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RADIOACTIVITY OF ^{210}Po IN GREEN MUSSELS (*Perna viridis*) AT THE WEST COAST OF JOHORE STRAITS, MALAYSIA

(Radioaktiviti ^{210}Po dalam Kupang (*Perna viridis*) di Pantai Barat Selat Johor, Malaysia)

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Abstract

Johor Straits is one of the most polluted coastal areas in the southern part of Peninsular Malaysia and sampling of green mussels in various sizes and locations (e.g., cultured, wild and local market) was conducted to investigate its ability to accumulate ^{210}Po into their organs. Levels of ^{210}Po varied according to the organ and origin of the organisms, where the level of activity in the stomach and tissues ranged from 64.51 ± 3.47 Bq kg^{-1} dry weight to 520.26 ± 27.25 Bq kg^{-1} dry weight and 25.44 ± 1.25 Bq kg^{-1} dry weight to 154.28 ± 5.62 Bq kg^{-1} dry weight, respectively. Green mussels from the wild contained the highest mean activity of ^{210}Po as 406.35 ± 14.10 Bq kg^{-1} dry weight in the stomach and 79.33 ± 0.87 Bq kg^{-1} dry weight in tissue because of contaminations from the industrial and domestic effluent discharges directly into the sampling locations. The activity levels were also relatively higher than other marine organisms from different areas in Malaysia as well as worldwide values. Therefore, it is assumed that green mussels might be a radiation risk to seafood consumers from the Johor Straits, since the radiation dose of ^{210}Po exceeds permitted levels by the USEPA.

Keywords: radioactivity, green mussel, seafood, radiation, contamination

Abstrak

Selat Johor adalah kawasan pinggir pantai yang tercemar di bahagian Selatan Semenanjung Malaysia dan pensampelan kupang dalam pelbagai saiz dan lokasi (contoh seperti ternak, liar dan pasaran tempatan) dilakukan untuk memeriksa keupayaan akumulasi ^{210}Po ke dalam organnya. Aras ^{210}Po adalah berbeza bergantung kepada jenis organ dan lokasi asal organisma tersebut, julat aras aktiviti dalam perut dan tisu masing-masing dari 64.51 ± 3.47 Bq kg^{-1} berat kering hingga 520.26 ± 27.25 Bq kg^{-1} berat kering dan 25.44 ± 1.25 Bq kg^{-1} berat kering hingga 154.28 ± 5.62 Bq kg^{-1} berat kering. Kupang liar mengandungi aktiviti purata ^{210}Po tertinggi iaitu 406.35 ± 14.10 Bq kg^{-1} berat kering dalam perut dan 79.33 ± 0.87 Bq kg^{-1} berat kering dalam tisu kerana bahan buangan pencemaran daripada industri dan domestik dikeluarkan terus ke kawasan pensampelan kerang. Aras aktiviti umumnya adalah tinggi berbanding dengan organisma marin yang lain diperolehi dari kawasan berlainan di Malaysia begitu juga nilai aktiviti peringkat dunia. Oleh itu, boleh dianggap bahawa kupang mungkin menjadi risiko radiasi kepada pengguna makanan laut dari Selat Johor, kerana dos radiasi ^{210}Po melebihi tahap yang dibenarkan oleh USEPA.

Kata kunci: radioaktiviti, kupang, makanan laut, radiasi, pencemaran

Introduction

The safety of seafood consumption garners serious attention in tandem with increased global preference for seafood [1]. Apart from the problems caused by the use of antibiotics, radioactivity levels in seafood are also a concern of seafood consumers. This fear seems to have worsened after the Fukushima Daiichi nuclear disaster in Japan in 2011. However, the presence of radionuclides in the marine environment could be from cosmogenic and primordial sources as well as from anthropogenic activities. Marine organisms become contaminated when radioactive materials are absorbed from surrounding waters and are accumulated in their body; this can be transferred to humans via the food chain [2-6]. Several studies on ^{210}Po and other natural radionuclides in marine organisms in Malaysian coastal waters have been conducted by other researchers [7-10]. However, studies on ^{210}Pb in the west coast of Johor Straits in marine organisms are limited.

The Straits of Johor is located in the southern part of Peninsular Malaysia where the west and east part of the straits is separated by a causeway built in 1924. The water body has been blocked and water in the strait cannot flow freely between the southern South China Sea or the Straits of Malacca. Heavy pollution occurs in both the water column and sediment from massive toxic elements deposited from the surrounding inland regions (i.e., Johor, Malaysia and Singapore). Since the west coast of Johor Strait is famous for the production of green mussels, this study was conducted to investigate levels of the natural radionuclide ^{210}Po as a bio-indicator of environmental pollution.

The production of green mussel in the Straits of Johor is also famous because of the availability of spat fall. This study would clearly reveal the impacts of urbanization from both sides i.e., Malaysia and Singapore, and their contribution to the increased natural radioactivity levels in the coastal area. Furthermore, the existence of natural radionuclide contaminants in seafood might indicate its potential impact on human health through consumption. The relationship between ^{210}Po and marine organisms has been widely investigated because it is one of the most important sources of internal radiation for most organisms that emit alpha radiation [11-13]. Thus, this study investigates the activity of ^{210}Po levels in green mussels from the west coast of Johor Straits, Malaysia as an *in-situ* bio-indicator.

Materials and Methods

Sampling was conducted on 25th March 2014 and 1st June 2014 in the west coast of the Johor Straits, Malaysia, indicated as culture farm station (ST02, ST03, ST07, ST08, ST09), wild station (ST04, ST05, ST06) and market station (ST01) (Figure 1). Samples collected were from culture farms (n=35), wild caught (n=21) and market bought (n=7). Shell lengths and widths of the green mussels were also measured immediately after sampling. The radiochemical separation method was used to estimate ^{210}Po in the samples [6]. The green mussels were dissected with a knife to obtain the stomach and soft tissue, and these were oven dried at 60°C. About 0.5 g of dried sample was taken and a known activity of ^{209}Po (12.17 dpm/mL) was added as a yield tracer. The samples were then digested with 15 mL of nitric acid and peroxide acid. The solution was filtered and gently evaporated to 2 mL as near dryness.

The sample was dissolved in 0.5 M hydrochloric acid and 1.0 g of ascorbic acid to reduce Fe (III), and ^{210}Po was spontaneously deposited on brightly polished silver discs (2 cm diameter) for a period of 1 to 2 hours at a temperature of 70-90 °C. The discs were counted for ^{210}Po activities with Alpha Spectrometry along a silicon-surface barrier detector by Canberra immediately after deposition process. The recovery yield varied from 65% to 90%. Depositions of ^{210}Po were carried out within two months of sampling and the calculation of ^{210}Po activities involved the date of sampling. Then, to ensure the quality of the methodology, ^{210}Po was estimated with a certified reference material IAEA-134 (Cockle flesh).

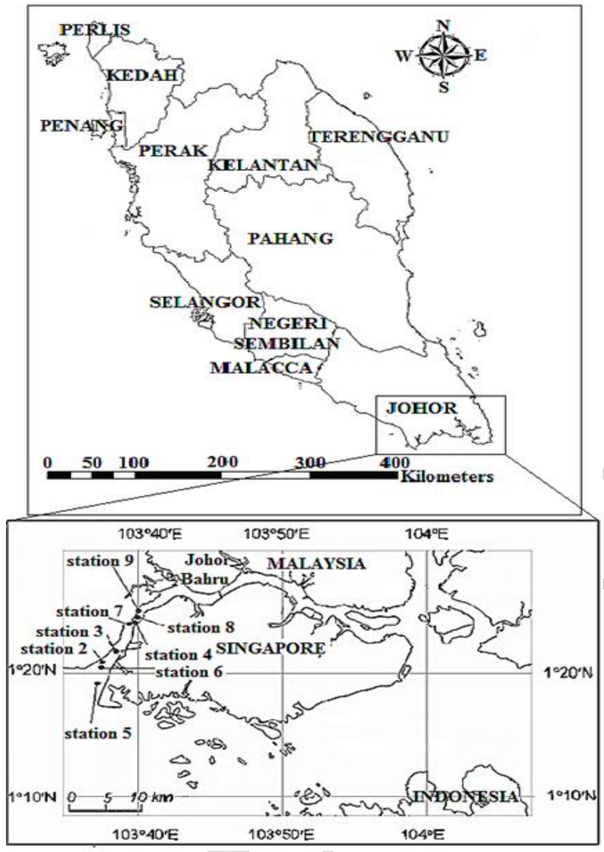

Figure 1. Sampling stations in the west coast of Johore Straits, Malaysia

Results and Discussion

^{210}Po activity concentrations in the green mussels

^{210}Po activity concentrations in green mussels of dry and wet samples varied between sampling locations (Table 1). A comparison of ^{210}Po activity concentrations between the stomach and tissue of the green mussels showed that the stomachs have a remarkably higher average activity concentration of ^{210}Po 168 ± 5.43 Bq/kg in dry weight, indicative of its nature as filter feeder organisms. The results shown in this study are also similar to a previous study done by Waska et al. [14]. Upon dissection of green mussels for radioactivity analysis, the stomach accounted for the highest activity. The statistical correlations between wet and dry weight of tissues found a positive correlation $y = 4.98x + 0.03$; $R^2 = 0.827$ (Figure 2, where y and x represent wet and dry weight in gram, respectively), and in general the body weight is inversely related to body fluid content as filter feeding processes [15, 16]. The contents of natural polonium in the body of green mussels are positively proportionate with feeding habit in the *in-situ* environment [17]. The content of natural polonium in mussels' tissue from the wild samples are higher than the cultured or local market samples because the sampling stations ST04, ST05 and ST06 are near/at the domestic discharge. However, the culture area is usually far from pollution sources and harvests for local market consumption with the sequence of contents of natural polonium in edible tissues are as follows: wild > culture > local market.

Table 1. ^{210}Po activity concentrations in the stomach and tissue of green mussel

Location	Station	Sample	Length (mm)	Wide (mm)	Stomach		Tissue		Po-210 in Dry Sample		Po-210 in Wet Sample	
					Wet (g)	Dry (g)	Wet (g)	Dry (g)	Stomach (Bq/kg)	Tissue (Bq/kg)	Stomach (Bq/kg)	Tissue (Bq/kg)
Local Market	ST 01 (n = 7)	1	96.20	39.65	2.41	0.45	8.88	1.47	64.51 ±3.47	43.49 ±1.94	12.08 ±0.65	7.21 ±0.32
		2	73.25	32.20	0.88	0.20	4.11	0.50	78.64 ±4.89	50.56 ±2.68	18.39 ±1.14	6.22 ±0.33
		3	71.20	36.10	1.41	0.28	4.94	0.87	78.22 ±4.50	39.73 ±2.02	15.56 ±0.89	7.05 ±0.36
		4	66.60	31.60	0.98	0.206	2.528	0.69	80.23 ±5.08	27.81 ±1.68	16.84 ±1.07	7.66 ±0.46
		5	80.45	35.90	1.63	0.27	5.41	0.78	69.72 ±3.98	42.86 ±2.19	11.71 ±0.67	6.21 ±0.32
		6	69.35	34.10	1.40	0.27	3.18	0.51	62.26 ±3.72	42.63 ±2.48	12.02 ±0.72	6.90 ±0.40
		7	95.65	38.15	2.14	0.39	5.99	1.10	70.00 ±3.70	46.72 ±2.00	12.81 ±0.68	8.64 ±0.37
Culture	ST 02 (n =7)	1	66.60	35.10	1.00	0.29	2.80	0.70	131.44 ±6.13	57.57 ±2.83	38.52 ±1.80	14.36 ±0.71
		2	69.20	34.15	0.84	0.25	3.33	0.80	154.61 ±7.45	63.00 ±2.68	47.73 ±2.30	15.15 ±0.64
		3	71.85	33.30	0.92	0.24	3.83	0.91	150.81 ±6.99	58.37 ±2.58	40.47 ±1.88	13.87 ±0.61
		4	75.90	35.60	1.57	0.41	4.53	1.14	110.56 ±4.94	46.59 ±2.09	29.25 ±1.31	11.82 ±0.53
		5	76.65	38.10	1.60	0.36	5.13	1.18	106.03 ±4.90	37.70 ±1.68	23.98 ±1.11	8.68 ±0.39
		6	76.10	34.40	1.11	0.27	4.29	1.04	128.97 ±6.33	60.53 ±2.64	31.54 ±1.55	14.71 ±0.64
		7	70.40	31.10	0.94	0.24	3.22	0.759	152.52 ±7.18	55.22 ±2.62	39.35 ±1.85	13.00 ±0.62
	ST 03 (n = 7)	1	70.25	29.25	1.03	0.28	4.17	1.07	124.96 ±5.52	45.95 ±1.92	34.68 ±1.53	11.83 ±0.49
		2	70.60	27.20	0.84	0.23	5.12	1.26	142.16 ±6.44	51.74 ±2.05	38.75 ±1.76	12.82 ±0.51
		3	64.20	29.45	0.82	0.23	3.32	0.84	117.19 ±5.74	45.22 ±2.05	33.11 ±1.62	11.53 ±0.52
		4	67.10	29.90	0.73	0.21	3.27	0.89	156.10 ±6.90	51.31 ±2.15	46.56 ±2.06	14.07 ±0.59
		5	66.40	31.30	0.95	0.27	3.62	0.94	125.05 ±5.86	50.39 ±2.12	36.00 ±1.69	13.11 ±0.55
		6	64.20	31.40	0.92	0.27	3.32	0.90	120.60 ±5.41	59.84 ±2.54	35.87 ±1.61	16.27 ±0.69
		7	67.40	30.00	0.97	0.26	3.27	0.82	124.29 ±5.76	46.01 ±2.20	34.33 ±1.59	11.54 ±0.55

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Table 1 (cont'd). ^{210}Po activity concentrations in the stomach and tissue of green mussel

Location	**Station**	**Sample**	**Length (mm)**	**Wide (mm)**	**Stomach**		**Tissue**		**Po-210 in Dry Sample**		**Po-210 in Wet Sample**	
					Wet (g)	**Dry (g)**	**Wet (g)**	**Dry (g)**	**Stomach (Bq/kg)**	**Tissue (Bq/kg)**	**Stomach (Bq/kg)**	**Tissue (Bq/kg)**
		1	61.4	30.30	1.34	0.23	2.23	0.48	176.27 ±7.78	50.52 ±2.65	30.38 ±1.34	11.01 ±0.58
		2	63.00	28.50	0.63	0.15	2.19	0.50	251.79 ±10.98	54.88 ±2.89	62.46 ±2.72	12.60 ±0.66
		3	72.00	32.40	1.66	0.25	2.64	0.62	139.32± 6.67	46.02 ±2.44	21.73 ±1.04	10.98 ±0.58
	ST 04 (n = 7)	4	69.60	30.50	0.73	0.19	3.54	0.80	178.49 ±8.72	32.38 ±1.63	45.93 ±2.24	7.39 ±0.37
		5	69.60	31.30	1.20	0.25	2.67	0.60	156.99 ±7.19	41.94 ±2.28	33.94 ±1.55	9.44 ±0.51
		6	60.30	31.40	0.71	0.17	1.40	0.35	266.83 ±11.76	67.11 ±3.71	64.84 ±2.86	16.96 ±0.94
		7	60.50	35.90	0.53	0.128	2.11	0.46	333.41 ±14.94	29.88 ± 1.83	80.48 ±3.61	6.54 ±0.40
		1	40.30	26.30	0.15	0.04	1.21	0.24	520.36 ±27.25	102.41 ±5.21	157.59 ±8.25	20.90 ±1.06
		2	58.20	31.60	0.45	0.12	2.35	0.50	413.32 ±16.72	123.46 ±4.60	112.78 ±4.56	26.77 ±1.00
		3	60.50	32.70	0.41	0.11	2.77	0.62	492.71 ±19.97	154.28 ±5.62	138.52 ±5.61	34.70 ±1.26
Wild	ST 05 (n = 7)	4	48.00	21.60	0.16	0.04	0.91	0.19	480.79 ±25.34	139.79 ±6.93	129.82 ±6.84	29.17 ±1.45
		5	49.65	24.10	0.21	0.06	1.48	0.35	384.17 ±18.96	72.99 ±3.64	118.79 ±5.86	17.30 ±0.86
		6	47.60	25.00	0.21	0.07	1.12	0.22	372.07 ±18.05	143.28 ±6.84	122.03 ±5.92	28.80 ±1.37
		7	53.30	32.10	0.31	0.06	1.05	0.21	457.32 ±22.89	143.53 ±6.64	93.16 ±4.66	29.23 ±1.35
		1	60.00	30.50	1.20	0.24	3.11	0.54	199.11 ±9.33	70.51 ±3.5	40.48 1±.90	12.33 ±0.61
		2	61.60	29.40	1.05	0.21	3.34	0.58	172.29 ±8.32	55.46 ±2.93	34.38 ±1.66	9.66 ±0.51
		3	60.30	29.10	1.06	0.22	2.80	0.53	224.13 ±10.38	70.89 ±3.45	46.99 ±2.18	13.47 ±0.65
	ST 06 (n = 7)	4	66.10	30.70	1.21	0.25	3.96	0.72	188.89 ±8.95	56.95 ±2.85	39.93 ±1.89	10.43 ±0.52
		5	66.30	29.40	1.11	0.23	3.90	0.70	196.22 ±9.13	65.95 ±3.10	42.11 ±1.96	11.98 ±0.56
		6	64.20	27.40	0.86	0.17	2.68	0.47	269.57 ±13.04	79.22 ±4.03	53.98 ±2.61	13.95 ±0.71
		7	63.8	29.10	0.83	0.16	3.52	0.62	252.12 ±12.79	64.52 ±3.08	49.89 ±2.53	11.42 ±0.55

Table 1 (cont'd). ^{210}Po activity concentrations in the stomach and tissue of green mussel

Location	Station	Sample	Length (mm)	Wide (mm)	Stomach		Tissue		Po-210 in Dry Sample		Po-210 in Wet Sample	
					Wet (g)	Dry (g)	Wet (g)	Dry (g)	Stomach (Bq/kg)	Tissue (Bq/kg)	Stomach (Bq/kg)	Tissue (Bq/kg)
	ST 07	1	78.30	32.2	2.05	0.44	6.50	1.09	101.35 ±4.78	38.15 ±1.78	22.24 ±1.05	5.03 ±0.30
		2	78.30	32.45	1.66	0.36	8.38	1.61	88.19 ±4.32	42.02 ±1.79	19.37 ±0.95	7.95 ±0.41
		3	82.80	38.30	1.80	0.36	7.61	1.37	114.51 ±5.39	30.67 ±1.41	23.01 ±1.08	6.43 ±0.36
		4	73.00	32.40	1.88	0.42	8.08	1.49	84.14 ±4.17	25.44 ±1.25	18.79 ±0.93	6.10 ±0.35
		5	81.20	34.40	1.78	0.37	6.71	1.16	130.84 ±6.03	35.24 ±1.64	27.60 ±1.27	6.87 ±0.38
		6	75.00	35.50	1.69	0.38	6.65	1.28	106.18 ±5.09	34.76 ±1.63	24.26 ±1.16	5.54 ±0.30
		7	73.00	30.00	1.69	0.36	7.43	1.21	98.44 ±4.67	25.50 ±1.25	21.15 ±1.00	8.40 ±0.43
Culture	ST 08	1	59.10	26.40	1.14	0.27	3.54	0.65	92.78 ±4.92	27.10 ±1.64	22.13 ±1.17	5.03 ±0.30
		2	62.10	26.10	1.48	0.32	3.72	0.64	86.33 ±4.42	45.73 ±2.35	18.98 ±0.97	7.95 ±0.41
		3	58.30	28.10	0.83	0.18	3.32	0.59	156.13 ±8.11	36.05 ±2.00	34.82 ±1.81	6.43 ±0.36
		4	59.90	26.60	1.16	0.22	3.33	0.56	106.06 ±5.74	36.23 ±2.08	20.55 ±1.11	6.10 ±0.35
		5	56.10	25.00	1.08	0.23	3.22	0.50	97.35 ±5.35	43.47 ±2.41	20.60 ±1.13	6.87 ±0.38
		6	57.10	25.00	1.04	0.23	3.89	0.70	80.35 ±4.75	30.65 ±1.66	18.13 ±1.07	5.54 ±0.30
		7	60.50	30.50	1.35	0.28	3.04	0.72	69.99 ±4.10	35.07 ±1.79	14.57 ±0.85	8.40 ±0.43
	ST 09	1	62.20	27.10	1.25	0.29	3.37	0.97	81.07 ±4.28	36.17 ±1.63	19.13 ±1.01	10.49 ±0.47
		2	69.10	34.00	1.53	0.33	5.15	1.30	90.36 ±4.27	25.73 ±1.23	19.97 ±0.94	6.49 ±0.31
		3	70.90	31.40	1.38	0.29	5.59	1.06	102.83 ±4.82	38.79 ±1.66	22.18 ±1.04	7.37 ±0.32
		4	72.20	34.10	1.31	0.29	5.85	1.07	115.13 ±5.46	30.64 ±1.40	25.57 ±1.21	5.62 ±0.26
		5	69.40	30.00	1.33	0.31	4.51	0.80	93.62 ±4.59	32.90 ±1.68	21.78 ±1.07	5.87 ±0.30
		6	68.10	30.50	1.31	0.31	5.03	1.01	108.21 ±5.07	31.78 ±1.53	26.10 ±1.22	6.38 ±0.31
		7	65.50	34.40	1.20	0.26	4.28	0.78	105.32 ±5.18	36.91 ±1.74	23.50 ±1.16	6.73 ±0.32
Average activity of ^{210}Po at wild area (ST 04, ST 05 & ST 06)									291.72 ±13.77	79.33 ±3.80	72.39 ±3.42	16.43 ±0.79
Average activity of ^{210}Po at culture area (ST 02, ST 03, ST 07, ST 08 & ST 09)									112.98 ±5.64	41.38 ±1.93	27.84 ±1.34	9.27 ±0.44
Average activity of ^{210}Po at local market area (ST 01)									71.94 ±4.19	41.97 ±2.14	14.20 ±0.83	7.13 ±0.37

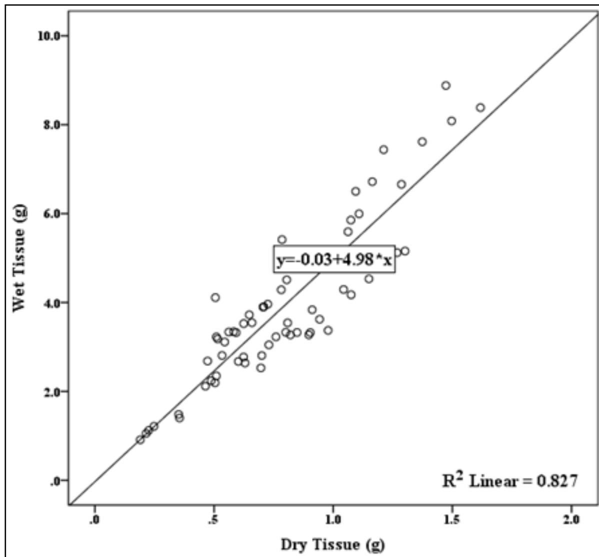

Figure 2. Correlation between wet and dry weight (g) of tissue of green mussels.

The distribution of natural radionuclide e.g., ^{210}Po will accumulate in the stomach and edible tissue body of green mussels. According to the International Commission on Radiological Protection (ICRP), ingested food will first accumulate into the stomach followed by the small intestine (SI) and 50% of the total activity concentration in the SI will be transferred with nutrition into the blood and will be distributed to other tissue parts [18]. The greater amount of radioactive materials remaining in the stomach with the greater chances of absorption of radionuclides occurred into the stomach. Thus, green mussel stomachs play the main role in absorption and digestion of this contaminant [19, 20]. Therefore, if the mussels' stomachs possess more than 36% of natural polonium before absorption in other organs, then the consumption of green mussel stomachs should not be recommended (Table 1).

^{210}Po activity concentrations vary in green mussels regardless of the origin of the samples obtained (Table 1). Although Carvalho and Fowler [21] showed that most dissolved ^{210}Po in water is absorbed by the outer surface of the organism instead of incorporation in internal tissues, this study found higher ^{210}Po concentration activity in the stomach which might be because of the filter feeding habits of green mussels.

Green mussels' diet

Radionuclide concentrations of ^{210}Po are consistently found in green mussels, though the strength of that concentration varies with sample stations (Table 1). Generally, green mussels obtained from wild locations showed higher mean ^{210}Po levels in the stomach (291.72 ± 13.77 Bq/kg) and tissue (79.33 ±3.80 Bq/kg) compared to samples taken from mussel culture sites and the local market, where the wild green mussels sampled were smaller than both cultured and local market samples. Moreover, the wild mussels were attached to the sub-strata such as on rock and pillars, and because of its attachment in a higher position than the low tide, it stops feeding due to limited water flow. But the cultured mussels maintained the status of physico-chemical parameters and timely food supply for effective muscle growth. Variations in size have also influenced activity concentrations of ^{210}Po in green mussels. If bioaccumulation and bioconcentration of contaminants occur in one individual, then the level of contaminants will eventually increase as the individual grows. However, this study found that the accumulation of radionuclides is size-dependent and similar results were reported by Theng et al [7], where juvenile green mussels tend to have more frequent feeding rates in order to recoup growth and a faster metabolism rate compared to adult green mussels. This is indicated in the higher accumulation levels of ^{210}Po in wild samples.

Therefore, precautions should be taken in the consumption of green mussels from the Straits of Johor due to the slightly higher risks of radiation as the levels found in the study are higher than the permitted levels recommended by the USEPA; an estimated effective radiation dose of ^{210}Po between 2.61 to 11.54 mSv/year. However, radionuclide content in terms of food safety has not been thoroughly studied. This study determined a negative statistical correlation between the concentration of natural polonium and shell length of green mussels, $y = -7.59x + 6.76E^2$; $R^2 = 0.424$ (Figure 3A); ^{210}Po activity concentrations (Bq/kg) in dry tissue vs. green mussels length (mm) as $y = -1.57x + 1.59E^2$; $R^2 = 0.269$ (Figure 3B); ^{210}Po activity concentrations (Bq/kg) in wet stomach vs. green mussels length (mm) as $y = -2.22x + 1.9E^2$; $R^2 = 0.433$ (Figure 3C); and ^{210}Po activity concentrations (Bq/kg) in wet tissue vs. green mussels length (mm) as $y = -0.34x + 34.24$; $R^2 = 0.265$ (Figure 3D) [where y and x represents ^{210}Po activity (Bg/kg) and length of shell mussels (mm), respectively]. It has been shown that ^{210}Po activity concentrations decrease with an increase in shell length. Hence the findings suggest that seafood consumers should select large shells for consumption rather than small shells so as to be less exposed to ^{210}Po radiation.

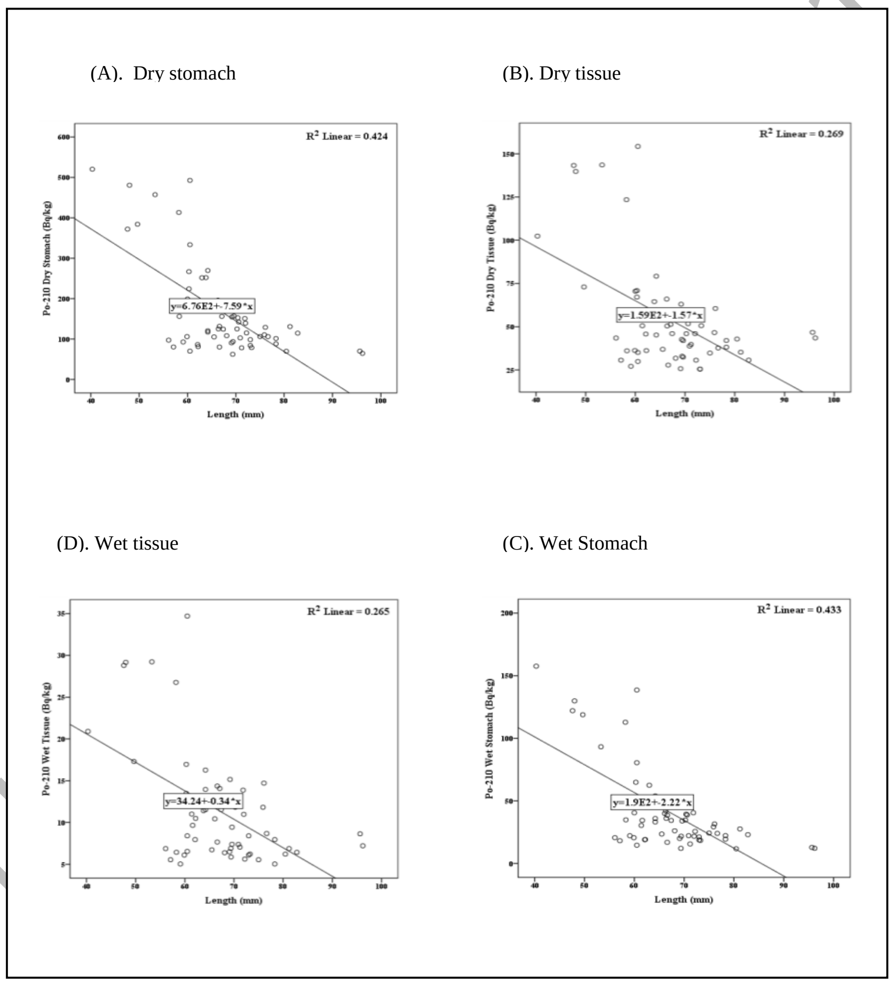

Figure 3. Correlation between mussel length (mm) and ^{210}Po activity concentrations (Bq/kg) in various organs obtained during this study

Risk assessment on the ^{210}Po contaminant

The samples collected have been classified into several classes and the activities of both ^{210}Po are shown in Table 2. Samples of wild origin have the highest activity distribution of ^{210}Po (mean: 310.48 ± 8.49 Bq kg^{-1} dry weight). The results have shown a remarkable decreasing trend in radioactivity as size increases. However, an inconsistent trend

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was noticed for the cultured samples. Furthermore it has been proven that radionuclide activity decreases as soft body tissue increases [22].

Table 2. Average activities of ^{210}Po in samples collected from different origin

Origin	**Range Size (mm)**	**^{210}Po Activity (Bq kg^{-1} dry weight)**
Market	Class 1 (60-80 mm)	109.77 ± 3.38 (n = 4)
	Class 2 (>80.1 mm)	107.35 ± 2.88 (n = 3)
	Mean	108.56 ± 3.13
Culture	Class 1 (50-60 mm)	124.76 ± 3.87 (n = 5)
	Class 2 (60.1-65 mm)	122.00 ± 3.43 (n = 5)
	Class 3 (65.1-71 mm)	150.26 ± 3.91 (n = 13)
	Class 4 (71.1-80mm)	138.73 ± 3.49 (n = 10)
	Class 5 (>81 mm)	144.71 ± 3.62 (n = 2)
	Mean	136.09 ± 3.66
Wild	Class 1 (40-50 mm)	466.25 ± 14.03 (n = 4)
	Class 2 (50-60 mm)	406.04 ± 10.61 (n = 3)
	Class 3 (60.1-65 mm)	307.22 ± 7.79 (n = 9)
	Class 4 (65-70 mm)	211.49 ± 5.48 (n = 4)
	Class 5 (>70 mm)	161.42 ± 4.55 (n = 1)
	Mean	310.48 ± 8.49

The daily intake of ^{210}Po in green mussels based on green mussel consumption and ^{210}Po accumulation in the human body are calculated with the equation (1):

$$\text{Daily intake (mBq day}^{-1}\text{ person}^{-1}) = \text{AC x AP x 0.4 / (MP x 365)} \qquad (1)$$

where AC is the average concentration (Bq kg^{-1} dry weight); AP is green mussel production (2384.97 metric tonnes) reported by the Department of Fisheries Malaysia [23], whereas 0.4 represents the edible portion of green mussels; MP is the Malaysia population (29.3 million) at the time the survey was conducted by Department of Statistics, Malaysia [24]; and 365 specifies the days in a year As seen in the calculations shown below (Table 3), the daily intake of ^{210}Po ranges from 9.70 – 29.12 m Bq day^{-1} person^{-1} regardless of the origin of the green mussels consumed.

Table 3. Estimation of daily intake, CED and cancer risk

Nuclide	**Origin**	**Daily intake (mBq day^{-1} person^{-1})**	**CED (mSv year^{-1})**	**Cancer Risk**	
				Lifetime Mortality Risk	**Lifetime Morbidity Risk**
^{210}Po	Market	9.70	2.61	1.17 x 10^{-5}	1.61 x 10^{-5}
	Culture	12.40	3.34	1.50 x 10^{-5}	2.06 x 10^{-5}
	Wild	29.12	7.83	3.52 x 10^{-5}	4.83 x 10^{-5}

The committed effective dose (CED) of ^{210}Po in green mussels can be calculated by the following equation (2):

$$\text{CED (mSv year}^{-1}) = \text{A x B x C} \qquad (2)$$

A is the igestion dose conversion factor (^{210}Po: 1.2 x 10^{-3} mSv Bq^{-1}; [25]); B is green mussel consumption per year (20.1 kg year^{-1}) as provided by Statisitics of Agro Food [26]; and C is the average concentration (Bq kg^{-1} dry weight). The annual effective dose via the ingestion of green mussels is shown to be very high for ^{210}Po (2.61 – 7.83 m Sv year^{-1}), and exceeds the safe limit recommended by ICRP (1 mSv year^{-1} ^{210}Po; [27]).

The cancer risk related with lifetime mortality risk and lifetime morbidity risk can be calculated with the provided equation (3):

$$R = r \times I \qquad (3)$$

r is the cancer risk coefficient where ^{210}Po is 4.44 x 10^{-8} risk Bq^{-1} and 6.09 x 10^{-8} risk Bq^{-1} for the lifetime mortality risk and lifetime morbidity risk respectively [28]; and I is the average lifetime intake of ^{210}Po. It can be derived from the multiplication of daily intake with time (365); and Malaysian average life expectancy at birth (74.55) by Department of Statistics, Malaysia [24]. The highest average mortality and morbidity risk taken for ^{210}Po are 3.52 x 10^{-5} and 4.83 x 10^{-5} per individual, respectively. In the opinion of US-EPA, risk values below 1 x 10^{-6} are insignificant. Attention should be given to risk calculations ranging between 1 x 10^{-6} – 1 x 10^{-4} as the risk calculation approaches baseline limits and a plan to remedy the situation needs to be framed [29].

In view of the assessments of risk discussed above, wild green mussels may result in some degree of health problems. This study has shown that smaller-sized green mussels are more likely to exceed suggested safety limits. In addition, most green mussels in the local markets are from both wild and cultured sources. Hence, oversight to sensure a minimum the marketable size of green mussels would minimise radioactivity exposure to the human body.

Conclusion

^{210}Po activity concentrations vary in green mussel body parts (e.g., stomach and tissues) and also vary between the organism's source (e.g. wild, cultured or market). Samples from the wild showed the highest concentrations of natural polonium activity because it received direct contaminants from industrial and domestic discharges. Moreover, ^{210}Po levels in wild organisms in the Johor Strait were relatively higher than other marine organisms in different areas of Malaysia as well as higher compared to worldwide values. Therefore, it is presumed that consumers of green mussels from the Straits of Johor probably have radiation risks exceeding those recommended by the USEPA. Despite the fact that mortality and morbidity risk were in acceptable range and no serious health problem will be caused, frequent consumption of green mussels is not recommended. Further analysis of pollutants (e.g., ^{210}Po) in green mussels at the Johor Strait needs to continue especially with regards to human consumption of those mussels.

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