

GAMMA HAZARDS AND RISK ASSOCIATED WITH NORM IN SEDIMENT FROM AMANG PROCESSING RECYCLING PONDS

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Abstract

Amang processing is an important down stream activity of tin mining noted for technologically enhancing naturally occurring radioactive materials. A study was carried out to determine the gamma radiation hazards associated with amang processing with special reference to the sediment accumulated in amang processing ponds. Twenty eight sediment samples from two amang processing plants employing the recycling close water management system were collected and analysed. The activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K in sediments were measured using gamma spectrometry analysis, with a Hyper Pure Ge-Li detector coupled to a Multi Channel Analyzer detector system. The range of mean activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K were between 40.94 – 189.58 Bq kg⁻¹, 104.90 – 516.17 Bq kg⁻¹ and 74.8-848.0 Bq/kg respectively. The maximum activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K recorded were higher than Malaysia's average and the world's natural highest. Gamma Radiation Representative Level Index, I_r, associated with these levels of activity concentrations of radionuclides in sediments, warrants an immediate attention from the regulatory authorities. The contribution of amang processing and the use of recycling close water management system in enhancing potential environmental radiological risk are discussed.

Abstrak

Pemprosesan amang merupakan satu aktiviti hiliran yang penting terutama bagi peningkatan secara teknologi bahan radioaktif semulajadi. Satu kajian telah dilakukan untuk menentukan bahaya sinaran gamma berkaitan dengan pemprosesan amang dengan merujuk kepada sedimen yang terkumpul di dalam kolam-kolam pemprosesan amang. Sebanyak dua puluh lapan sampel sedimen dari dua loji pemprosesan amang yang menggunakan sistem pengurusan air tertutup telah diambil dan dianalisis. Kepekatan keaktifan ²²⁶Ra, ²³²Th dan ⁴⁰K dalam sedimen telah diukur menggunakan spektrometer gamma dengan pengesan Ge-Li hiper-tulen berganding dengan satu sistem Multi Channel Analyzer. Julat min kepekatan keaktifan bagi masing-masing ²²⁶Ra, ²³²Th dan ⁴⁰K ialah di antara 40.94 – 189.58 Bq kg⁻¹, 104.90 – 516.17 Bq kg⁻¹ dan 74.8-848.0 Bq/kg. Nilai kepekatan keaktifan maksimum yang dicatat bagi ²²⁶Ra, ²³²Th dan ⁴⁰K ini adalah lebih tinggi daripada aras purata bagi Malaysia dan bagi aras tertinggi semulajadi dunia. Indeks aras wakil sinaran gamma, I_r, berkaitan dengan aras kepekatan keaktifan radionuklida dalam sedimen yang dikaji ini menunjukkan perlunya tindakan segera pihak berkuasa. Sumbangan pemprosesan amang dan penggunaan sistem pengurusan air kitar tertutup terhadap peningkatan potensi risiko radiology dibincangkan dalam kertas ini.

Introduction

Malaysia is one of the major world's tin producing countries. Besides tin, tin mining also produces amang or tin tailing, a by product of rough concentrate of cassiterite. Amang, from tin mining industry is processed to extract valuable minerals such as ilmenite [FeO, TiO₂], zircon [ZrSiO₄], monazite [{Ce,La,Y,Th}PO₄], xenotime [YPO₄], columbit [{Fe,Mn} {NbTa}₂O₆] and struverite [Ta,Nb bearing TiO₂] that are most demanding in other manufacturing industries [1, 2, 3]. These valuable minerals contain naturally occurring radionuclides that include ⁴⁰K, ²³⁸U, ²²⁶Ra and ²³²Th. Among these, ²²⁶Ra has been the reference radionuclide in assessing radiological risk.

Rivers passing through tin mining and amang processing areas would carry in their load naturally occurring radionuclides plus the host of other toxic compounds such as inorganic arsenic species, and heavy metals [4]. The contamination of water and sediments with radionuclides has given rise to radiological concern among the regulatory authorities and members of the public especially when it is also realized that amang processing is enhancing the NORM into what is widely termed as TENORM or Technologically Enhanced Naturally Occurring Radioactive Materials. Such concern is elevated when most amang processing plants employs the recycling close water management system. In such system, water used in the physical separation of valuable minerals from amang is recycled. Either a man-made or natural pond is used to maintain the recycle water as well as becoming the “tank” to collect effluent sediments from the plants. Over the years, new questions have arisen as to the fate of these collected sediments. There is a growing concern that these sediments and sands are used in brick making.

Two major questions may be raised from the above-mentioned development. The first relates to the types of radiation hazards and the second the potential radiological risk.

This paper identifies all possible types of radiation hazards as well as determines the potential radiological risk of the accumulated sediments in amang processing ponds and discusses how it will impact the environment. This study is of importance to Malaysia because the information gathered will be very useful not only in determining environmental impact but also potential radiological impact of amang processing activities, especially those plants that employs close recycling water management system. The information gathered will also be useful in future consideration for land use development.

Materials and methods

Sampling

Two amang processing plants, one each from the states of Selangor and Perak, Malaysia were chosen for this study. Both plants employ the recycle close water natural management system, i.e. the water is first drawn from a river and subsequently pumped into a natural pond. Water from this pond is used in amang processing and is recycled back into the same pond. In addition both plants have been in operation for the past two decades. The difference between these two plants is that plant No. 1 (located in the state of Selangor) is associated with one large tin mining pond, while plant No. 2 (located in the state of Perak) is located near a large river.

Only undisturbed sediment samples were collected and analyzed in this study. Based on the size of the pond, a total of 4 sampling locations were selected for plant number 1, and 3 sampling stations were chosen for plant number 2. These sediment samples were collected in special PVC container (120 mm length and 63 mm diameter). An undisturbed sediment sampler model Ejkelkamp with PVC transparent tubes (60, 100, 150 cm length and 63 mm diameter) was employed to sample the sediment. These samples were subsequently labeled S1-S4, representing sampling locations 1 to 4. Sample from each sampling location was divided into 10 cm portions, and labeled L1-L4. L1 indicates the top 10 cm portion of the undisturbed sample (i.e. nearest to surface) while L4 represents the bottom portion of the sediment sample. Such sampling and partitioning of undisturbed sediment sample was design to facilitate studies to be made on the time-concentration profile of the deposited sediment in areas where sediment mixing due to water turbulence is not expected or is at a minimum.

Treatment of samples

Collected sediment samples were removed of pebbles, dried in oven at 105°C for 24 hours to constant mass, and then sieved through mesh 500µm. All sediment samples were weighed and sealed in Marinelli container. The capped and sealed sediment samples were kept for at least four weeks before counting in order to allow the in-growth of uranium and thorium decay products and achievement of secular equilibrium for ^{238}U and ^{232}Th with their respective progenies.

Gamma spectroscopy

High-resolution gamma spectrometric system with a relative efficiency of 15 % and a resolution of 2.0 KeV at the 1.33 MeV was employed for the measurement of the ^{232}Th , ^{226}Ra and ^{40}K activity in the sediment samples. This system was used for measuring energy spectrum of the emitted gamma rays in the energy range between 50 KeV and 3000 KeV. The gamma spectroscopy system consists of a hyper pure

germanium-Lithium (HPGe-Li) detector from Oxford Company, connected to a multi channel analyzer through the amplifier Canberra model 2020. A multi isotopic elements (^{22}Na , ^{137}Cs , and ^{60}Co) standard was used to calibrate the gamma spectrometric system. Soil IAEA -375 was used as standard reference material. Each and every sample was calculated for 12 hours. Activity concentrations of ^{226}Ra , ^{40}K and ^{232}Th , were calculated using the established relative counting method at energy peaks of 186.1 keV, 1460.8 keV and 2614.4 keV respectively.

Gamma radiation representative level Index, I_{gr}

An estimate of the gamma radiation hazard levels associated with natural radionuclides in sediment sampled was calculated based on radiation hazard index I_{gr} [21] (Equation 1)

$$I_{gr} = \left(\frac{C_{Ra}}{150} + \frac{C_{Th}}{100} + \frac{C_K}{1500} \right) \quad (1)$$

Where C_{Ra} , C_{Th} and C_K are the specific activities of ^{226}Ra , ^{232}Th and ^{40}K (Bqkg^{-1}) respectively.

Results and discussions

Th-232 and U-238 in sediment samples

The mass and activity concentrations of ^{232}Th and ^{238}U in sediment samples from among plants number 1 and 2 are presented in Tables 1 and 2. Again S1-S4 indicates sampling stations 1 - 4 and L1-L4 indicates depth from where the sediment samples were collected. The number 1 or 2 in front of the letter S denotes the plant number. As such 1S1L2 denotes sample taken from plant no. 1, at sampling station 1 and level 2 from the top of the undisturbed sediment sample.

At plant no. 1 the mass concentrations of ^{232}Th ranged from 26.00 - 157.73 mg kg^{-1} corresponding to activity concentrations of 105.10 - 637.61 Bq kg^{-1} . The mass concentrations ^{238}U were in the range of 7.44 - 69.75 mg kg^{-1} , corresponding to activity concentrations of 91.79 - 472.27 Bq kg^{-1} . Detail readings are shown in Table 1.

Table 2 shows data on ^{232}Th and ^{238}U collected at plant no. 2. Mass concentrations of ^{232}Th ranged from 11.92 up to 150.80 mg kg^{-1} (equivalent to 48.10 - 609.60 Bq kg^{-1}) while ^{238}U were between 4.96 and 27.59 mg kg^{-1} (equivalent to 61.20 and 150.80 Bq kg^{-1} respectively) (Table 2).

A Kruskal-Wallis One Way Analysis of Variance on Ranks comparison of ^{232}Th activity concentrations among the different locations at both plants showed the differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability, i.e. there is not a statistically significant difference ($P = 0.160$ at plant no. 1 and $P = 0.269$ at plant no. 2) among pooled samples from all locations. However, the maximum mean activity concentration of ^{232}Th was measured at stations located at the point of discharge from each plant. Such readings were expected especially because this is the location outside the amang plant where effluent discharge first settles.

Similar statistical analysis carried out on ^{238}U at plant no. 1 showed similar result to ^{232}Th at $p = 0.160$. However, a Kruskal-Wallis One Way Analysis of Variance on Ranks for ^{238}U at plant no. 2 showed statistically significant difference in samples from different locations ($p = 0.045$). A Pairwise Multiple comparison Procedures (Dunn's Method) showed significant higher ($p < 0.05$) ^{238}U median activity concentrations in sediment collected at the point of discharge (133.87 Bq kg^{-1}) than at location 2.

Mass and activity concentrations of ^{238}U and ^{232}Th in amang water (in the same lakes and same locations with this study) were reported by Mohsen et al. [10]. Results from their study showed that the mean mass and activity concentrations of ^{238}U were higher than mass and activity concentrations of ^{232}Th in whole water samples. But results from this study showed that, the mean mass and activity concentrations of ^{232}Th in all sediment samples were higher than the mass and activity concentrations of ^{238}U in sediment samples. Ismail et al. [12,18] reported similar results.

Mohsen et al. [10] reported that activity concentrations of ^{232}Th in amang water (in the same ponds and similar locations with this study) ranged between 0.03–6.90 Bq/l. The mean concentration of ^{232}Th in water samples was 0.37 ± 0.06 ppm. Comparisons of results showed that the concentrations of this radionuclide in sediment samples were higher than in water samples. Higher concentrations of ^{232}Th in sediment samples observed in this study, relative to water, supported earlier studies [11, 12]. Higher concentrations of radionuclides in sediment are attributed to the insolubility of minerals bearing radionuclide in this water. Such minerals include monazite, zircon and ilmenite.

Table 1 Mass and Activity Concentrations of ^{238}U and ^{232}Th in sediment samples in amang plant no. 1 as measured using Hyper Pure GeLi - MCA detector system

No	Station Code	Mass concentration		Activity Concentration	
		^{238}U	^{232}Th	^{238}U	^{232}Th
1	1S1L1	11.78	64.13	145.34	259.24
2	1S1L2	7.91	26.00	97.53	105.10
3	1S1L3	8.84	39.87	109.00	161.17
4	1S1L4	8.68	36.40	107.10	147.14
5	1S2L1	34.00	157.73	472.27	637.61
6	1S2L2	29.54	105.73	364.46	427.41
7	1S2L3	30.85	119.60	380.56	483.48
8	1S3L1	69.75	26.00	860.57	105.10
9	1S3L2	7.44	29.47	91.79	119.13
10	1S3L3	16.28	84.93	200.8	343.32
11	1S3L4	6.82	32.93	84.14	133.12
12	1S4L1	8.06	46.80	99.44	189.19
13	1S4L2	10.23	74.53	126.22	301.28
14	1S4L3	7.75	46.80	95.62	189.19
15	1S4L4	7.75	39.87	95.62	161.17
16	Soil.375	1.86	5.20	22.95	21.02

Table 2 Concentrations of ^{238}U and ^{232}Th in sediment samples in amang plant no. 2 as measured using Hyper Pure GeLi - MCA detector system

No	Stations Code	Mass Concentrations		Activity Concentrations	
		^{238}U	^{232}Th	^{238}U	^{232}Th
1	2S1L1	27.59	150.80	340.40	609.60
2	2S1L2	10.85	46.83	133.87	189.19
3	2S1L3	10.08	32.94	124.37	133.00
4	2S2L1	8.84	53.71	109.01	217.08
5	2S2L2	4.96	19.10	61.20	77.21
6	2S2L3	5.58	19.16	68.85	77.21
7	2S2L4	4.96	11.92	61.20	48.10
8	2S3L1	12.71	50.33	156.81	203.33
9	2S3L2	7.13	22.57	87.97	90.95

10	2S3L3	6.82	22.51	84.14	90.95
11	2S3L4	6.36	15.60	71.00	63.06
12	Soil 375	1.86	5.20	22.95	21.02

Ismail et al. [11, 12], Redzuwan et al.[13] carried out similar studies in Perak and Selangor, Malaysia respectively. Ismail et al. reported mass concentrations of ^{232}Th ranging from 27.72-120.88 mg/kg. Redzuwan reported activity concentrations of ^{232}Th ranging from 12.90-301.59 Bq/kg. Our findings were in agreement with those of Ismail et al. and Redzuwan et al. The determination of uranium and thorium is important because ^{238}U , ^{235}U and ^{232}Th are the first elements of the natural radioactive series [14].

Ibeanu [15] showed that the measured concentration levels of uranium and thorium in tin tailing samples and the measured dose rates in Nigeria were found to be elevated with values up to approximately 100 times above background levels of control soils. Table 5 shows a comparison of radioactivity in soil and sediment observed in this study relative to other areas of the world. Data no(s). 14 and 15 belong to this study. The Kuwait national wide average concentration of ^{232}Th in soil was 10.0 ± 3.4 Bq/kg [20]. Concentrations of radionuclides in among sediment were higher than those of Kuwait national wide average [20].

According to Bikit [16], the concentration of thorium in earth's crust is between 1.1-10 ppm. This corresponds to maximum activity concentration of 39.4 Bq/kg. This study shows that the concentrations of this radionuclide in sediment samples from among plants were much higher.

According to Firyal [20] the world average concentration for ^{232}Th is 40 Bq/kg. According to UNSCEAR [17] the world average of ^{232}Th activity is 25 Bq/kg and the $^{232}\text{Th}/^{238}\text{U}$ quotient is 1.0. Present study of among sediments (plant 1 and 2) showed activity concentrations of between more than 10– 16 times higher than those reported of the world's average.

As an overall comparison, valuable minerals such as monazite, xenotime and ilmenite extracted from among contain 10287.1 ± 9.3 Bq/kg, 3733.1 ± 6.0 Bq/kg and 142.7 ± 1.2 Bq/kg for ^{232}Th respectively [18]. Results showed that, activity concentrations of radionuclides in all sediment samples were much lower than radionuclides in valuable minerals. Radionuclides contamination of sediments are largely due to minerals containing NORM found in sediment and not from free radionuclides dissolved in the water [18]. Thorium, found only as tetravalent cation, is concentrated in minerals such as monazite, rutile and thorianite, or adsorbed onto natural colloidal sized materials [19].

K-40 and Ra-226 in sediment samples

Statistical calculation of ^{40}K in sediments from among plant no.1 (Table 3) shows the activity concentration ranged between 74.80 - 823.10 Bq/kg and mean activity concentration of ^{40}K in similar samples was 502.15 ± 64.02 Bq/kg. Maximum activity concentration of 823.10 Bq/kg of ^{40}K was recorded at station 4 (1S4L2).

Table 4 shows that the activity concentration of ^{40}K in among plant No 2 ranged between 399.10 – 848.00 Bq/kg. The mean activity concentration of ^{40}K in sediment samples was 684.77 ± 44.92 Bq/kg. Maximum activity and mass concentrations were 848 Bq/kg and 30.69 mg/kg respectively and was measured in station 3 (2S3L4).

However, a Kruskal-Wallis One ANOVA on Ranks of the ^{40}K median activity concentrations at different locations in plant no.1 showed no significant difference ($p = 0.096$). Similar tests on samples from plant no. 2 showed significant difference between the median activity concentrations in samples collected.

Tables 3 and 4 also show the mass and activity concentrations of ^{226}Ra in sediment collected in plants nos. 1 and 2 respectively. The mass concentrations of ^{226}Ra were found to be between 5.71×10^{-7} - 9.62×10^{-6} mg kg⁻¹ for plant no. 1, and these correspond to 21.25 - 230.00 Bq kg⁻¹. In plant no. 2, the mass and activity concentrations of the same radionuclide ranged between 5.71×10^{-7} - 9.62×10^{-6} mg kg⁻¹ and 23.75- 151.25 Bq kg⁻¹ respectively.

A One Way ANOVA tested on ²²⁶Ra activity concentrations found in all locations at plant no. 1 showed significant differences (p = 0.008). A Holm-Sidak method (i.e. a Pairwise Multiple Comparison Procedures) showed ²²⁶Ra activity concentration significantly higher at station 2 (189.58 ± 35.93 Bq kg⁻¹) than stations 1 and 3. However, no such levels of differences were seen for the same radionuclide in plant no.2.

Comparison of average concentrations of ⁴⁰K and ²²⁶Ra in among sediments and those found in sediments elsewhere in the world is shown in table 5. The activity concentrations of ²²⁶Ra in among sediments were higher than in all of the world's sediments listed [9, 16, 23] (Table 5). The activity concentrations of ⁴⁰K measured in this study was within the range of those measured elsewhere. However, the mean concentrations of ⁴⁰K in among sediment from plants 1 and 2 were 502.15 Bq/kg and 684.77 Bq/kg respectively, were higher than the world's average concentration of 370 Bq/kg [20].

Table 3 Mass and activity concentrations of ⁴⁰K and ²²⁶Ra in sediment samples from among plant no. 1

No	Station	Mass Concentration		Activity Concentration	
		⁴⁰ K	²²⁶ Ra	⁴⁰ K	²²⁶ Ra
1	1S1L1	18.95	3.14x10 ⁻⁶	523.8	110.00
2	1S1L2	21.66	6.06 x 10 ⁻⁷	598.6	21.25
3	1S1L3	17.15	1.35 x 10 ⁻⁶	473.9	47.50
4	1S1L4	13.54	9.98 x 10 ⁻⁷	374.1	35.01
5	1S2L1	2.70	6.56 x 10 ⁻⁶	74.8	230.00
6	1S2L2	2.70	4.6 x 10 ⁻⁶	74.8	161.25
7	1S2L3	2.70	5.06 x 10 ⁻⁶	74.8	177.50
8	1S3L1	21.66	1.18 x 10 ⁻⁶	598.6	41.25
9	1S3L2	22.56	8.91 x 10 ⁻⁷	623.5	31.25
10	1S3L3	19.86	2.25 x 10 ⁻⁶	548.7	78.75
11	1S3L4	21.66	1.03 x 10 ⁻⁶	598.6	36.25
12	1S4L1	23.47	4.02 x 10 ⁻⁶	648.5	141.25
13	1S4L2	29.79	5.67 x 10 ⁻⁶	823.1	198.75
14	1S4L3	25.27	1.68 x 10 ⁻⁶	69.0	58.75
15	1S4L4	28.88	1.24 x 10 ⁻⁶	798.1	43.75
16	Soil 375	15.34	5.71 x 10 ⁻⁷	424.0	20.00

Table 4 Mass and activity concentrations of ⁴⁰K and ²²⁶Ra in sediment samples from among plant no. 2

No	Station	⁴⁰ K	²²⁶ Ra	⁴⁰ K	²²⁶ Ra
1	2S1L1	18.05	4.31 x 10 ⁻⁶	498.8	151.25
2	2S1L2	14.44	1.53 x 10 ⁻⁶	399.1	53.75
3	2S1L3	19.86	1.32 x 10 ⁻⁶	548.7	46.25
4	2S2L1	25.27	2.06 x 10 ⁻⁶	69.0	72.50
5	2S2L2	25.27	9.62 x 10 ⁻⁷	69.0	33.75
6	2S2L3	23.47	6.77 x 10 ⁻⁷	648.5	23.75
7	2S2L4	26.18	9.62 x 10 ⁻⁶	723.3	33.75
8	2S3L1	29.79	1.96 x 10 ⁻⁶	823.1	68.75

9	2S3L2	29.79	1.03×10^6	823.1	36.25
10	2S3L3	29.79	8.55×10^7	823.1	30.00
11	2S3L4	30.69	9.98×10^7	848.0	35.00
12	Soil 375	15.34	5.71×10^7	424.0	20.00

Gamma Radiation Representative Level Index, I_{gr}

Contributions of radium, thorium and potassium radionuclides in sediments toward gamma radiation hazard levels were reported as I_{gr} . Results showed that the I_{gr} from sediments collected in both plants were greater than unity (Table 6). The highest being in sediment collected at the point of discharge for both plants. Such high indices suggest a potential high external dose rates associated with these significant naturally occurring radionuclides.

Using conversion factors provided by UNCEAR (2002), the outdoor Effective Dose rates to adult from these naturally occurring radionuclides were calculated and the result presented in Table 7. Although the minimum Effective Dose rates for all radionuclides were within Malaysia's range, the maximum values were noticeably higher. These data provide pertinent information on the potential Effective Dose rates posed by these sediments containing radionuclides if the ponds were to become dry exposing the sediments. Such high values are indicative of enhance radiological risk, if this area were to be used for future land use.

Table 5 Comparison of average concentrations of NORM in among sediments and those found in sediments elsewhere in the world

No	Location	²³² Th	²²⁶ Ra	⁴⁰ K	Reference
		Bq/kg	Bq/kg	Bq/kg	
1	World average concentration	40	-	370	Firyal (1996)
2	Kuwait national wide	10.0 ± 3.4	11.8 ± 4.0	332 ± 104	Firyal (1996)
3	Spain river Tagus	63	42	572	Baeza (1992)
4	Spain all soils	49	45	650	Baeza (1992)
5	Lake Nasser , Egypt	23	21	155	Ibrahiem (1995)
6	Lousiana, USA	36	64	472	Delune (1986)
7	French river -1	38	38	599	Lambrechts (1992)
8	French river -2	44	28	700	Descamps(1988)
9	Belgium	9-47	13-43	170-610	Deworm (1988)
10	China	90	50	527	Ziqiang (1988)
11	Greece-Milos island	60	50	881	Florou (1992)
12	Bangladesh, Karnaphuli river	65.5	35.9	272	Chowdhury (1999)
13	Bangladesh, Shango river	57.5	27.8	255	Chowdhury (1999)
14	Amang sediment (plant No 1)	250.84 ± 59.06	94.16 ± 69.92	502.15 ± 247.97	This study
15	Amang sediment (plant No 2)	163.60 ± 159.34	53.18 ± 36.13	684.77 ± 148.97	This study

Source: Chowdhury et al. 1999 (for items 3-13)

Table 6: I_{gr} calculated from significant naturally occurring radionuclides in sediments of different locations in the amang plant.

Plants/sampling sites	I_{gr}
Amang plant 1	
Point of Discharge	6.5 ± 0.8
S1	2.4 ± 0.5
S2	2.5 ± 0.6
S3	3.3 ± 0.6
Amang plant 2	
Point of Discharge	4.0 ± 1.8
S1	1.8 ± 0.5
S2	2.0 ± 0.4

Table 7: Outdoor Effective Dose rate to adult for significant naturally occurring radionuclides

Radionuclides	Activity Concentrations (Bq kg ⁻¹)		Conversion factor* (nSv h ⁻¹ per Bq kg ⁻¹)	Effective Dose Rate (nSv h ⁻¹)	Malaysia** (nSv h ⁻¹)
⁴⁰ K	min	74.80	0.029	2.17	4.93(170)
	max	848.0	0.029	245.92	12.47(430)
²³² Th	min	63.06	0.46	29.01	28.98(63)
	max	637.61	0.46	293.30	134.92(110)
²³⁸ U	min	61.20	0.30	18.36	5.51(49)
	max	860.57	0.30	258.17	77.45(86)

*Conversion factor calculated as $E = X \times 0.0087 \text{ G R}^{-1} \times 0.7 \text{ Sv Gy}^{-1}$ (UNSCEAR 2000)

** Calculated Effective Dose rate based on natural radionuclide content in Malaysia's soil. Values in parentheses indicate concentration in soil (Bq kg⁻¹) (UNSCEAR 2000)

Conclusion

Gamma hazards and risk associated with significant naturally occurring radionuclides present in sediments from two amang processing ponds employing close water management system were studied. Results showed that amang processing enhanced the activity concentrations of ²³²Th, ²²⁶Ra, ²³⁸U and ⁴⁰K in sediment to levels higher than Malaysia's average. Maximum activity concentrations, Gamma Radiation Representative Level Index (I_{gr}), and subsequently outdoor Effective Dose rates suggested elevated levels of radiological risk associated with these technologically enhanced naturally occurring radionuclides found in amang ponds sediments. Further study is recommended to elucidate the potential radiological risk

associated with amang effluent.

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