011; Meli et al., 2013). In addition, human activities such as uranium, titanium ore, and phosphate rock processing, oil and gas industries can increase the concentration of ^{210}Po in the marine environment (Carvalho, 1988; Betti et al., 2004; Khater and Bakr, 2011; Garcia-Orellana et al., 2016; Villa et al., 2009). It is reported that various marine species contain a high concentration of ^{210}Po (Carvalho, 1988; Brown et al., 2004; Connan et al., 2007; Khan and Wesley, 2011). Therefore, assessment the concentration of ^{210}Po accumulated in marine species and radiological health hazard due to ingestion of seafood is one of the great interests around the world (Yamamoto et al., 1994; Saito and Cunha, 1997; Hassona et al., 2008; Štrok and Smodiš, 2011; Uddin et al., 2012; Aközcan and Uğur, 2013; Marsico et al., 2014; Khan and Wesley, 2016, 2011; Kim et al., 2017; Ababneh et al., 2018; Al-Masri et al., 2019; Musthafa et al., 2019; Guy et al., 2020; Van, 2020). Most of these investigations showed that a significant contribution of ^{210}Po to the radiation dose was received by consumption of seafood. Recently, the research of Van et al. (2020) also indicated that the annual effective dose from ^{210}Po due to ingestion of seafood in Vietnam was highest among different radionuclides. As reported in the literature, the concentration of ^{210}Po in seafood can be affected by many factors such as the concentration of ^{210}Po in the environment, different kinds of marine species

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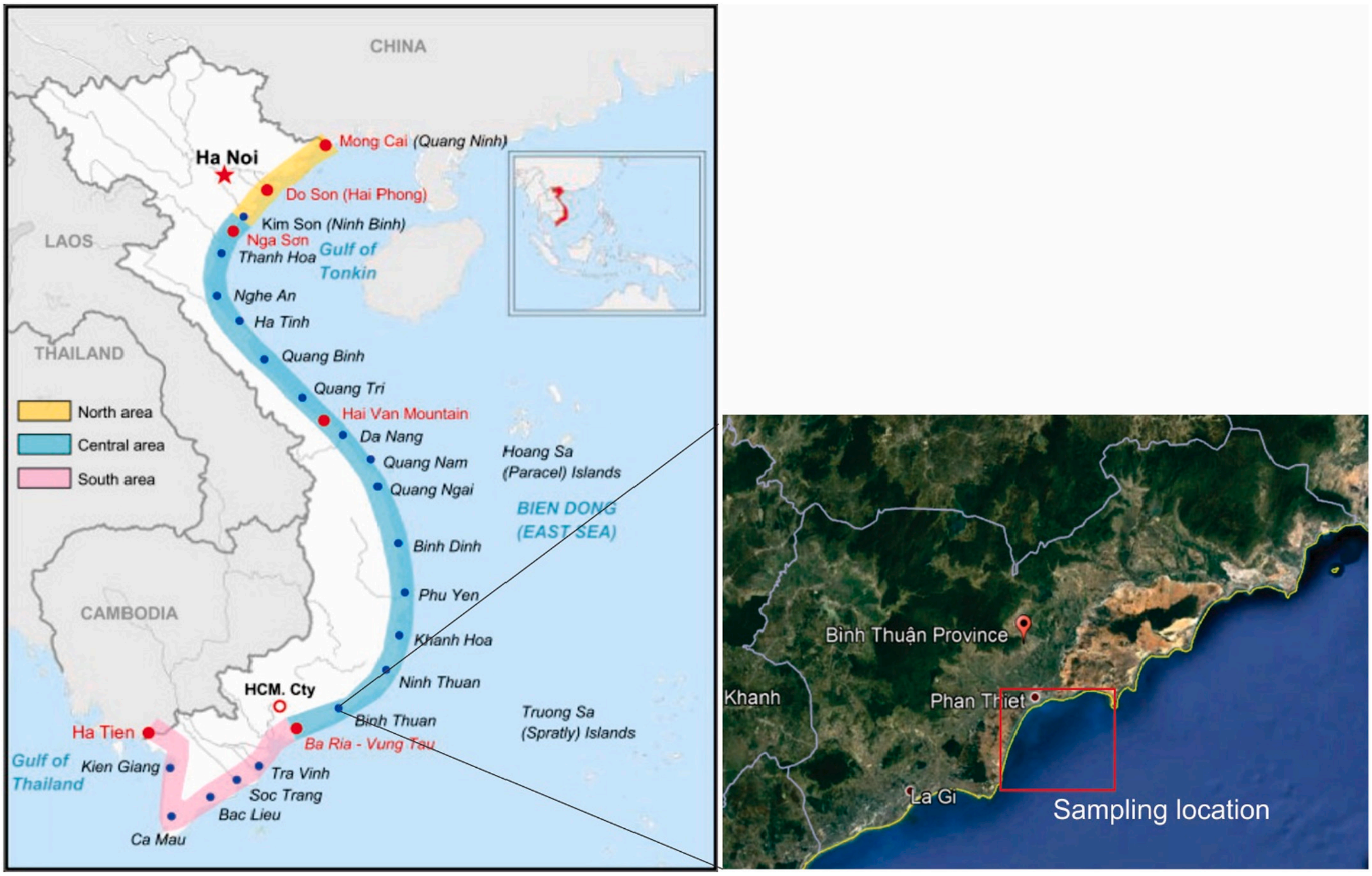

Fig. 1. Location of study area and sampling points.

and targeted organs (Makmur et al., 2020).

Binh Thuan is a southeastern coastal of province of Vietnam, with a coastline of 192 km in length and a fishing area of about 60,000 km^2. Binh Thuan has favorable fishing grounds and rich in aquatic resources. This area has been identified as one of the three key fishing grounds of the whole country; annual fishing output is 190,000 tons of all kinds of seafood (http://www.thuysanvietnam.com.vn/binh-thuan-phat-huy-tiem-nang-kinh-te-thuy-san-article-16269.tsvn). Binh Thuan is also just south of the central upwelling cell and is considered a major fisheries region of Vietnam, consisting of local bottom draggers, gill netting, and hook-and-line fishers. The shelf region is typical of most of Vietnam's coastline with depths of <50 m as far as 50 km offshore, and a relatively flat relief with bottom substrates of sand, mud, and cobble. As a result, the coastal waters are easily fished by use of trawl or push nets that often have small mesh sizes that indiscriminately take almost all sizes of macro-organisms (Pomeroy et al., 2009). Besides aquatic resources, Binh Thuan has abundant mineral resources, especially titanium placers. Binh Thuan is one of the coastal provinces with the distribution of titanium placer and is considered to be the province with the largest titanium placer potential in the country, even the largest in Southeast Asia. However, according to the Department of Natural Resources and Environment of Binh Thuan, the mining and processing activities of titanium in many areas such as Phan Thiet, Ham Thuan Nam have discharged gross alpha and beta radioactive concentration to the environment exceeding the limitation. The province has banned the use of seawater to serve titanium ore mining, but most titanium mining companies secretly use seawater to sort ore and directly discharge waste water into the sea. These activities have caused a serious effect on the marine environment (https://www.vietnamplus.vn/binh-thuan-dau-dau-voi-bai-toan-khai-thac-titan/103745.vnp). Thus, it is necessary to evaluate the ^{210}Po concentration in marine species Binh Thuan coastal area to obtain the baseline and calculate the radiation dose from ^{210}Po due to seafood ingestion. Besides, there is now no information about the distribution of ^{210}Po in seafood and the effective radiation dose from ^{210}Po due to seafood consumption and report of the relation between ^{210}Po in different marine species with different feeding, living habitats, and trophic levels in Binh Thuan region. Therefore, this study aims to evaluate the activity concentrations of ^{210}Po in the most popular marine species, to estimate the effective radiation dose from ^{210}Po to inhabitants due to consumption of seafood and its characteristics related to different feeding, living habitats, and trophic levels in Binh Thuan region.

2. Materials and methods

2.1. Sampling and sample preparation

Thirty different types of fresh marine species samples were collected from sea near the shore of Phan Thiet town in Binh Thuan province in 2019 (Fig. 1) by using a benthic otter trawl consistent with regular fishing gear by local fishers, with a maximum mouth opening of 17 m wide by 15 m in height, and a net length of 30 m. Mesh size at the mouth was 6 cm, tapering down to 1 cm toward the cod end. The collected marine species are different in trophic levels, feeding types, habitats and commonly consumed in Vietnam. The seawater in sampling location was also collected (three samples with 10 L for each). The analysis results show that the average concentration of ^{210}Po in seawater is 1.38 ± 0.12 mBq/L. These samples were transferred to both of the laboratories of The Institute for Nuclear Science and Technology (INST), Vietnam; the Key Laboratory of Environmental and Climate Change Response, Vietnam University of Science (VNU), and Center for Life Science Research (CELIFE), VNU for radioactivity investigation. The marine species were

Table 1
Local, English and scientific names of marine species, feeding types, habitats and ^{210}Po concentration of each marine species.

Local name	English name	Scientific name	Trophic level[a]	Feeding types	Habitats	Average of ^{210}Po (Bq/kg w.w)
Cá lưỡi trâu ($n = 56$)	Fourlined tonguesole	*Cynoglossus bilineatus*	3.5	Carnivorous	Demersal	28.6 ± 1.2
Cá đàn lia Nhật Bản (n = 56)	Longtailed dragonet	*Callionymus japonicus*	3.4	Carnivorous		7.67 ± 0.63
Cá lượng Nhật ($n = 29$)	Japanese threadfin bream	*Nemipterus japonicus*	4.1	Carnivorous		3.15 ± 0.10
Cá lú lưng sợi ($n = 17$)	Threadfin sandperch	*Parapercis filamentosa*	3.5	Carnivorous		7.17 ± 0.71
Cá lịch khoang răng khía ($n = 6$)	Dusky-banded moray	*Gymnothorax reticularis*	4.0	Carnivorous		8.25 ± 0.99
Cá chai Nhật Bản ($n = 58$)	Japanese flathead	*Inegocia japonica*	3.7	Carnivorous		11.0 ± 1.8
Cá bơn vằn ($n = 8$)	Speckled tonguesole	*Cynoglossus puncticeps*	3.3	Omnivorous		12.3 ± 0.70
Cá đối lá (n = 5)	Longarm mullet	*Moolgarda cunnesius*	2.4	Omnivorous		7.37 ± 0.97
Cá đàn lia đuôi lõm ($n = 100$)	Richard's dragonet	*Callionymus curvicornis*	3.2	Omnivorous		4.29 ± 0.26
Sò lụa ($n = 41$)	Undulate venus	*Paphia undulata*	2.1	Omnivorous		58.2 ± 3.2
Vẹm xanh (n = 5)	Green mussel	*Perna viridis*	2.0	Omnivorous		78.6 ± 5.3
Ghẹ đá (n = 5)	Blue crab	*Portunus pelagicus*	2.5	Omnivorous		60.1 ± 3.6
Sò nước (n = 5)	Hooked ark	*Cucullaea labiata*	2.1	Omnivorous		50.8 ± 3.5
Ngao giá (n = 5)	Turgid venus	*Tapes dorsatus*	2.1	Omnivorous		22.6 ± 2.4
Cá mối thường ($n = 9$)	Greater lizardfish	*Saurida tumbil*	4.4	Carnivorous	Reef-associated	8.73 ± 0.62
Cá sòng gió (n = 5)	Torpedo scad	*Megalaspis cordyla*	4.4	Carnivorous		7.47 ± 0.69
Cá trác đuôi ngắn ($n = 59$)	Red bigeye	*Priacanthus macracanthus*	4.1	Carnivorous		9.12 ± 0.98
Cá khế đầu u (n = 6)	Bumpnose trevally	*Carangoides hedlandensis*	4.0	Carnivorous		3.07 ± 0.38
Cá sơn ki ($n = 53$)	Rifle cardinal	*Ostorhinchus kiensis*	3.4	Carnivorous		12.9 ± 0.66
Cá sạo chấm (n = 56)	Saddle grunt	*Pomadasys maculatus*	4.0	Carnivorous		23.5 ± 1.1
Cá hồng chấm (n = 5)	Russell's snapper	*Lutjanus russellii*	4.1	Carnivorous		13.0 ± 1.2
Cá đục bạc (n = 8)	Silver sillago	*Sillago sihama*	3.3	Carnivorous		10.2 ± 0.96
Cá lượng mắt gai một sọc ($n = 7$)	Monocle bream	*Scolopsis affinis*	3.3	Carnivorous		5.76 ± 0.58
Cá nhệch ăn cua (n = 5)	Longfin snake-eel	*Pisodonophis cancrivorus*	3.8	Carnivorous		3.49 ± 0.33
Cá tráo mắt to ($n = 51$)	Bigeye scad	*Selar crumenophthalmus*	3.8	Omnivorous		9.35 ± 0.43
Cá bàng chài công (n = 5)	Razorfish	*Iniistius trivittatus*	3.5	Omnivorous		5.23 ± 0.45
Cá liệt chấm thân (n = 59)	Dots and dashes ponyfish	*Secutor indicius*	2.8	Carnivorous	Pelagic-neritic	8.85 ± 0.87
Cá bao áo (n = 5)	Cleftbelly trevally	*Atropus atropos*	3.6	Carnivorous		6.68 ± 0.32
Cá trích xương (n = 5)	Goldstripe sardinella	*Sardinella gibbosa*	2.9	Carnivorous		6.22 ± 0.55
Cá bạc má (n = 6)	Indian mackerel	*Rastrelliger kanagurta*	3.2	Omnivorous		4.52 ± 0.25
Min						3.07 ± 0.18
Max						78.6 ± 5.3
Average						16.6

[a] The Trophic levels refer from Froese and Pauly, 2019; Palomares and Pauly, 2019.

divided into two groups according to feeding types, including carnivorous, omnivorous and into three groups according to habitats, including demersal, reef-associated, pelagic-neritic species. The local, English, and scientific names of each collected marine species used in this study along with feeding types, habitats are shown in Table 1.

Before ^{210}Po measurements, the collected samples were washed with distilled water, then skinned with removing bones for fish samples and removing the shell for other samples. About 5 g of edible muscle tissues (wet weight) of five individuals of each species were analyzed for ^{210}Po activity to obtain a more representative biological sample. Therein, the foot and adductor muscle bivalves were used for analysis.

2.2. Measurement of ^{210}Po

The edible muscle tissues were prepared for ^{210}Po measurement. The procedure was presented by Van (2020). As a brief, ^{209}Po tracer was added to the samples then was wet-digested to complete digestion by acids and continuous for separate ^{210}Po concentration by chemical reagents and anion-exchange resins, then was spontaneously deposited on one side of a polished silver disk in solution of HCl acid 0.5 M. The obtained silver disc was dried at the room temperature and measured by ORTEC detectors (four ALPHA-DUO-M1–450 mm^2 area detector) with Alpha-vision software and a minimum detectable limit 0.5mBq. The chemical recovery was reported about 90%, and quality control procedure were performed with reference material IAEA-414 mixed fish sample, which was reported with confidence interval from 1.8 to 2.5 Bq/kg and the reference value 2.1 Bq/kg (IAEA-414).

The annual committed effective dose (ACED) contributed by ^{210}Po concentration for an adult due to the ingestion of edible muscle tissues of seafood can be calculated based on the following formula:

$$ACED = A \times D \times X \times F \times Y$$

where ACED is the annual committed effective dose contributed by ^{210}Po (μSv), A is the average activity concentration of ^{210}Po in edible tissue of studied marine species (Bq/kg w.w), D is the average daily consumption rate of seafood (kg) - For Vietnamese people, the average consumption of seafood is estimated at 27 kg/person/year in 2015 (https://www.vietnam-briefing.com/news/seafood-industry-vietnam-aquaculture-year-plans-tpp.html/), X is the factor of ^{210}Po dose conversion per unit intake which is employed for adults (X = 1.2 μSv/Bq for ^{210}Po) (IAEA, 2003), F is decay factor for ^{210}Po which depends on the time between seafood catching and consumption (In this study, F = 1 since the seafood was assumed to consume right after catching), Y is 1 year.

3. Results and discussions

3.1. ^{210}Po activity concentrations

The results of ^{210}Po concentration (Bq/kg wet weight) in different marine species are shown in Table 1. As shown in this table, the highest concentration of ^{210}Po in selected marine species is detected in Green mussel (*Perna viridis*) with the value of 78.6 ± 5.3 Bq/kg, while the lowest one is found in Bumpnose trevally (*Carangoides hedlandensis*) with the value of 3.07 ± 0.18 Bq/kg. The Green mussel organism often live in demersal zone with the feeding types of omnivorous foods such as phytoplankton and detritus, whereas the Bumpnose trevally is reef-associated species with the feeding type of carnivorous food such as zoobenthos, nekton. In Kakart bay, Indonesia, the highest concentration of ^{210}Po in seafood was also found in Green mussel with the value of 137 ± 25 Bq/kg dry weight (Makmur et al., 2020). Green mussel is bivalve species with filter feeding, the feed behavior was well-known with high ^{210}Po accumulation (Fowler, 2011; Belivermiş et al., 2019). Bumpnose trevally is the predation type feeding species, the marine predators

Table 2
Concentration of ^{210}Po in marine species detected in different countries of the world.

Countries	^{210}Po (Bq/kg w.w)	References
India (Kudankulam coast)	1.2–248	Khan and Wesley, 2011
Izmir Bay (Turkey)	ND-91.3	Aközcan and Uğur, 2013
Syria	0.27–27.5	(Al-Masri, 2000)000
Japan	0.27–26.3	Yamamoto et al., 1994
Gulf countries	0.14–14.7	Ababneh et al., 2018
Slovenia	0.039–35	Štrok and Smodiš, 2011
Poland	0.9–5	(Skwarzec, 1997)
Kuwait	0.089–3.3	Uddin et al., 2012
Sudan	0.25–6.4	Hassona et al., 2008
Brazil	0.5–0.53	Saito and Cunha, 1997
Korea	0.51–5.6	Kim et al., 2017
Vietnam	0.82–70.3	Van, 2020
This study (Binh Thuan pro.)	3.07–78.6	This study

which was reported by previous studies with low ^{210}Po concentration accumulation (Fowler, 2011; Carvalho, 2011; Carvalho et al., 2017). It can be seen that ^{210}Po concentration observed in seafood in this study widely ranges from 3.07 to 78.6 Bq/kg with the average value of 16.6 Bq/kg. The wide variation of ^{210}Po concentration in this study is attributed to the differences in metabolism, trophic levels, habitats and feeding types. The range of ^{210}Po concentration detected in all the studied edible muscle tissues in this study is compared with some of other research results in different countries of the world (Table 2). In this table, the ^{210}Po concentration in marine species in this study is higher than that in those countries, except for India and Turkey. The concentration of ^{210}Po in Kudankulma coast (India) and Izmir Bay (Turkey) was ranged from 1.2 to 248 Bq/kg w.w and from not detected to 91.3 Bq/kg w.w respectively. The wide range of ^{210}Po concentration in seafood in different countries of the world may be affected by select organs, different study areas and the pollution in the marine environment (Garcia-Orellana et al., 2016; Ababneh et al., 2018). The result of ^{210}Po concentration in Binh Thuan province (this study) meets the results of Van (2020) the author investigated the ^{210}Po concentration in selected of only twelve of popular seafoods from Vinh town to Nha Trang, Vietnam. As indicated in the introduction part, the ^{210}Po concentration in seawater in the study area is 1.38 mBq/L in average. This value is significantly lower than the ^{210}Po concentration observed in marine species. As reported in Carvalho et al. (2017) for high trophic level organisms (e.g., fish, shrimp…), the main source of ^{210}Po in these organisms is from ingested food, the uptake of ^{210}Po from seawater is insignificant.

Fig. 2 shows the relationship between ^{210}Po concentration in different marine species and trophic levels. It can be seen that the higher trophic levels may result in lower ^{210}Po concentration detected in marine species (Pearson correlation coefficient, R (30) = −0.66, *p-value* = 0.001). As reported by Van et al. (2020) the higher trophic levels may lead to a lower gross alpha activity concentration in some selected marine species in Vietnam. This finding is well consistence with previous studies (Skipperud et al., 2013; Kılıç et al., 2018; Belivermiş et al., 2019). In this study, the Pearson correlation coefficient is moderate negative, and the relationship between trophic levels and ^{210}Po concentration is significant since the *p-value* of 0.001 is less than 0.05. As shown in Table 1, the shellfishes such as Undulate venus (*Paphia undulate*), Green mussel (*Perna viridis*), Blue crab (*Portunus pelagicus*), Turgid venus (*Tapes dorsatus*), and Hooked ark (*Cucullaea labiata*) have a low trophic level of 2.1 to 2.9 and a rather high concentration of ^{210}Po.

Regarding the living habitats, in demersal species, the average concentration of ^{210}Po is 25.7 Bq/kg with the highest concentration of 78.6 ± 5.3 Bq/kg in Green mussel - *Perna viridis* (omnivorous feeding types) and the lowest one of 3.15 ± 0.10 Bq/kg in Japanese threadfin bream - *Nemipterus japonicus* (carnivorous feeding types). The high concentration of ^{210}Po is also found in other species with omnivorous feeding types such as Undulate venus (*Paphia undulate*), Blue crab (*Portunus pelagicus*), and Hooked ark (*Cucullaea labiate*) with the value of 58.2 ± 3.0, 60.1 ± 3.6, and 50.8 ± 3.0 Bq/kg w.w in respective. Although the Richard's dragonet (*Callionymus curvicornis*) and Longarm mullet (*Moolgarda cunnesius*) demersal species were belong to omnivorous feeding types but the ^{210}Po concentration was significant low in comparison with others of the same group (demersal species - omnivorous feeding types) with 7.37 ± 0.97 and 4.29 ± 0.26 Bq/kg respective. It should be noted here that the different ^{210}Po concentration's characteristics not only depend on the environment of living habitats, feeding habits but the metabolism, trophic level and other parameters. This was also mentioned by previous study (Van, 2020). In reef-associated species, the ^{210}Po concentration varies from 3.07 ± 0.18 Bq/kg to 23.5 ± 0.18 Bq/kg with an average value of 9.30 Bq/kg. The highest concentration of ^{210}Po is found in Saddle grunt (*Pomadasys maculatus*) while the lowest one is detected in Bumpnose trevally (*Carangoides hedlandensis*). The two species have the feeding types of zoobenthos, nekton (carnivorous). In pelagicneritic species, the concentration of ^{210}Po shows a small variation with the range from 4.52 ± 0.25 Bq/kg (Indian mackerel - *Rastrelliger kanagurta*) to 8.85 ± 0.87 Bq/kg (Dots and dashes ponyfish - *Secutor indicius*) and the average value of 6.60 Bq/kg. It should note here that the highest average concentration of ^{210}Po is observed in demersal species, followed by reef-associated species and pelagic-neritic species (Fig. 3). This phenomenon could be related to different ^{210}Po concentration in different depth (Narayana and Prakash, 2010; Thomson and

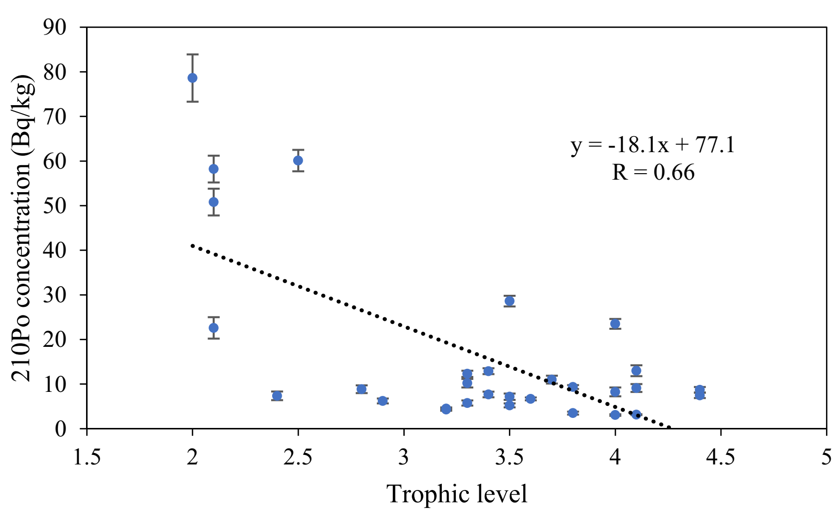

Fig. 2. Relationship between ^{210}Po concentration and trophic levels.

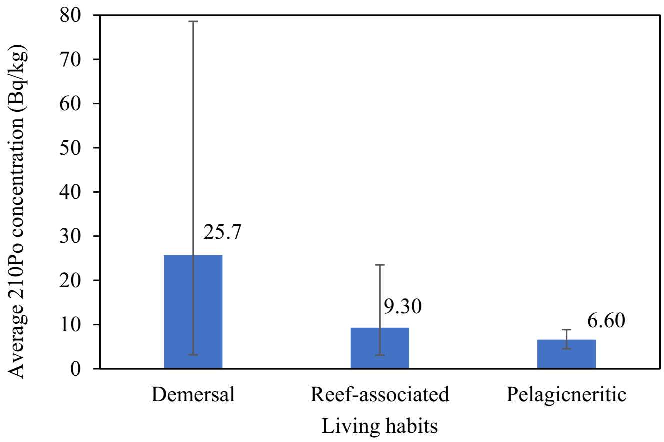

Fig. 3. The average ^{210}Po concentration and detected in marine species for different habitats.

Turekian, 1976). The concentration of ^{210}Po concentration in surface water can increase due to the atmospheric deposition. However, it will be taken-up by phytoplankton, zooplankton (Carvalho et al., 2017; Al-Masri et al., 2019). In addition, the sediment, organic matter often contains a high concentration of ^{210}Po (Bañobre et al., 2020). Bañobre et al. (2020) also indicated that ^{210}Po concentration had a good relationship with the organic fractions in the sediment. The high concentration of ^{210}Po in depth seawater and sediment in the seabed maybe lead to a high concentration of ^{210}Po in demersal species. In addition, marine sediments can accumulate the high concentration of ^{210}Po due to the discharge of waste sediments from titanium placer exploration in the study area. As shown in Table 1, the concentration of ^{210}Po in some species, including Undulate venus (*Paphia undulate*), Green mussel (*Perna viridis*), Blue crab (*Portunus pelagicus*), and Hooked ark (*Cucullaea labiate*) (Shellfishes) is about 2 to 20 times higher than that in other species in the study area. Since the feeding types of these species are omnivorous foods, including detritus, zooplankton, phytoplankton and these foods often contain a high content of ^{210}Po concentration (Bañobre et al., 2020; Raja and Hameed, 2010; Carvalho et al., 2017; Al-Masri et al., 2019), this may lead to a high concentration of ^{210}Po in these species. In addition, three of them are belong to bivalve species with filter feeding type which as mentioned above can accumulate high ^{210}Po concentration. The other reason of high ^{210}Po activity in a given marine species could be the relatively long biological half-life of ^{210}Po (138 days). The retention and assimilation capacity of ^{210}Po could be high, which caused a relatively high ^{210}Po activities in tissues which was mentioned by Belivermiş et al. (2019).

Table 1 shows that the average concentration of ^{210}Po in marine species with feeding types of omnivorous foods is 28.5 Bq/kg. It is about 2.9 times higher than the ^{210}Po concentration in marine species with feeding types of carnivorous foods (9.73 Bq/kg). As mentioned above, the omnivorous foods such as detritus, zooplankton, and phytoplankton often contain a high concentration of ^{210}Po. This will lead to a high concentration of ^{210}Po in marine species with the feeding types of omnivorous (predation type feeding). This trending met the results of the published investigations (Hassona et al., 2008; Raja and Hameed, 2010; Štrok and Smodiš, 2011; Uddin et al., 2012; Aközcan and Uğur, 2013; Chen et al., 2016; Ababneh et al., 2018; Van, 2020; Fowler, 2011; Carvalho, 2011; Carvalho et al., 2017).

3.2. Annual committed effective dose and risk assessment

Due to lack of data in Vietnam, and it is difficult to accurate assumption how much each fish, bivalve, and crab which people consumed in a year since each person has different favorite seafood, or type of group foods. Thus, accurate consumption data is hard to find, and the total valued consumption was used as assumption for each marine species for daily and annually. Which showed that if people using as recommendation of the total value will receive the ACED as this report. The radionuclide intake and associated committed effective dose (CED), ACED values due to consumption of seafood are shown in Table 3. As shown in this table, the dose intake (Bq) and CED (μSv) contributed by ^{210}Po via ingestion of seafood in Binh Thuan province, Vietnam vary 0.23–5.81 Bq/d (1.23 Bq/d); 83–2120 Bq/y (448 Bq/y); 0.27–6.98 μSv/d (1.47 μSv/d); 99–2550 μSv/y (538 μSv/y). It can be seen that the highest ACED contributed by ^{210}Po is observed for Green mussel (*Perna viridis*) with the value of 2550 (μSv/y) while the lowest one is found in Bumpnose trevally (*Carangoides hedlandensis*) with the value of 99 (μSv/y). This indicates that the ACED from ^{210}Po due to the ingestion of seafood in the study area is widely ranged from 99 to 2550 (μSv/y) and 538 (μSv/y) on average. The wide variation of ACED is attributed to the large difference in ^{210}Po concentration in different

Table 3
Radionuclide intake and associated dose.

Species	^{210}Po (Bq/kg w. w)	Intake/d (Bq)	Intake/y (Bq)	CED/d (μSv)	CED/y (ACED) (μSv)
Fourlined tonguesole	28.6	2.12	772	2.54	927
Longtailed dragonet	7.67	0.57	207	0.68	249
Japanese threadfin bream	3.15	0.23	85.0	0.28	102
Threadfin sandperch	7.17	0.53	194	0.64	232
Dusky-banded moray	8.25	0.61	223	0.73	267
Speckled tonguesole	12.3	0.91	332	1.09	399
Longarm mullet	7.37	0.55	199	0.65	239
Japanese flathead	11.0	0.81	297	0.98	356
Richard's dragonet	4.29	0.32	116	0.38	139
Undulate venus	58.2	4.31	1570	5.17	1890
Green mussel	78.6	5.81	2120	6.98	2550
Blue crab	60.1	4.45	1620	5.33	1950
Hooked ark	50.8	3.76	1370	4.51	1650
Turgid venus	22.6	1.67	610	2.01	732
Torpedo scad	7.47	0.55	202	0.66	242
Red bigeye	9.12	0.67	246	0.81	295
Razorfish	5.23	0.39	141	0.46	169
Bumpnose trevally	3.07	0.23	83.0	0.27	99.0
Rifle cardinal	12.9	0.95	348	1.15	418
Saddle grunt	23.5	1.74	635	2.09	761
Russell's snapper	13.0	0.96	351	1.15	421
Silver sillago	10.2	0.75	275	0.91	330
Monocle bream	5.76	0.43	156	0.51	187
Longfin snake-eel	3.49	0.26	94.0	0.31	113
Bigeye scad	9.35	0.69	252	0.83	303
Greater lizardfish	8.73	0.65	236	0.77	283
Indian mackerel	4.52	0.33	122	0.40	146
Dots and dashes ponyfish	8.85	0.65	239	0.79	287
Cleftbelly trevally	6.68	0.49	180	0.59	216
Goldstripe sardinella	6.22	0.46	168	0.55	202
Minimum	3.07	0.23	83.0	0.27	99.0
Maximum	78.6	5.81	2120	6.98	2550
Average	16.6	1.23	448	1.47	538

Table 4
ACED from ^{210}Po due to seafood consumption in different countries.

Country	Seafood consumption rate (kg/year)	Dose conversion factor (μSv/Bq)	Decay factor	ACED (μSv/y)	References
Slovenia	3.7 (Marine fish)	1.2	1	32	Štrok and Smodiš, 2011
Sudan	4.45	0.43	1	3.5–4.8	Hassona et al., 2008
Republic Korea	42.8	1.2	0.6	19–189	Kim et al., 2017
Izmir Bay (Turkey)	–	0.43	0.9	0.044–8.9	Aközcan and Uğur, 2013
India	–	1.2	1.0	11–515.6	Khan and Wesley, 2011
Arabian Gulf	19.2	1.2	1	38–85	Ababneh et al., 2018
Vietnam	18.8	1.2	1	18.5–1590	Van, 2020
Binh Thuan pro., Vietnam	27	1.2	1	99–2550	This study

species as mentioned above. However, the average value of ACED in this study is lower than the limit value of ACED of 1000 (μSv/y) as reported in ICRP (2007).

The ACED from ^{210}Po obtained from this study is compared with that obtained from previous studies in different countries, regions and shown in Table 4. It can be seen that the ACED in this study is higher than that in other countries listed in this table. However, it should be noted that the dose calculation of the ACED significantly depends on the consumption rate per year, the calculation factors such as dose conversion and decay factors, which was also mentioned by Van (2020). The values of these parameters for calculation are also listed in Table 4. In particular, as mentioned in Table 2, the ^{210}Po concentration in seafood in Izmir Bay (Turkey) and Kudankulma Coast (Turkey) is higher than that in Binh Thuan (Vietnam). Nevertheless, the calculated ACED in this study is much higher than that in the two regions. The difference here is mainly contributed to the difference in the consumption rate of seafood.

Regarding the risk assessment, in this study, the limit of annual consumption rate of seafood to reach the limit of radiation dose recommended by ICRP (2007) for different species, living habits, and feeding habits will be estimated. According to the estimation, the limit of annual consumption rate of marine species in the study region varies from 10.6 to 271 kg. The lowest annual consumption is recommended for *Green mussel* (10.6 kg) while the highest one is observed for *Bumpnose trevally* (271 kg). It is suggested that the consumption of *Green mussel* in the study region should be considered. Regarding the living habit, the calculation results show that the annual intake of marine species living in demersal zone of 32.4 kg is necessary to reach the threshold radiation level of 1000 μSv/y, whereas this value is 89.4 kg and 127 kg for reef-associated and pelagicneritic zone species, respectively. With regards to feeding habit, the annual consumption rate of 85.7 kg is limited for carnivorous feeding species while that of 29.3 kg for omnivorous feeding habit. Additionally, in this study, thirty marine species can be divided into twenty-five fishes, four bivalves, and one crab species. The dose calculation reveals that the threshold of annual consumption rate of fish is 91.4 kg while that of bivalves and crab is only 15.9 kg and 13.9 kg, respectively.

4. Conclusions

In this study, the distribution of ^{210}Po concentration in different marine species with different trophic levels, habitats and feeding types in Binh Thuan, Vietnam has been extensively investigated. The research results showed that the ^{210}Po concentration detected in different marine species was widely varied from 3.07 ± 0.18 to 78.6 ± 5.3 Bq/kg w.w with the average value of 16.6 Bq/kg w.w. The highest ^{210}Po concentration was observed in Green mussel (*Perna viridis*) - a bivalve, filter feeder, demersal organism with the feeding types of omnivorous foods while the lowest one was detected in Bumpnose trevally (*Carangoides hedlandensis*) - a fish, predator, reef-associated organism with the feeding types of carnivorous foods. In generally, the bivalve, filter feeder, omnivorous type of feeding resulted in the ^{210}Po activity higher than the fish, predator, carnivorous type of feeding. In term of trophic levels, the marine species with a low trophic level could accumulate a high concentration of ^{210}Po. Regarding the habitats, the highest average concentration of ^{210}Po was found in the species living in demersal zone, followed by the species living in reef-associated and pelagic-neritic zone. The reference dose calculation showed that the ACED from ^{210}Po due to the ingestion of seafood in the study area was rather high in comparison with that in some countries. The results of this study will provide a baseline of ^{210}Po in marine species to calculate the total ACED of local population as well as to provide one of the proofs for estimating the impact of titanium ore exploitation along the coast (in current and future). To assessment the impact of ore exploitation, the extra work should be further done. The result of this study just reported the distribution of ^{210}Po activity in common marine species for some of different environmental conditions, food types and trophic levels, so for well-understanding of the uptake pathway of ^{210}Po concentration, ingestion rate, assimilation efficiency, physiology, organism size, life cycle stage, and relation with local environment, climate, seasonal of marine species in this study area, the further study needs to be conducted.

Declaration of competing interest

No conflict of interest exists.

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