Sains Malaysiana 52(8)(2023): 2267-2286
http://doi.org/10.17576/jsm-2023-5208-08

Exploring Strategies Post- Revocation of Licensing Exemption for Malaysia's Tailing Processing Industry

(Meneroka Strategi Selepas Pembatalan Pengecualian Pelesenan untuk Industri Pemprosesan Amang Malaysia)

MUHAMMAD ABDULLAH RAHMAT[1], AZNAN FAZLI ISMAIL[1,2,*], ELI SYAFIQAH AZIMAN [1], NURSYAMIMI DIYANA RODZI[1,] RATNA SUFFHIYANNI OMAR[1,2], WAN MOHD RAZI IDRIS[3,4] & TUKIMAT LIHAN[4]

[1]*Nuclear Science Programme, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*
[2]*Nuclear Technology Research Centre, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*
[3]*Water Analysis Research Centre (ALIR), Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*
[4]*Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

Received: 12 April 2023/Accepted: 18 Julai 2023

ABSTRACT

The extraction of heavy metals and rare-earth elements from tailing residue has caused a significant impact towards the environment as well as the industrial workers as a result from the contamination caused by the processing activities. The radionclide concentration of ^{226}Ra, ^{232}Th, and ^{40}K in soil and tailing residue were found to be within the range of 0.31 - 4.97 Bqg^{-1} and 1.24 - 4.47 Bqg^{-1}, 0.16 - 11.07 Bqg^{-1} and 1.08 - 8.56 Bqg^{-1}, 0.22 - 1.24 and 0.18 - 1.32 Bqg^{-1}, respectively. The radiological impack assessment findings indicated significant overexposure risks where the annual effective dose was estimated to be within the range of 0.7 – 207.6 mSvy^{-1} while the excess lifetime cancer risks we found to have exceeded the limit let by the local regulatory body. The correlation between study findings and the enactment of the licensing exemption order was done to identify the effects of non-regulatory compliance to the Atomic Energy Licensing Act. The study also emphasized on the remediation importance of industrial sites before implementing any form of changes towards new regulatory adherence. Hence, the study recommeneds potential remediation techniques but taking into account the operational status of each proceesing plant, degree of contation and possible future use of the contaminated site.

Keywords: Legislative improvement; NORM; Radiological Impact Assessment; tailing processing; waste management

ABSTRAK

Pengekstrakan logam berat dan nadir bumi daripada sisa amang telah memberi impak yang ketara terhadap alam sekitar dan juga pekerja industri akibat pencemaran yang berlaku di lokasi yang melibatkan aktiviti pemprosesan. Kandungan kepekatan radionuklid ^{226}Ra, ^{232}Th dan ^{40}K dalam tanah dan sisa amang masing-masing berada dalam julat antara 0.31 - 4.97 Bqg^{-1} dan 1.24 - 4.47 Bqg^{-1}, 0.16 - 11.07 Bqg^{-1} dan 1.08 - 8.56 Bqg^{-1}, 0.22 - 1.24 dan 0.18 - 1.32 Bqg^{-1}. Hasil penilaian impak radiologi menunjukkan risiko pendedahan berlebihan yang ketara dengan nilai dos berkesan tahunan berada dalam julat 0.7 - 207.6 mSvthn^{-1} serta risiko kanser sepanjang hayat didapati melebihi had yang ditetapkan oleh pihak berkuasa tempatan. Hasil kajian ini seterusnya dikaitkan dengan perintah pengecualian pelesenan bagi mengenal pasti kesan akibat ketidakpatuhan terhadap Akta Perlesenan Tenaga Atom. Kajian turut menekankan kepentingan tindakan pemulihan kawasan industri sebelum membuat sebarang perubahan bagi mematuhi akta perlesenan yang baharu. Oleh itu, kajian ini mencadangkan langkah pemulihan dengan mengambil kira status pengoperasian setiap kilang, tahap pencemaran dan juga kebarangkalian penggunaan semula kawasan tercemar.

Kata kunci: NORM; pemprosesan amang; penambahbaikan undang-undang; pengawalan sisa; Penilaian Impak Radiologi

INTRODUCTION

The expansion and development of the tailing processing (TP) industry began with the rapid decline of the global tin market value in the 20th century (Kontol, Ahmad & Omar 2007; Omar et al. 2007; Rahmat et al. 2022; Thoburn 1994). With the accumulated tailing material accumulated over the years of active processing, Malaysia began to divert attention to the reprocessing and extraction of valuable heavy minerals from this waste residue. Employing a combination of several processing techniques, monazite, ilmenite, xenotime, and zircon are commonly processed and extracted for the trace amounts of rare-earth elements and valuable metals associated with them (Ahmad Fauzan, Jasmi Aziz & Muhammad Hatta 2022; Alnour et al. 2017; Omar et al. 2007; Sanusi et al. 2021).

Within the same time frame, the Department of Atomic Energy (DAE) was founded; tasked to enforce and regulate radiation safety, security and safeguarding on a national scale under the jurisdiction of the Atomic Energy Licensing Regulation 1984 (henceforth known as Act 304). Shortly after the establishment, the DAE enacted an exemption order for all 'small amang (tailing) factories' to the Licensing Act 304, allowing operations to continue without the need for a license. This was done to repurpose and minimize the waste accumulated over the years (AELB 1994; Alnour et al. 2017; Kontol, Ahmad & Omar 2007; Sanusi et al. 2021).

As a result of this, studies in the past two decades have reported that the TP activities conducted in the industry have shown signs of serious radiological impact on the environment; environmental studies assessing the on-site Naturally Occurring Radioactive Material (NORM) contamination of these processing plant reported that the concentration of ^{226}Ra and ^{232}Th were within the range of 0.01 - 203.0 Bq/g and 0.02 - 365.4 Bq/g, respectively, with most reporting the average exceeding clearance level enforced by the local regulatory body (Al-Areqi et al. 2016; Alnour et al. 2017; Azlina et al. 2003; Ismail, Teng & Muhammad Samudi 2011; Ismail et al. 2003; Nasirian, Ismail & Abdullah 2008; Omar et al. 2007; Sanusi et al. 2021; Solehah & Samat 2018).

As the NORM environmental contaminations have reached such concentrations, the risk of radiological exposure to workers undoubtedly would be proportional, thus indicating a clear presence of overexposure risks. Prior studies in the past few decades have reported findings that support this hypothesis as annual external exposure dose estimations reached up to 280.4 mSv/y while internal exposure dose values were up to 118.5 mSv/y (Rahmat et al. 2023; Sanusi et al. 2021; Zaidan Kandar & Bahari 1996). These findings were also supported by studies conducted in other major tin-producing countries that are facing similar environmental challenges such as Indonesia and Nigeria (Atipo et al. 2020; Gunawan et al. 2019; Ibeanu 2003). These doses exceed the 20 mSv/y exposure limit enforced on supervised radiation workers who are licensed and are governed by strict radiation safety measures. This is a major cause for concern as the exempted tailing processing industry is not subjected to the same strict guidelines which ultimately results in the dose threshold for industrial workers in the industry being equal to that of the general public, specifically 1 mSv/y only.

To improve the working safety standards of the industry, the government has revisited the existing legislation and has deemed it necessary to revoke enacted exemption orders in 2021, thus enforcing the national licensing act on the TP industry. Though this is a step in the right direction, significant changes to the industry must be made in several aspects for the new legislation to have any meaningful effect, primarily in the aspect of site remediation and waste management. To the best of our knowledge, there has yet to be any guidance concerning the transition from being unlicensed to the licensing of the TP industry post-revocation from the DAE. This lack of guidance could potentially result in the execution of ineffective or incorrect actions taken by the parties involved to adhere to the newly imposed regulations. It is worth noting that though the subject matter has been conducted before, the monitoring of the recoccuring TP is essential in the safety assurance of the TP industry towards workers as well as the environment, especially in the midst legislative changes and improvements.

To effectively improve the industrial conditions of the TP industry, a firm understanding of the initial scenario must first be established. Consequently, existing as well as new remediation efforts must be thoroughly explored to maximise the effectiveness of remediating actions. Hence, the study aims to assess the radiological impact the TP industry has had on the environment as well as the workers in the industry. The findings would be used to identify the most suitable method of remediation that could be applied to the local TP industry to improve worker radiation safety while maintaining the longevity of the industry.

MATERIALS AND METHODS

SAMPLING AND SAMPLE PREPARATION

To assess the situation of the local industry, 5 TP plants located in Kinta, Perak were chosen as the study site where a total of 57 soil samples and 99 tailing samples were collected compositely. Soil samples were taken at a depth of between 5-15 cm from the plants' main passages using a hand auger in varying grid sizes that represent key areas of the processing plant. Tailing samples were collected from tailing stockpiles stored in the study areas. A total of 5 control soil samples were also taken at a location that was free from any processing activities. Figure 1 shows the layout of selected study sites. Samples were brought to the laboratory and dried at 105 °C until the uniform weight was obtained before ground and sieved per the International Atomic Energy Agency (IAEA) technical reports 295 (IAEA 1989). Each sample was triplicated before being sealed in an air-tight acrylic sample bottle for a 3-week incubation period. Details of the sample collected from each processing plant are stated in Table 1.

GAMMA-RAY SPECTROMETRY ANALYSIS

To evaluate the presence of NORM contamination in samples collected, a gamma spectroscopy system equipped with a hyper-pure germanium detector was used in this study to measure the concentration of ^{226}Ra, ^{232}Th, and ^{40}K. Encased in a lead housing, the calibration of the system was done in accordance with a multinuclear standard. To ensure that the measurements were reliable, the detection limit (DL) and minimum detectable activity for photopeak 351 keV, 911 keV, and 1461 keV for ^{226}Ra, ^{232}Th, and ^{40}K, respectively (Rahmat et al. 2021; Shittu, Aznan Fazli & Supian 2019). The DL and MDA values, shown in Table 2, were calculated using Equations (1) and (2):

$$\mathrm{DL} = 2.71 + 4.66\sqrt{N_b} \tag{1}$$

$$\mathrm{MDA} = \frac{\mathrm{DL}}{\mathrm{T}\varepsilon\mathrm{BM}} \tag{2}$$

where N_b represents the background radiation count; DL represents the detection limit; T denotes the counting time in seconds; B represents the branching ratio; and M is the sample mass.

TABLE 1. Sample collection summary and details

Location	Coordinates	Sample type	Collection site	Number of samples	Sampling area grid (m^2)
PP1	4°33'44.8"N 101°02'04.8"E	Soil	Walkway	12	400-600
		Tailing	Tailing stockpile	9	Stockpile size dependant
PP2	4°21'54.2"N 101°07'40.9"E	Soil	Walkway	9	500-600
		Tailing	Tailing stockpile	18	Stockpile size dependant
PP3	4°15'42.5"N 101°08'44.6"E	Soil	Walkway	12	400-500
		Tailing	Tailing stockpile	24	Stockpile size dependant
PP4	4°19'57.9"N 101°09'22.0"E	Soil	Walkway	12	300-500
		Tailing	Tailing stockpile	24	Stockpile size dependant
PP5	4°14'06.0"N 101°13'17.9"E	Soil	Walkway	12	400-500
		Tailing	Tailing stockpile	24	Stockpile size dependant

TABLE 2. Detection limit and minimum detectable limit values for the detector used in the study

Radionuclide	Detection limit (DL)	Minimum detectable activity (MDA)
^{226}Ra	58.78±9.61	0.56±0.09
^{232}Th	42.14±6.68	1.18±0.19
^{40}K	92.29±10.36	25.1±2.82

Samples were ground and sieved to a fineness of 500 µm before being triplicated in polyethylene bottles and sealed in airtight sample bottles. Each sample was stored for 30 days to ensure secular equilibrium between ^{226}Ra and ^{232}Th and their prognosis (Friedmann et al. 2017). The concentration of ^{226}Ra, ^{232}Th, and ^{40}K was measured by counting each sample for 12 h. The IAEA *standard reference material* (IAEA-Soil-375) was used to determine the NORM concentrations in collected samples by employing Equation (3):

$$C = \frac{M_{std} \times A_s}{M_s \times A_{std}} C_{std} \qquad (3)$$

where C and C_{std} represent the activity concentration for the sample and standard material (Bqkg^{-1}); M_s and M_{std} represent the sample and standard material; while A_s and A_{std} denotes the number of counts per second of samples and standard materials detected, respectively (Canberra 2000).

RADIOLOGICAL IMPACT ASSESSMENT

The radium equivalence (Ra_{eq}) value is a gamma-ray dose rate estimate where the activity concentration of ^{232}Th at 259 Bqkg^{-1}, ^{40}K at 4810 Bqkg^{-1}, and 370 Bqkg^{-1} of ^{226}Ra is assumed to produce identical dose rates (Atipo et al. 2020; Qureshi et al. 2014). The Ra_{eq} value was calculated using Equation 2 (Shittu, Aznan Fazli & Muhamad Samudi 2020).

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K \qquad (4)$$

where C_{Ra}, C_{Th}, and C_K denote the activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K. Ra_{eq} values above 370 Bqkg^{-1} are considered to have exceeded the permissible level as it may result in an exposure dose beyond the public dose limit (1 mSvy^{-1}) (Abdullahi, Ismail & Yasir 2020; Gunawan et al. 2019).

The absorbed dose (D) is a measure of the raw dose received by exposed individuals in both indoor and outdoor scenarios which was used to calculate the total annual effective dose ($AEDE_{tot}$) that considers the tissue and radiation weighting factor. Both dose assessments were calculated using Equations (5) - (10):

$$D_{in}\ (\mathrm{nGyh^{-1}}) = 0.92(C_{Ra}) + 1.1(C_{Th}) + 0.08(C_K) \qquad (5)$$

$$D_{out}\ (\mathrm{nGy/hr}) = 0.462\ C_{Ra} + 0.604\ C_{Th} + 0.0417\ C_K \qquad (6)$$

$$D_{tot}\ (\mathrm{nGy/hr}) = D_{in} + D_{out} \qquad (7)$$

$$AEDE_{in}\ (\mathrm{mSv/y}) = D_{in} \times T \times D_f \times 0.8 \times 10^{-6} \qquad (8)$$

$$AEDE_{out}\ (\mathrm{mSv/y}) = D_{out} \times T \times D_f \times 0.2 \times 10^{-6} \qquad (9)$$

$$AEDE_{tot}\ (\mathrm{mSv/y}) = AEDE_{in} + AEDE_{out} \qquad (10)$$

where D_f denotes the dose conversion factor (0.7); O represents the occupancy factor both indoor (0.8); and outdoor (0.2); respectively. T denotes the exposure time (8670 hy^{-1}) (Kolo et al. 2015; Shittu et al. 2018).

Using the obtained AEDE value obtained, a probabilistic estimate of cancer risk that occurs due to radiological exposure was done. The excess lifetime cancer risk (ELCR) is a probabilistic assessment of exposed individuals developing cancerous diseases after a certain amount of time. The $ELCR_{tot}$ is calculated using Equations (11) - (13).

$$ELCR_{in} = AEDE_{in} \times DL \times RF \qquad (11)$$

$$ELCR_{out} = AEDE_{tot} \times DL \times RF \qquad (12)$$

$$ELCR_{tot} = ELCR_{in} + ELCR_{out} \qquad (13)$$

where the average life expectancy of an individual (DL) is considered to be 70 years and the risk factor (RF) is considered to be 0.055 Sv^{-1} (Belyaeva et al. 2019; Kolo et al. 2015; Shittu, Aznan Fazli & Supian 2019).

RESULTS AND DISCUSSION

NORM CONCENTRATION IN SAMPLES

The summary of the NORM concentration is shown in Table 3 where it could be seen that the concentration of ^{226}Ra and ^{232}Th were within the range of 0.10 - 7.2 and 0.05 - 16.3 Bqg^{-1} for soil as well as 0.05 - 9.8 and 0.05 - 25.3 Bqg^{-1} for tailing samples, respectively. On average, the concentration of both ^{226}Ra and ^{232}Th were 1.80 ±1.90 and 3.11 - 4.73 Bqg^{-1}, nearly 15 and 45 times higher than the natural concentration found in the control soils of the study, respectively. This indicates to the study that the soil samples collected from the TP sites have undergone significant levels of NORM concentration from the processing activities conducted. It was also found that 63.2% of the soil samples, as well as 84.8% of tailing samples, were seen to have exceeded the regulatory concentration limit of 1 Bqg^{-1}, requiring the need for extra

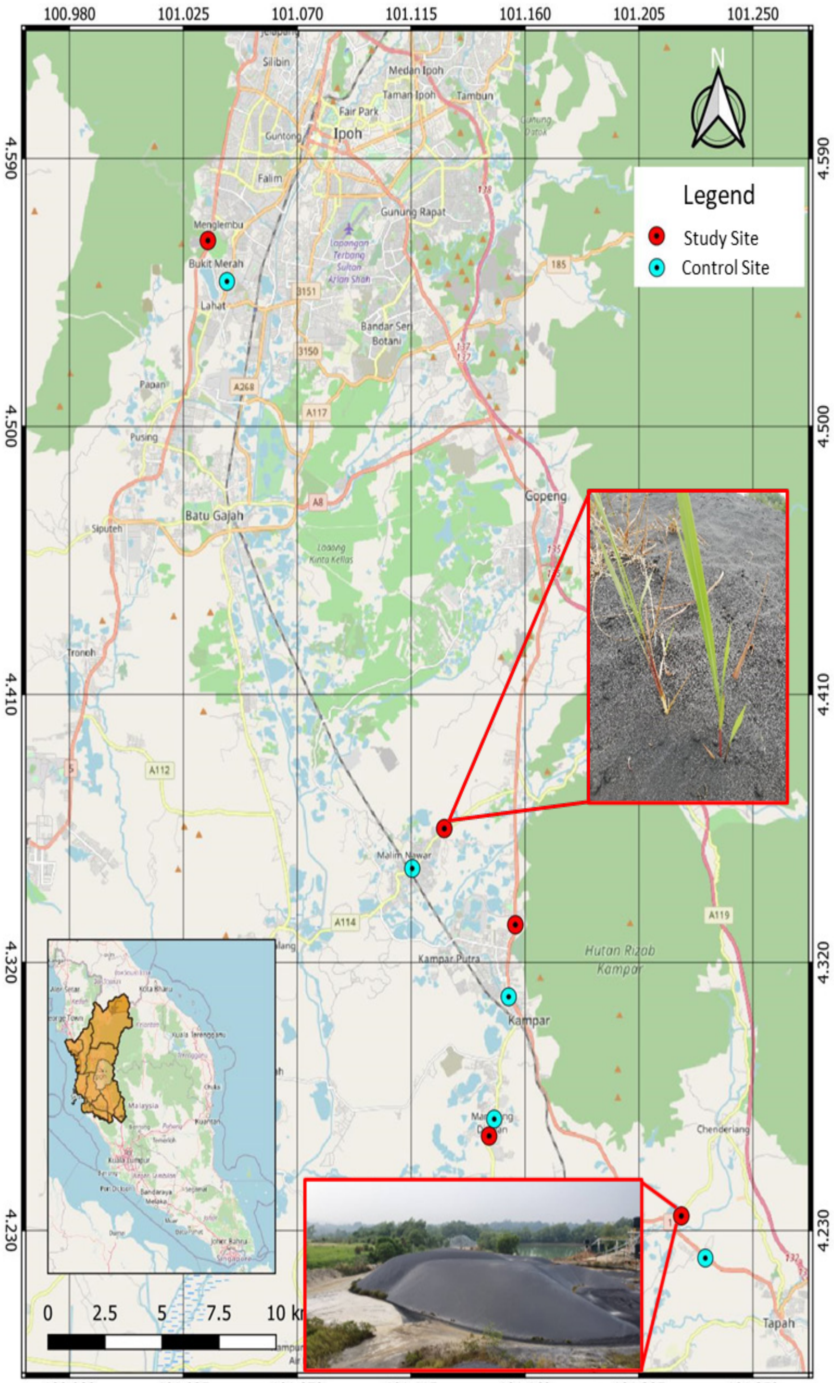

FIGURE 1. Distribution of sampling locations for the factories and controlled locations

precautionary radiation safety measures when managing or being in proximity of these materials according to the national licensing regulation (AELB 2010).

Study findings were also shown to be parallel to findings reported in prior local studies towards the industry, indicating little to no improvement action has been taken in the past decades in the effort to manage the processing residue accordingly (Alnour et al. 2017; Azlina et al. 2003; Omar et al. 2007; Sanusi et al. 2021; Solehah & Samat 2018; Rahmat et al. 2021). In three separate studies conducted by Alnour et al. (2017), Rahmat et al. (2021), and Sanusi et al. (2021), the highest contributors to the NORM concentration commonly found were monazite, xenotime as well as zircon, which indicates the primary source of associated NORM radionuclides which contributes primarily to the environmental contamination caused by the industry. Studies in the early 2000s also reported similar findings with an emphasis on ilmenite, indicating that the elevation of NORM caused by processing activities could not only contaminate the immediate surrounding but also spread via rainwater washout and groundwater leaching (Azlina et al. 2003; Nasirian, Ismail & Abdullah 2008). Studies have also shown that with the increase of NORM concentrations in the surrounding soil, the rate of emanation of the colourless and odourless radon gas also increases which contributes significantly to the internal exposure of individuals in the vicinity (Omar et al. 2007). This finding was supported by a recent study conducted by Rahmat et al. (2023) who reported that a NORM concentration of 226Ra within the range of 0.1-7.2 Bqg-1 could result in the release of radon gas between the range of 41.8 to 669.6 Bqm−3, which could result in an annual effective exposure dose of 0.5 - 7.2 mSvy-1.

The findings of the current study are further supported by the other studies conducted on the same industry in other major tin-producing countries, namely Indonesia and Nigeria; NORM concentrations reported by both countries were parallel to the concentration values found in the study, as shown in Table 4 (Atipo et al. 2020; Gunawan et al. 2019; Ibeanu 2003; Permana et al. 2018). The commonality between the three nations lies in the challenge of waste management where the standard practice employed by the industries does not put much emphasis on very low-level radioactive material and waste management, in this case, comes in the form of extracted minerals and tailing residue (Atipo, Olarinoye & Awojoyogbe 2020; Ibeanu 2003; Rahmat et al. 2022; Syarbaini, Warsona & Iskandar 2014)

TABLE 3. NORM's concentration values in soil and tailing samples

Processing plant	Sample code	Concentration (Bqg^{-1})		
		^{226}Ra	^{232}Th	^{40}K
PP1-Soil	T1	0.69 ± 0.08	0.37 ± 0.04	0.40 ± 0.03
	T2	0.34 ± 0.01	0.17 ± 0.01	1.34 ± 0.03
	T3	0.10 ± 0.00	0.06 ± 0.00	0.44 ± 0.01
	T4	0.11 ±0.00	0.05 ±0.00	0.54± 0.02
PP1-Tailing	A1	4.88 ± 0.06	1.37 ± 0.00	0.15 ± 0.01
	A2	1.95 ± 0.30	1.11 ± 0.16	0.16 ± 0.02
	A3	0.58 ± 0.01	0.75 ± 0.03	0.12 ± 0.01
PP2-Soil	T1	1.85 ± 0.07	2.20 ± 0.09	0.26 ± 0.01
	T2	1.37 ± 0.01	1.35 ± 0.04	0.18 ± 0.01
	T3	1.39 ± 0.07	1.67 ± 0.04	0.21 ± 0.01
PP2- Tailing	A1	2.10 ± 0.05	1.28 ± 0.06	0.16 ± 0.01
	A2	2.64 ± 0.04	4.42 ± 0.06	0.49 ± 0.04
	A3	4.86 ± 0.08	12.64 ± 2.10	1.27 ± 0.05
	A4	2.52 ± 0.05	1.46 ± 0.04	0.17 ± 0.01
	A5	3.97 ± 0.27	6.45 ±0.37	0.70 ± 0.06
	A6	2.16 ± 0.16	2.20±0.18	0.30 ± 0.05

PP3-Soil	T1	7.21 ± 0.1	16.34 ± 0.27	1.63 ± 0.05
	T2	4.61 ± 0.19	6.28 ± 0.42	0.68 ± 0.05
	T3	3.81 ± 0.03	14.03 ± 0.1	1.78 ± 0.009
	T4	4.23 ± 0.19	7.61 ± 0.37	0.85 ± 0.06
PP3- Tailing	A1	3.74 ± 0.06	5.82 ± 0.28	0.66 ± 0.004
	A2	1.83 ± 0.05	2.39 ± 0.28	0.32 ± 0.009
	A3	3.72 ± 0.09	4.50 ± 0.76	0.49 ± 0.01
	A4	1.04 ± 0.02	0.71 ± 0.01	0.09 ± 0.004
	A5	5.04 ± 0.08	8.530 ± 0.72	1.04 ± 0.04
	A6	5.42 ± 0.33	11.59 ± 1.93	1.43 ± 0.20
	A7	5.17 ± 0.17	9.60 ± 0.47	0.95 ± 0.03
	A8	9.80 ± 0.24	25.30 ± 0.48	5.60 ± 0.23
PP4-Soil	T1	1.44 ± 0.19	2.44 ± 0.48	0.30 ± 0.04
	T2	1.37 ± 0.01	1.31 ± 0.09	0.20 ± 0.01
	T3	1.66 ± 0.09	1.54 ± 0.06	0.21 ± 0.01
	T4	1.67 ± 0.07	1.23 ± 0.12	0.18 ± 0.01
PP4- Tailing	A1	1.29 ± 0.03	1.10 ± 0.04	0.15 ± 0.003
	A2	1.28 ± 0.09	1.24 ± 0.14	0.17 ± 0.02
	A3	2.01 ± 0.06	1.45 ± 0.06	0.18 ± 0.005
	A4	2.13 ± 0.02	1.62 ± 0.03	0.21 ± 0.01
	A5	0.98± 0.01	0.90 ± 0.01	0.24 ± 0.09
	A6	1.09 ± 0.07	0.59 ± 0.02	0.07 ± 0.01
	A7	2.03 ± 0.05	0.92 ± 0.10	0.12 ± 0.02
	A8	8.80 ± 0.06	7.62 ± 0.09	0.78 ± 0.03
PP5-Soil	T1	0.24 ± 0.01	0.21 ± 0.01	0.24 ± 0.01
	T2	0.22 ± 0.01	0.14 ± 0.01	0.24 ± 0.01
	T3	1.67 ± 0.05	2.06 ± 0.02	0.33 ± 0.02
	T4	0.15 ± 0.03	0.11 ± 0.001	0.20 ± 0.01
PP5- Tailing	A1	1.03 ± 0.02	1.75 ± 0.071	0.22 ± 0.01
	A2	1.83 ± 0.06	0.52 ± 0.02	0.09 ± 0.01
	A3	2.45 ± 0.04	1.96 ± 0.08	0.23 ± 0.15
	A4	1.65 ± 0.03	1.29 ± 0.01	0.17 ± 0.01
	A5	0.08 ± 0.002	0.05 ± 0.001	0.05 ± 0.01
	A6	0.24 ± 0.003	0.09 ± 0.001	0.12 ± 0.01
	A7	2.62 ± 0.08	3.57 ± 0.12	0.46 ± 0.03
	A8	0.05 ± 0.02	0.07 ± 0.001	0.07 ± 0.002
Range	Soil	0.10 - 7.2	0.05 - 16.3	0.12 – 1.7
	Tailing	0.05 - 9.8	0.05 - 25.3	0.07 - 5.6
Control	Soil	0.12 ± 0.07	0.07 ± 0.05	0.16 ± 0.13

TABLE 4. NORM concentration report by prior studies

Type of Processing Plant	Sample Type	Concentration (Bq/g)				References
		^{238}U	^{226}Ra	^{232}Th	^{40}K	
Industrial TP Plant	Soil	-	0.1- 7.2	0.1 -16.3	0.1 – 1.7	Current study
	Tailing	-	0.1 - 9.8	0.05 - 25.3	0.1 - 5.6	
Industrial TP Plant (Malaysia)	Contaminated Soil	0.04–1.8	0.2	0.1- 4.52	0.04 – 0.7	(Alnour et al. 2017; Azlina et al. 2003; Omar et al. 2007; Rahmat et al. 2021; Sanusi et al. 2021; Solehah & Samat 2018)
	Tailing Residue	0.3 - 4.2	0.08 – 0.5	0.3 – 3.6	0.1 – 0.3	
	Sediment	0.01 -1.1	0.02 – 0.2	0.1 – 1.5	0.4 – 0.8	
	Mineral Stockpile	0.04 - 203.0	0.02 - 170.4	0.03 - 365.4	0.07 - 19.6	
Industrial TP Plant (Indonesia)	Tin Slag	1.5 - 13.9	3.1 - 7.7	9.9 - 22.8	0.9 - 2.1	(Permana et al. 2018)
Tin smelting industry (Indonesia)	Tin Slag	3.4	-	0.01	-	(Gunawan et al. 2019)
Tin Mining and TP Site (Nigeria)	Contaminated soil	0.6 - 16.6	-	1.0 - 49.3	-	(Ibeanu 2003)
	Tin Tailing	2.4 - 27.0	-	32.5 - 251.6	-	
Tin mining and processing plant (Nigeria)	Tin Tailing	0.1 - 0.2	-	0.1 - 0.8	0.1 - 2.1	(Atipo et al. 2020)
	Mineral soil	0.2 -0.6	-	0.4 - 1.9	0.1 - 2.1	
Mineral extraction From Tin (China)	Tin ore	0.2	0.5	0.1	0.3	(Liu & Pan 2012)
	Tin tailing	0.9	1.4	0.8	0.6	
Rare earth mining site (China)	Tailing	0.02 - 0.06	-	1.2-1.4	-	(Li et al. 2016)
Monazite Mining Site (Spain)	Monazite	0.04 - 0.06	-	0.0-0.1	0.7-0.9	(García-Tenorio et al. 2018)
Heavy Mineral Processing Site (Mozambique)	Ilmenite	0.09	0.212	-	-	(Conceição et al. 2018)
	Heavy mineral concentrate	0.6 - 0.7	0.4 - 0.9	-	-	
Malaysia Average	Soil	0.1	0.07	0.08	0.3	(UNSCEAR 2000)
Global Average	Soil	0.03	0.03	0.05	0.4	

RADIOLOGICAL IMPACT ASSESSMENT AND ESTIMATED DOSE

The radiological impact assessment findings in Table 5 indicate that the Ra_{eq} value was within the range of 596.64±488.04 - 20881.72±7979.43 Bqkg^{-1}. Nearly all samples were found to have exceeded the permissible value of 370 Bqkg^{-1}. This indicates the study that exposure to both residue tailing and the contaminated soil found in these processing plants can cause an exposure beyond 1.5 mSvy^{-1} (Gunawan et al. 2019; Lee et al. 2009).

The study also discovered that exposure to soil and tailing samples collected from the study sites could result in an estimated $AEDE_{tot}$ within the range of 2.9 - 93.6 and 13.5 - 76.1 mSvy^{-1}, respectively. Adding to the concern that nearly all samples could cause an exposure dose that exceeds the regulatory limit enforced on the general masses (1 mSvy^{-1}), 63.5% of the samples collected indicate the potential to exceed the radiation worker dose limit of 20 mSvy^{-1}. Said dose estimation values were found to be comparable to the values reported by studies conducted towards licensed industries; oil and gas, as well as rare-earth extraction industries, are examples of licensed industries due to the generally known fact that the materials handled contain high concentrations of ^{226}Ra and ^{232}Th as shown in Table 4 (Abdel-Razek et al. 2016; Al-Areqi et al. 2016; Ali et al. 2019; Ismail, Teng & Muhammad Samudi 2011; Nurrul Assyikeen et al. 2019). These comparably high dose estimations are more concerning knowing that the TP has little emphasis on radiation safety and security countermeasures.

As the potential for cancer occurrences is directly proportional to the dose an individual receives, the ELCR values calculated in the study were also seen to be relatively high, falling within the range of 2.7 × 10^{-3} - 7.99 × 10^{-1}. The global average ELCR value derived from the global average effective dose was calculated to be 9.24 × 10^{-3}, indicating that 86.5% of the samples exceeded said value (UNSCEAR 2000). This indicates that workers in the industry have a higher possibility of developing cancer occurrences than the average person if exposed.

TABLE 5. Average radiological impact assessment parameters (Ra$_{eq,}$ D, AEDE, and ELCR) values from collected samples

Processing plant	Sample code	Ra$_{eqn}$ (Bqkg^{-1})	D$_{tot}$ (nGyhr^{-1})	AEDE$_{tot}$ (mSvy^{-1})	ELCR$_{tot}$ (10^{-3})	References
PP1	Soil	596.6 ± 488.0	779.5 ± 624.4	2.9 ± 2.3	11.1 ± 8.9	Current study
	Tailing	4017.5 ± 2625.7	5170.9 ± 3465.7	19.1 ± 12.9	73.6 ± 49.7	
PP2	Soil	4044.1 ± 875.3	5061.3 ± 1085.1	18.5 ± 4.0	71.4 ± 15.3	
	Tailing	9867.3 ± 7333.6	12240.6 ± 8918.6	44.7 ± 32.4	172.2 ± 124.6	
PP3	Soil	20881.7 ± 7979.4	25748.8 ± 9797.4	93.6 ± 35.3	360.5 ± 135.8	
	Tailing	16907.5 ± 13820.9	20872.3 ± 16925.7	76.1 ± 61.5	293.0 ± 236.9	
PP4	Soil	3878.5 ± 762.5	4863.7 ± 906.5	17.8 ± 3.3	68.7 ± 12.6	
	Tailing	5232.6 ± 5930.1	6619 ± 7472	24.3 ± 27.4	93.7 ± 105.6	
PP5	Soil	1490.3 ± 2099.9	1871.02 ± 2616.4	6.9 ± 9.6	26.4 ± 36.9	
	Tailing	2916.5 ± 2715.2	3671.6 ± 3389.0	13.5 ± 12.4	51.9 ± 47.8	
Range		219.4 - 46460.6	63.7 - 19701.4	0.7 – 207.6	2.7 – 799.0	
Control		247.3 ± 148.8	106.3 ± 64.0	1.2 ± 0.7	4.5 ± 2.7	
TP industry (Malaysia)	Contaminated soil	600.0 – 21000.0	240 - 8900	2.9 - 93.6	11.0 – 42.0	(Alnour et al. 2017; Hewson 1996; Omar et al. 2007; Rahmat et al. 2021; Sanusi et al. 2021)
	Tailing residue	4000 – 9900	1000 - 8000	1.5 - 2.1	8.1 - 34.0	
	Mineral stockpile	-	3881 - 228,020	0.1 - 280	0.5 - 1080.0	
Rare-earth Industry	Monazite	-	-	0.46 – 172.0	-	
Oil and gas	Scale	-	-	0.16 – 321.0	-	
Global	Soil			2.4	9.24*	(UNSCEAR 2000)

* Values were calculated using AEDE values reported mentioned study

REPERCUSSIONS OF THE EXEMPTION ORDER TOWARDS THE TAILING INDUSTRY

At the time of the study, the TP industry has already been in operation for over 30 years, with most plants adopting the same operating procedures employed since the early developmental years of the industry albeit with minor changes. This stagnation in operating procedure could potentially be the explanation for the underlying trend of high NORM concentration in environmental soil reported by many studies prior.

An obvious point of contention is the method of material management and storage. The industrial materials are commonly kept in large stockpiles that are scattered throughout the plant grounds, often without any form of top or bottom cover, as shown in Figure 2. This exposes the NORM bearing material directly to the soil, causing further soil contamination, while also increasing the likelihood of human exposure as these stockpiles are commonly situated in common walk and driveways of the processing plants. Prior studies have emphasised the subject matter, noting that prolonged contamination will only increase the level of NORM contamination in the environment (Hewson 1996; Rahmat et al. 2023; Sanusi et al. 2021).

Adding to the concern is the potential expansion of the contamination zone and affected areas. As these stockpiles are kept out in the open, it is more susceptible to being exposed to the elements, primarily rainwater, which could potentially wash out mobile components of the contaminants and be carried off into large water bodies. This concern even extends to the potential groundwater seepage that could occur, thus contaminating the groundwater flowing into nearby lakes and rivers. Several studies have stressed this concern noting that it could lead to the potential pathways of human internal exposure via direct or indirect exposure via ingestion of affected foods (Aslam, Yousafzai & Javed 2022; Jumaat & Ab Hamid 2023; Muhammad Abdullah et al. 2023; Sanusi et al. 2021; Schoenberger 2016). A simulation study conducted by Muhammad Abdullah et al. (2023) reported that groundwater has the potential to carry trace amounts of contaminant particles into large water bodies and subsequently affect aquatic creatures; the study reported that the consumption of the affected fish could contribute to internal exposure albeit relatively low (maximum of 0.01 mSvy-1) due to the very low-level waste involved in the study. Figure 3 illustrates the transport of contaminating particles through different mediums and subsequently into aquatic life and other foodstuffs.

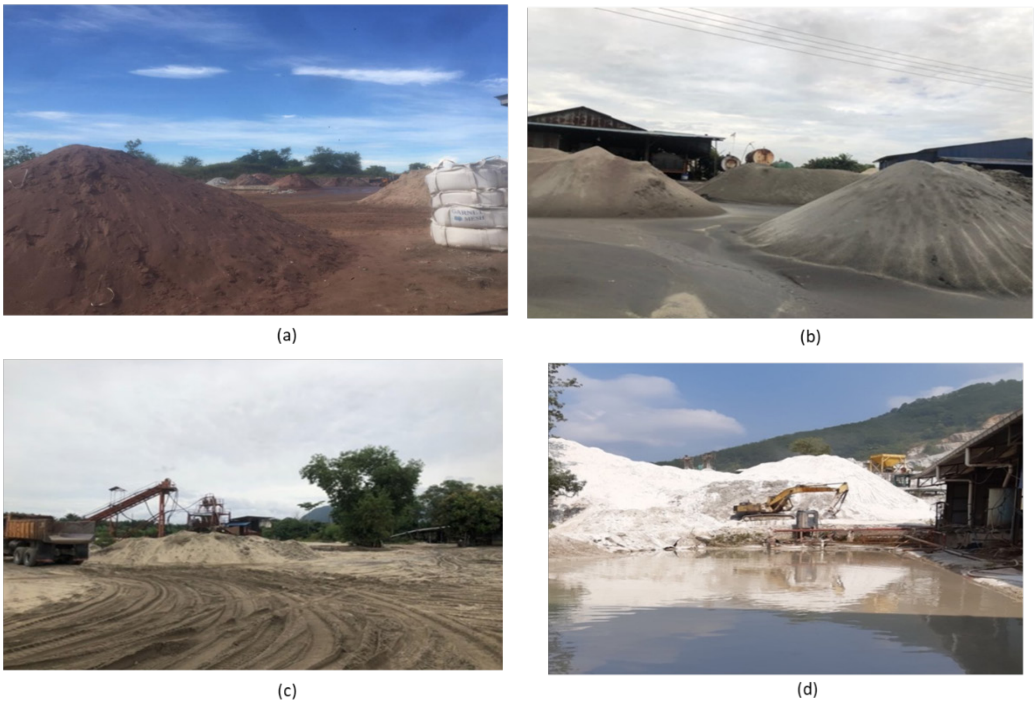
(a) (b) (c) (d)

FIGURE 2. Tailing and material storage stockpiles scattered throughout the TP plants

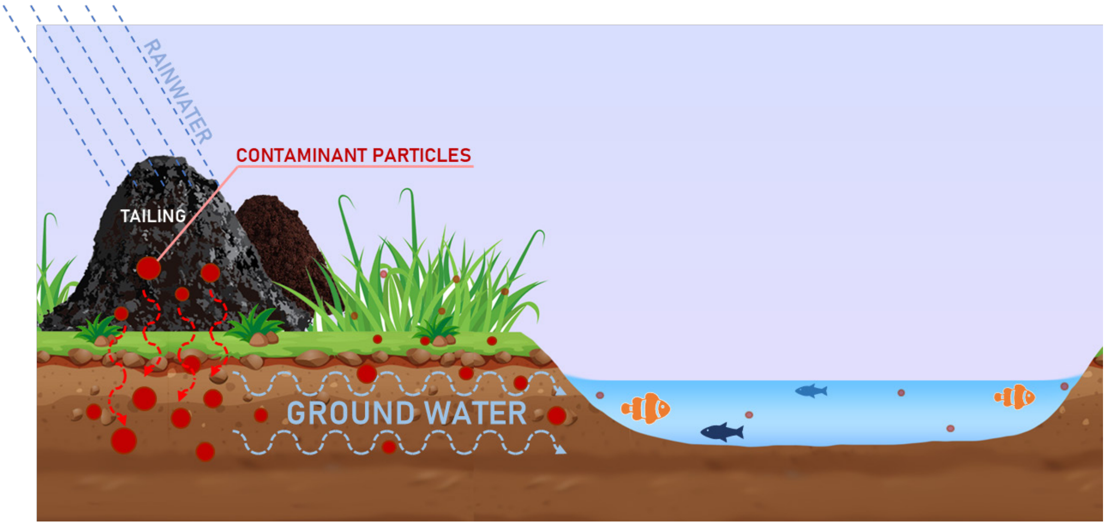

FIGURE 3. Spreading of contaminants into different mediums

A consequence of the establishment of the exemption order is leniency towards radiation safety alertness of the plant owners and workers throughout the industry. This could be seen in the lack of monitoring systems in most processing plants in the country. This was highlighted in a study done by Hewson (1996), stating the need for both monitoring systems as well as the provision of personal safety equipment among industrial personnel which was supported by recent studies (Muhammad Abdullah et al. 2022). Figure 4 illustrates this fact as it could be seen that the industrial personnel were not equipped with proper safety gear during operations involving very fine particles containing elevated concentrations of NORM.

PROMISING DEVELOPMENTS IN ENVIRONMENTAL REMEDIATION ACTIONS

With the new revocation order enacted, the tailing processing industry is expected to undergo significant changes in the coming years. Though that may be, the industry must first address the soil contamination issue before new changes could produce any meaningful effect. In this aspect, the Malaysian Department of Environment (DOE) released 3 guidelines concerning Contaminated Land Management in 2009 (Department of Environment Malaysia 2009a, 2009b, 2009c). Since then, there have been significant research and development efforts relating to soil rehabilitation actions as well as waste and residue management. This section of the study aims to highlight said improvements which could be implemented in the TP industry.

Topsoil Layering and Dilution

In the third addition to the ‘Contaminated Land Management and Control’ guideline series, the DOE recommended the complete excavation of contaminated soil layers as a viable form of soil remediation (Department of Environment Malaysia 2009a). Said method is effective in removing most if not all, of the affected soil from the remediated site (Hinrichsen et al. 2021; Khalid et al. 2017; Roed et al. 2006). However, under certain circumstances, the complete removal of the contaminated soil may not be necessary; exposure risk from light to moderate levels of contamination could potentially be reduced with the partial replacement of new soil or the introduction of a new layer of clean soil atop the initial layer.

A simulation study conducted by Ziajahromi, Khanizadeh and Nejadkoorki (2014) reported that the increase in thickness of a clean cover soil layer up to 100 cm could reduce the initial estimated effective dose of 107.0 $mSvy^{-1}$ to 0.002 $mSvy^{-1}$. Said findings were supported by a study conducted by Muhammad Abdullah et al. (2023) who reported that the addition of 0.2 m of cover soil has the potential to reduce the AEDE of industrial workers up to 23.8-30.5%.

A recent study also discussed the viability and advantages of contaminated soil dilution as opposed to removal as it would be significantly more cost-effective than soil stabilization/solidification techniques while having a more immediate effect as compared to phytoremediation or bioremediation techniques (Hou 2021). The study must emphasize however that


(a) (b)

FIGURE 4. Lack of personal protection equipment and monitoring devices during operations in both (a) and (b)

these techniques are more suitable for immediate to intermediate remediation actions as there are disadvantages associated with the long-term applications; among these disadvantages is the leaching and migration of contaminations vertically, endangering the spread of the contamination zone via groundwater flow and channels as elaborated prior.

Soil Stabilization and Solidification

The concept of soil stabilization and solidification revolves around the primary principle of the immobilization of contaminant substances in the soil. In essence, soil stabilization involved the incorporation of a mixture that reduces the contaminant mobility by making it less soluble. While solidification involves a binder that immobilizes contaminants by physically binding and hardening all contaminated soil components (Ahmad Tajudin, Mohammad Azmi & Ain Nabila 2016; Falciglia et al. 2014).

The most common application of this technique is cementation where cement is used to immobilize all contaminants by being allowed to harden (Ahmad Tajudin, Mohammad Azmi & Ain Nabila 2016; Falciglia et al. 2014; Gou, Zhou & Then 2019). A detailed study conducted by Lal and Fronczyk (2022) listed the functionality of alternative binders that could be used in this technique with most being industrial waste that could be easily obtainable and repurposed for remediation applications.

The concept of cementation is currently being explored further by applying incorporating the contaminated or residue material (such as tailing residue) in the mixture and using it as backfill material in mined-out dig sites and pits. This application offers several benefits as the otherwise hazardous material can be stored safely from where it was mined while acting as a support structure in potentially subsidence areas (Wu 2020). The cement and binder in the backfill mixture will immobilize any contaminants contained in it, posing little to no environmental contamination hazard once hardened (Qi & Fourie 2019; Zhang et al. 2021; Zhao, Fourie & Qi 2020).

Bioremediation and Phytoremediation

Amongst the three plausible remediation methods proposed by the study, both bioremediation and phytoremediation are the most complex and delicate as it requires specific bio-organisms to grow and thrive to observe significant results. Both methods use the concept of employing natural biological processing in reducing the concentration of contaminants in a medium with the difference being bioremediation primarily uses microorganisms while phytoremediation involves plants (Lloyd & Renshaw 2005; Lourenço, Mendo & Pereira 2019; Vishwakarma et al. 2020).

In bioremediation, the microorganism-contaminant interaction primarily involves the dissolution and immobilization of contaminants in the medium be it directly or indirectly. Direction interactions involve the biosorption of the contaminants into the microbe which will consequently reduce or oxidize said contaminant depending on the type of contaminant and microbe involved. Indirect microbial interactions primarily involve the dissolution of contaminants via the resulting acids produced from microbial interactions with other components in the medium content (Francis & Nancharaiah 2015; Lloyd & Renshaw 2005).

Prior studies on the subject matter reported that the interaction of specific microbial species with NORM and heavy metals contaminants could increase environmental remediation effectiveness by either increasing or decreasing the mobility of contaminants. This increases the selective segregation of contaminants from the medium, allowing the removal of said materials via natural or man-made processes. Table 6 summarises the findings reported by prior studies in the past two decades highlighting the biomechanism interactions between the affected contaminant and the studied microbe species. Though the technique is still in development, prior studies have shown the potential general feasibility in both in-situ as well as ex-situ studies.

TABLE 6. Microorganism interaction with contaminant elements in environmental mediums

Affected elements	Fungi/Bacterium	Interaction	References
Uranium	*Thiobacillus ferrooxidans*	Dissolution	(Francis & Nancharaiah 2015; Lourenço, Mendo & Pereira 2019; Roh, Kang & Lloyd 2015)
	Micrococcus lactilyticus	Immobilization	
	Clostridium sp.	Immobilization	
	Geobacter metallireducens	Immobilization	
	Shewanella oneidensis	Immobilization	
	Clostridium sp.	Immobilization	
	Desulfovibrio desulfuricans	Immobilization	
	Desulfovibrio vulgaris	Immobilization	
	Thiobacillus thiooxidans	Immobilization	
	Serratia sp.	Biomineralization	(Francis & Nancharaiah 2015)
Radium	*Desulfovibrio vulgaris* + $BaSO_4$	Immobilization	
Thorium	*Pseudomonas*	Biosorption	
	Rhizopus arrhizus	Biosorption	
	Aspergillus niger	Biosorption	
	Aspergillus ficuum	Biosorption	
	Sargassum filipendula	Biosorption	
	Bradyrhizobium (Chamaecytisus)	Immobilization	
	Micrococcus luteus	Biosorption	
Cadmium	*Bacillus cereus*	Dissolution	(Chibuike & Obiora 2014; González Henao & Ghneim-Herrera 2021; Mohideen et al. 2010)
	Bacillus thuringiensis	Dissolution	
	Desulfovibrio desulfuricans	Immobilization	
Zinc	*Bacillus cereus*	Dissolution	(Chibuike & Obiora 2014; Mohideen et al. 2010)
	Bacillus thuringiensis	Dissolution	
	Desulfovibrio desulfuricans	Immobilization	
Nickle	*Bacillus cereus*	Dissolution	(Mohideen et al. 2010)
	Bacillus thuringiensis	Dissolution	
Chromium	*Bacillus subtilis*	Immobilization	(Chibuike & Obiora 2014)
	Pseudomonas putida	Immobilization	
	Enterobacter cloacae	Immobilization	

On the other hand, the principle of phytoremediation revolves around the exploitation of certain plants' ability to absorb and uptake certain amounts of heavy metal and radioactive contaminants (Lorenzo-González et al. 2019). Studies in the past two decades have highlighted the potential of specific plant species (such as *Brassica juncea, Zea mays, Dryopteris scottii, Helianthus annuus, Phaseolus acutifolius, Beta vulgaris,* and *Medicago truncatula*) has the potential to accumulate radium and uranium into their system, essentially removing said radionuclides from the soil (Chibuike & Obiora 2014; Francis & Nancharaiah 2015; Hu et al. 2014). In addition to this, local studies conducted in the past decade have also reported several plant species that show positive indications to be used as an accumulator for toxic heavy metals as shown in Table 7. This is exceedingly beneficial as TP activities also tend to cause significant heavy metal contaminations (Muhammad Abdullah et al. 2021). Additionally, studies have also indicated that the combination of both bioremediation and phytoremediation produces a beneficial synergy between the two organisms which increases the effectiveness of the accumulation of contaminants in the affected medium without posing harm to the surrounding ecosystem; the direct dissolution of contaminants via microbe biosorption allows the material to be absorbed by the plant, increasing the rate of soil-to-plant transfer of the contaminants (Chibuike & Obiora 2014; Lourenço, Mendo & Pereira 2019).

Despite the potential of both remediation techniques, however, it must be noted that more long-term *in-situ* experimentations that extensively study the synergy of both the bioremediation as wells as the phytoremediation component must be conducted before any measure of permanent implementation could be conducted be it in the TP or any other industries (González Henao & Ghneim-Herrera 2021; Lourenço, Mendo & Pereira 2019).

WAY FORWARD OF THE TAILING INDUSTRY POST-REVOCATION ENACTMENT

With the viable options in remediation actions highlighted, the industry could then begin moving towards aligning itself with the regulations under Act 304. That being said, however, remediation actions will differ from one processing plant to another as certain parameters and circumstances will require different approaches; these parameters include the status of operation of the said plant, degree of soil contamination and future development plans of the plot of land currently occupied by the plant. Taking these parameters into consideration, the study proposes a new approach that also takes into account processing plants and sites that have been left abandoned over the years as shown in Figure 5. This approach will not only allow involved parties to individually gauge potentially viable options moving forwards but also to guide future prospectors be it from the same industry or others.

TABLE 7. Plant species suitable for phytoremediation of heavy metals in tailing and mining sites

Study site	Fungi/Bacterium	Affected elements	References
Ex-tin Mine (Malaysia)	*Acacia mangium*	Pb	(Ang et al. 2010)
	Hopea odorata	Pb Cd	
	Intsia palembanica	Pb Cd	
Ex-Copper Mine (Malaysia)	*Typha angustifolia*	Cd, Cr, Cu, Fe, Ni, Pb and Zn	(Yen & Kartini 2013)
Ex-tin Mining Catchmen (Malaysia)	*Pteris vittata*	Pb	(Muhammad Aqeel, Mohd Jamil & Ismail 2013)
	Phragmites australi	Cu	
	Nelumbo nucifera	As	
	Imperata cylindrica	Zn	
TP processing Plant (Malaysia)	*Acacia mangium*	Zn, As	(Ahmad & Jeyanny 2018)

The study segregates these remediation routes into phases of immediate, intermediate and long-term remediation routes based on specific parameters. The study begins by first taking into account the status of operation of the remediation-intended processing plant. For operable processing plants, the remediation actions to be implemented must cause as little production disruption as possible. In scenarios such as this, the study speculates the employment of topsoil mixing followed by soil stabilization would have an immediate effect in reducing both contaminant concentration and mobility. Optionally, bioremediation methods could also be followed up to further reduce contaminant mobility for future treatment if necessary.

Alternatively, for the processing plant to be shut down with no future development plants or abandoned sites, phytoremediation would be the most efficient and cost-effective method to be used as it does not require extensive human intervention and treatment once a self-sufficient ecosystem is established. From there, periodical monitoring will be necessary to determine whether minor adjustments are required. This route is classified under the long-term remediation route as a significant time elapse is needed to observe any meaningful effects.

The intermediate remediation route is primarily for sites that are to be closed to be reused for other developments that are not related to any NORM-related industry. This is because any development intended for civilian use requires the dose exposure limit to be below 1 mSv/y. Hence a more intensive remediation effort is required to meet this criterion. Thus, the study speculates that the most suitable method of remediation for this route is to employ both topsoil replacement and soil solidification. This allows most of the contaminants to be removed while immobilizing the ones below. Additionally, solidification via cementation could also act as a good shielding material to help reduce residual NORM exposure of the contaminants that are not successfully removed during the initial topsoil replacement process.

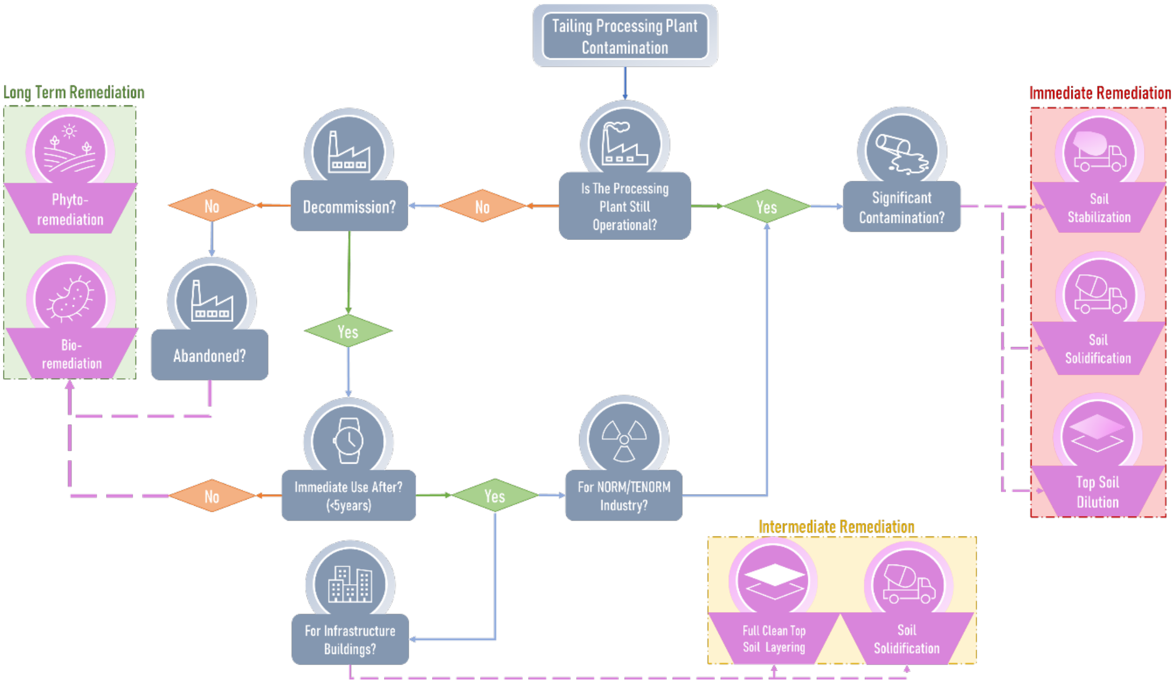

FIGURE 5. Decision assessment for remediation actions to be taken

CONCLUSIONS

Tin TP activities that have been operating for decades have been found to have a negative radiological impact on the environment and workers in the industry where radiological contamination can be detected in the processing area. The research found that the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were in the range of 0.31- 4.97 Bqg^{-1} and 1.24- 4.47 Bqg^{-1}, 0.16- 11.07 Bqg^{-1} and 1.08- 8.56 Bqg^{-1}, 0.22- 1.24 and 0.18^{-1}.32 Bqg^{-1} for soil and tailing samples. Radiological impact assessments conducted showed that Ra$_{eq}$, and D values have exceeded the UNCSEAR recommended values while the AEDE exceeded the local regulatory limit for members of the public, indicating the presence of potential overexposure. These potentially hazardous values could be attributed to the enacted of the old exemption order which allowed the industry to disregards key components of radiation safety and waste management. With the implementation of the new revocation order, hence binding all processing plants to the regulation of Act 304, significant changes and adjustments must first be made beginning with the remediation efforts. The study proposes the employment of three primary remediation methods which the study deems to be most suitable in the removal of contaminants while causing minimal industrial disruption, all while being economically feasible.

REFERENCES

Abdel-Razek, Y.A., Desouky, O.A., Elshenawy, A., Nasr, A.S., Mohammed, H.S. & Elsayed, A.A. 2016. Assessment of the radiation exposures during separation of rare earth elements from monazite mineral. *International Journal of Advanced Research* 4(4): 144-149. doi:10.21474/IJAR01

AELB. 2010. *Atomic Energy Licensing Act 1984, (Basic Safety Radiation Protection) Regulation 2010*. Atomic Energy Licensing Act 1984.

AELB. 1994. *Perintah Perlesenan Tenaga Atom (Kilang Amang Kecil) (Pengecualian) 1994*. Akta Perlesenan Tenaga Atom 1984.

Ahmad Fauzan, Y., Jasmi Hafiz, A.A. & Muhammad Hatta, R. 2022. Mineralogy and geochemistry of gold mineralization at Southern Part of Ulu Sokor Gold Deposit, Kelantan, Malaysia. *Sains Malaysiana* 51(12): 3865-3877. doi:10.17576/jsm-2022-5112-01

Ahmad Tajudin, S.A., Mohammad Azmi, M.A. & Ain Nabila. 2016. Stabilization/solidification remediation method for contaminated soil: A review. *IOP Conference Series: Materials Science and Engineering* 136(1): 012043. doi:10.1088/1757-899X/136/1/012043

Ahmad, Z.Y. & Jeyanny, V. 2018. Phytoremediation of heavy metals using *Acacia mangium* in Rahman Hydraulic Tin (RHT) Tailings, Klian. *Advances in Plants & Agriculture Research* 8(3): 247-249. doi:10.15406/apar.2018.08.00322

Al-Areqi, W.M., Che Nor Aniza Che Zainul Bahri, Amran Ab. Majid & Sukiman Sarmani. 2016. Separation and radiological impact assessment of thorium in Malaysian Monazite Processing. *Malaysian Journal of Analytical Sciences* 20(4): 770-776. doi:10.17576/mjas-2016-2004-09

Ali, M.M.M., Zhao, H., Li, Z. & Maglas, N.N.M. 2019. Concentrations of TENORMs in the petroleum industry and their environmental and health effects. *RSC Advances* 9(67): 39201-39229. doi:10.1039/c9ra06086c

Alnour, I.A., Wagiran, H., Ibrahim, N., Hamzah, S. & Elias, M.S. 2017. Determination of the elemental concentration of uranium and thorium in the products and by-products of amang tin tailings process. *AIP Conference Proceedings* 1799. doi:10.1063/1.4972913

Ang, L.H., Tang, L.K., Ho, W.M., Hui, T.F. & Theseira, G.W. 2010. Phytoremediation of Cd and Pb by four tropical timber species grown on an ex-tin mine in Peninsular Malaysia. *World Academy of Science, Engineering and Technology* 62(2): 244-248.

Aslam, S., Yousafzai, A.M. & Javed, A. 2022. Bioaccumulation of hexavalent chromium in commercially edible fish grass carp, *Ctenopharyngodon idella. Sains Malaysiana* 51(9): 2757-2762. doi:10.17576/jsm-2022-5109-02

Atipo, M., Olarinoye, O. & Awojoyogbe, B. 2020. Comparative analysis of NORM concentration in mineral soils and tailings from a tin-mine in Nigeria. *Environmental Earth Sciences* 79(16): 1-17. doi:10.1007/s12665-020-09136-7

Atipo, M., Olarinoye, O., Awojoyogbe, B. & Kolo, M. 2020. High terrestrial radiation level in an active tin-mine at Jos South, Nigeria high terrestrial radiation level in an active tin-mine at Jos South, Nigeria. *Journal of Applied Sciences and Environmental Management* 24(3): 435-442. doi:10.4314/jasem.v24i3.6

Azlina, M.J., Ismail, B., Samudi Yasir, M., Syed Hakimi Sakuma & Khairuddin, M.K. 2003. Radiological impact assessment of radioactive minerals of amang and ilmenite on future landuse using RESRAD computer code. *Applied Radiation and Isotopes* 58(3): 413-419. doi:10.1016/S0969-8043(02)00347-0

Belyaeva, O., Pyuskyulyan, K., Movsisyan, N., Saghatelyan, A. & Carvalho, F.P. 2019. Natural radioactivity in urban soils of mining centers in Armenia: Dose rate and risk assessment. *Chemosphere* 225: 859-870. doi:10.1016/j.chemosphere.2019.03.057

Canberra. 2000. *Genie ™ 2000 Spectroscopy Software.*

Chibuike, G.U. & Obiora, S.C. 2014. Heavy metal polluted soils: Effect on plants and bioremediation methods. *Applied and Environmental Soil Science* 2014: Article ID. 752708. doi:10.1155/2014/752708

Conceição, F., Catuane, F., Taímo, S., Carvalho, F.P., Oliveira, J.M. & Malta, M. 2018. Radiological assessment of heavy-mineral sand exploitation in Mozambique. In *Naturally Occurring Radioactive Material (NORM VIII). Proceedings of an International Symposium*. pp. 244-247.

Department of Environment Malaysia. 2009a. *Contaminated Land Management and Control Guidelines No. 3: Remediation of Contaminated Sites*. Vol. 3.

Department of Environment Malaysia. 2009b. *Contaminated Land Management and Control Guidelines No. 1*: Malaysian Recommended Site Screening Levels for Contaminated Land.

Department of Environment Malaysia. 2009c. *Contaminated Land Management and Control Guidelines No. 2*: Assessing and Reporting Contaminated Sites. No. 2: 48.

Falciglia, P.P., Cannata, S., Romano, S. & Vagliasindi, F.G.A. 2014. Stabilisation/solidification of radionuclide polluted soils - Part I: Assessment of setting time, mechanical resistance, γ-radiation shielding and leachate γ-radiation. *Journal of Geochemical Exploration* 142: 104-111. doi:10.1016/j.gexplo.2014.01.016

Francis, A.J. & Nancharaiah, Y.V. 2015. *In situ* and *ex situ* bioremediation of radionuclide-contaminated soils at nuclear and norm sites. *Environmental Remediation and Restoration of Contaminated Nuclear and Norm Sites*. pp. 185-236. doi:10.1016/B978-1-78242-231-0.00009-0

Friedmann, H., Nuccetelli, C., Michalik, B., Anagnostakis, M., Xhixha, G., Kovler, K., de With, G., Gascó, C., Schroeyers, W., Trevisi, R., Antropov, S., Tsapalov, A., Kunze, C & Petropoulus, N.P. 2017. Measurement of NORM. In *Naturally Occurring Radioactive Materials in Construction: Integrating Radiation Protection in Reuse*, edited by Schroyers, W. Woodhead Publishing. pp. 61-133. doi:10.1016/B978-0-08-102009-8.00005-0

García-Tenorio, R., Sanz, E., Burkhalter, E., Manjón, G., Vioque, I. & Diaz, I. 2018. Radiological evaluation of monazite mining in central Spain. In *Naturally Occurring Radioactive Material (NORM VIII). Proceedings of an International Symposium*. pp. 220-224.

González Henao, S. & Ghneim-Herrera, T. 2021. Heavy metals in soils and the remediation potential of bacteria associated with the plant microbiome. *Frontiers in Environmental Science* 9(April): 1-17. doi:10.3389/fenvs.2021.604216

Gou, M., Zhou, L. & Then, N.W.Y. 2019. Utilization of tailings in cement and concrete: A review. *Science and Engineering of Composite Materials* 26(1): 449-464. doi:10.1515/secm-2019-0029

Gunawan, O., Pudjadi, E., Musbach, M. & Wahyudi. 2019. Technologically Enchanced Naturally Occurring Radioactive Materials (TENORM) analysis of Bangka *Tin Slag*. *Journal of Physics: Conference Series* 1198: 022006. doi:10.1088/1742-6596/1198/2/022006

Hewson, G.S. 1996. Overview of radiation safety in the tin by-product (amang) industry of South East Asia. *Health Physics* 71(2): 225-234. doi:10.1097/00004032-199608000-00016

Hinrichsen, Y., Finck, R., Martinsson, J. & Rääf, C. 2021. Maximizing avertable doses with a minimum amount of waste for remediation of land areas around typical single family houses after radioactive fallout based on Monte Carlo simulations. *Scientific Reports* 11(1): 1-9. doi:10.1038/s41598-021-84103-1

Hou, D. 2021. Sustainable remediation in China: Elimination, immobilization, or dilution. *Environmental Science and Technology* 55(23): 15572-15574. doi:10.1021/acs.est.1c06044

Hu, N., Ding, D., Li, G., Zheng, J., Li, L., Zhao, W. & Wang, Y. 2014. Vegetation composition and 226Ra uptake by native plant species at a uranium mill tailings impoundment in South China. *Journal of Environmental Radioactivity* 129: 100-106. doi:10.1016/j.jenvrad.2013.12.012

IAEA. 1989. *Measurement of Radionuclides in Food and the Environment. A Guidebook*. Technical Report No. 295. doi:10.1016/0265-931x(90)90062-z

Ibeanu, I.G.E. 2003. Tin mining and processing in Nigeria: Cause for concern? *Journal of Environmental Radioactivity* 64(1): 59-66. www.elsevier.com/locate/jenvrad.

Ismail, B., Teng, I.L. & Muhammad Samudi, Y. 2011. Relative radiological risks derived from different TENORM wastes in Malaysia. *Radiation Protection Dosimetry* 147(4): 600-607. doi:10.1093/rpd/ncq577

Ismail, B., Yasir, M.S., Redzuwan, Y. & Amran, A.M. 2003. Radiological environment risk associated with different water system in amang factory. *Pakistan Journal of Biological Science* 6(17): 1544-1547.

Jumaat, A.H. & Ab Hamid, S. 2023. Monitoring heavy metal bioaccumulation in rivers using damselflies (Insecta: Odonata, Zygoptera) as biological indicator. *Sains Malaysiana* 52(2): 321-331. doi:10.17576/jsm-2023-5202-01

Khalid, S., Shahid, M., Niazi, N.K., Murtaza, B., Bibi, I. & Dumat, C. 2017. A comparison of technologies for remediation of heavy metal contaminated soils. *Journal of Geochemical Exploration* 182: 247-268. doi:10.1016/j.gexplo.2016.11.021

Kolo, M.T., Siti Aishah Binti Abdul Aziz, Khandaker, M.U., Asaduzzaman, K. & Mohd Amin, Y. 2015. Evaluation of radiological risks due to natural radioactivity around Lynas Advanced Material Plant environment, Kuantan, Pahang, Malaysia. *Environmental Science and Pollution* 22(17): 13127-13136. doi:10.1007/s11356-015-4577-5

Kontol, K.M., Ahmad, S.H.S.S. & Omar, M. 2007. *Radiological Impact Assessment for Landfill Disposal of NORM Wastes in Malaysia*. IAEA.

Lal, A. & Fronczyk, J. 2022. Does current knowledge give a variety of possibilities for the stabilization/solidification of soil contaminated with heavy metals? - A review. *Materials* 15(23): 8491. doi:10.3390/ma15238491

Lee, S.K., Husin Wagiran, Ahmad Termizi Ramli, Nursama Heru Apriantoro & A. Khalik Wood. 2009. Radiological monitoring: Terrestrial natural radionuclides in Kinta District, Perak, Malaysia. *Journal of Environmental Radioactivity* 100(5): 368-374. doi:10.1016/j.jenvrad.2009.01.001

Li, B., Wang, N., Wan, J., Xiong, S., Liu, H., Li, S. & Zhao, R. 2016. *In-situ* gamma-ray survey of rare-earth tailings dams - A case study in Baotou and Bayan Obo Districts, China. *Journal of Environmental Radioactivity* 151: 304-310. doi:10.1016/j.jenvrad.2015.10.027

Liu, H. & Pan, Z. 2012. NORM situation in non-uranium mining in China. *Annals of the ICRP* 41(3-4): 343-351. doi:10.1016/j.icrp.2012.06.015

Lloyd, J.R. & Renshaw, J.C. 2005. Bioremediation of radioactive waste: radionuclide - microbe interactions in laboratory and field-scale studies. *Current Opinion in Biotechnology* 16(3): 254-260. doi:10.1016/j.copbio.2005.04.012

Lorenzo-González, M., Ruano-Ravina, A., Torres-Durán, M., Kelsey, K.T., Provencio, M., Parente-Lamelas, I., Leiro-Fernández, V., Vidal-García, I., Castro-Añón, O., Martínez, C., Golpe-Gómez, A., Zapata-Cachafeiro, M., Piñeiro-Lamas, M., Pérez-Ríos, M., Abal-Arca, J., Montero-Martínez, C., Fernández-Villar, A. & Barros-Dios, J.M. 2019. Lung cancer and residential radon in never-smokers: A pooling study in the northwest of Spain. *Environmental Research* 172: 713-718. doi:10.1016/j.envres.2019.03.011

Lourenço, J., Mendo, S. & Pereira, R. 2019. Rehabilitation of radioactively contaminated soil: Use of bioremediation/phytoremediation techniques. In *Remediation Measures for Radioactively Contaminated Areas*, edited by Gupta, D. & Voronina, A. Springer: Cham. doi:10.1007/978-3-319-73398-2_8

Mohideen, A.H., Thirumalai Arasu, R., Narayanan, V. & Zahir Hussain, M.I. 2010. Bioremediation of heavy metal contaminated soil by the exigobacterium and accumulation of Cd, Ni, Zn and Cu from soil environment. *International Journal of Biological Technology* 1(2): 94-101.

Muhammad Abdullah Rahmat, Aznan Fazli Ismail, Nursyamimi Diyana Rodzi, Eli Syafiqah Aziman, Syazwani Mohd Fadzil, Norsyahidah Mohd Hidzir, Mohd Idzat Idris, Irman Abdul Rahman & Faizal Mohamed. 2023. A window into the future: Case study of long-term radiological risk modelling posed by unregulated mining waste repurposing activities. *Environmental Monitoring and Assessment*. Springer International Publishing, 1-18. doi:10.1007/s10661-023-11308-4

Muhammad Abdullah Rahmat, Aznan Fazli, Eli Syafiqah, Nursyamimi Diyana, Faizal Mohamed & Irman Abdul Rahman. 2022. The impact of unregulated industrial tin-tailing processing in Malaysia: Past, present and way forward. *Resources Policy* 78: 102864. doi:10.1016/j.resourpol.2022.102864

Muhammad Abdullah Rahmat, Aznan Fazli Ismail, Nursyamimi Diyana Rodzi, Eli Syafiqah Aziman, Wan Mohd Razi Idris & Tukimat Lihan. 2021. Assessment of natural radionuclides and heavy metals contamination to the environment: Case study of Malaysian unregulated tin-tailing processing industry. *Nuclear Engineering and Technology* 54(6): 2230-2243. doi:10.1016/j.net.2021.12.013

Muhammad Aqeel Ashraf, Mohd Jamil Maah & Ismail Yusoff. 2013. Evaluation of natural phytoremediation process occurring at ex-tin mining catchment. *Chiang Mai Journal of Science* 40(2): 198-213.

Nasirian, M., Ismail, B. & Abdullah, P. 2008. Assessment of natural radioactivity in water and sediment from amang (tin tailing) processing ponds. *The Malaysian Journal of Analytical Sciences* 12(1): 150-159.

Nurrul Assyikeen Md. Jaffary, Kok Siong Khoo, Nor Hasimah Mohamed, Mohd Abd Wahab Yusof & Syazwani Mohd Fadzil. 2019. Malaysian Monazite and its processing residue: Chemical composition and radioactivity. *Journal of Radioanalytical and Nuclear Chemistry* 322: 1097-1105. doi:10.1007/s10967-019-06813-1

Omar, M., Sulaiman, I., Hassan, A. & Wood, A.K. 2007. Radiation dose assessment at amang processing plants in Malaysia. *Radiation Protection Dosimetry* 124(4): 400-406. doi:10.1093/rpd/ncm212

Permana, S., Soedarsono, J.W., Rustandi, A., Maksum, A., Widana, K.S., Trinopiawan, K. & Anggraini, M. 2018. The enhancement of uranium and thorium in Bangka *Tin Slag*. *Atom Indonesia* 44(1): 37-42. doi:10.17146/aij.2018.529

Qi, C. & Fourie, A. 2019. Cemented paste backfill for mineral tailings management: Review and future perspectives. *Minerals Engineering* 144: 106025. doi:10.1016/j.mineng.2019.106025

Qureshi, A.A., Tariq, S., Ud Din, K., Manzoor, S., Calligaris, C. & Waheed, A. 2014. Evaluation of excessive lifetime cancer risk due to natural radioactivity in the rivers sediments of northern Pakistan. *Journal of Radiation Research and Applied Sciences* 7(4): 438-447. doi:10.1016/j.jrras.2014.07.008

Roed, J., Andersson, K.G., Barkovsky, A.N., Fogh, C.L., Mishine, A.S., Ponamarjov, A.V. & Ramzaev, V.P. 2006. Reduction of external dose in a wet-contaminated housing area in the Bryansk Region, Russia. *Journal of Environmental Radioactivity* 85(2-3): 265-279. doi:10.1016/j.jenvrad.2004.03.039

Roh, C., Kang, C.K. & Lloyd, J.R. 2015. Microbial bioremediation processes for radioactive waste. *Korean Journal of Chemical Engineering* 32(9): 1720-1726. doi:10.1007/s11814-015-0128-5

Sanusi, M.S.M., Ramli, A.T., Hashim, S. & Lee, M.H. 2021. Radiological hazard associated with amang processing industry in Peninsular Malaysia and its environmental impacts. *Ecotoxicology and Environmental Safety* 208: 111727. doi:10.1016/j.ecoenv.2020.111727

Schoenberger, E. 2016. Environmentally sustainable mining: The case of tailings storage facilities. *Resources Policy* 49: 119-128. doi:10.1016/j.resourpol.2016.04.009

Shittu Abdullahi, Aznan Fazli Ismail & Supian Samat 2019. Determination of indoor doses and excess lifetime cancer risks caused by building materials containing natural radionuclides in Malaysia. *Nuclear Engineering and Technology* 51(1): 325-336. doi:10.1016/j.net.2018.09.017

Shittu Abdullahi, Aznan Fazli Ismail & Muhamad Samudi Yasir. 2020. Radioactive investigation of Malaysia's building materials containing NORM and potential radiological risks analysis using RESRAD-BUILD computer code. *International Journal of Environmental Analytical Chemistry* 102(9): 2000-2012. doi:10.1080/03067319.2020.1746778

Shittu Abdullahi, Aznan Fazli Ismail, Supian Samat & Muhamad Samudi Yasir. 2018. Assessment of natural radioactivity and associated radiological risks from tiles used in Kajang, Malaysia. *AIP Conference Proceedings* 1940. doi:10.1063/1.5027916

Solehah, A.R. & Samat, S.B. 2018. Radiological impact from natural radionuclide activity concentrations in soil and vegetables at former tin mining area and non-mining area in Peninsular Malaysia. *Journal of Radioanalytical and Nuclear Chemistry* 315(2): 127-136. doi:10.1007/s10967-017-5654-7

Syarbaini, Warsona, A. & Iskandar, D. 2014. Natural radioactivity in some food crops from Bangka-Belitung Islands, Indonesia. *Atom Indonesia* 40(1): 27-32. doi:10.17146/aij.2014.260

Thoburn, J.T. 1994. The tin industry since the collapse of the international tin agreement. *Resources Policy* 20(2): 125-133. doi:10.1016/0301-4207(94)90025-6

UNSCEAR. 2000. Sources and effects of ionizing radiation, United Nations Scientific Committee on the effects of atomic radiation UNSCEAR 2000 report to the General Assembly. *UNSCEAR Report* I: 1-556.

Vishwakarma, G.S., Bhattacharjee, G., Gohil, N. & Singh, V. 2020. Current status, challenges and future of bioremediation. *Bioremediation of Pollutants*. pp. 403-415. INC. doi:10.1016/B978-0-12-819025-8.00020-X

Wu, D. 2020. Traditional treatment of mine waste. In *Mine Waste Management in China: Recent Development*. Singapore: Springer. doi:10.1007/978-981-32-9216-1.

Yen, L.V. & Kartini, S. 2013. Phytoremediation using *Typha angustifolia* L. for mine water effluence treatment: Case study of ex-mamut copper mine, Ranau, Sabah. *Borneo Science* 33: 16-22.

Zaidan Kandar, M. & Bahari, I. 1996. Radiation-induced chromosomal aberrations among TENORM workers: Amang- and ilmenite-processing workers of Malaysia. *Mutation Research - Fundamental and Molecular Mechanisms of Mutagenesis* 351(2): 157-161. doi:10.1016/0027-5107(95)00174-3

Zhang, Q., Zhang, B., Chen, Q., Wang, D. & Gao, X. 2021. Safety analysis of synergetic operation of backfilling the open pit using tailings and excavating the ore deposit underground. *Minerals* 11(8): 818. doi:10.3390/min11080818

Zhao, X., Fourie, A. & Qi, C.C. 2020. Mechanics and safety issues in tailing-based backfill: A review. *International Journal of Minerals, Metallurgy and Materials* 27(9): 1165-1178. doi:10.1007/s12613-020-2004-5

Ziajahromi, S., Khanizadeh, M. & Nejadkoorki, F. 2014. Total effective dose equivalent assessment after exposure to high-level natural radiation using the RESRAD code. *Environmental Monitoring and Assessment* 186(3): 1907-1915. doi:10.1007/s10661-013-3504-9

*Corresponding author; email: aznan@ukm.edu.my

SUPPLEMENTARY MATERIAL

S1. Dose estimation summary for indoor and outdoor D, AEDE, ELCR

Processing plant	Sample code	D (nGyhr^{-1})		AEDE (mSvy^{-1})		ELCR (10^{-3})	
		D_{in}	D_{out}	$AEDE_{in}$	$AEDE_{out}$	$ELCR_{in}$	$ELCR_{out}$
PP1	Soil	520.5 ± 417.4	259.1 ± 207.0	2.6 ± 2.1	0.3 ± 0.3	9.8 ± 7.9	1.2 ± 1.0
	Tailing	3466.1 ± 2350.8	1704.8 ± 1115.0	17.0 ± 11.5	2.1 ± 1.4	65.5 ± 44.4	8.1 ± 5.3
PP2	Soil	3347.2 ± 714.2	1714.1 ± 370.9	16.4 ± 3.5	2.1 ± 0.5	63.3 ± 13.5	8.1 ± 1.8
	Tailing	8060.01 ± 5814.3	4180.6 ± 3104.3	39.6±28.6	5.1 ± 3.8	152.4 ± 109.9	19.8 ± 14.7
PP3	Soil	16837.8 ± 6309.7	8911 ± 3487.8	82.7 ± 31.0	11.0 ± 4.3	318.3 ± 119.3	42.2±16.5
	Tailing	13707 ± 11065.6	7165.2 ± 5860.2	67.3 ± 54.3	8.8 ± 7.2	259.1 ± 209.2	33.9 ± 27.8
PP4	Soil	3219.4 ± 584.2	1644.3 ± 322.4	15.8 ± 2.9	2.0 ± 0.4	60.9 ± 11.0	7.8 ± 1.5
	Tailing	4400.16 ± 9.4	2218.9 ± 2513.7	21.6 ± 24.4	2.7 ± 3.1	83.2 ± 93.8	10.5 ± 11.9
PP5	Soil	1237.8 ± 1727.0	633.3 ± 889.4	6.1 ± 8.5	0.8±1.1	23.4 ± 32.7	3.0 ± 4.2
	Tailing	2434.86 ± 2238.7	1236.8 ± 1150.6	12.1 ± 10.9	1.5 ± 1.4	46.0 ± 42.3	5.9 ± 5.5