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RESEARCH ARTICLE

Evaluation of radiological risks due to natural radioactivity around Lynas Advanced Material Plant environment, Kuantan, Pahang, Malaysia

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Abstract Understanding the public awareness concerning the Lynas Advanced Material Plant (LAMP), an Australian rare earths processing plant located in Malaysia, a radiological study in soil and water samples collected at random surrounding the LAMP environment was undertaken using HPGe gamma-ray spectrometry. The mean soil activities for ^{226}Ra, ^{232}Th, and ^{40}K were found to be 6.56±0.20, 10.62±0.42, and 41.02±0.67 Bq/kg, respectively, while for water samples were 0.33±0.05, 0.18±0.04, and 4.72±0.29 Bq/l, respectively. The studied areas show typical local level of radioactivity from natural background radiation. The mean gamma absorbed dose rate in soils at 1 m above the ground was found to be 11.16 nGy/h. Assuming a 20 % outdoor occupancy factor, the corresponding annual effective dose showed a mean value of 0.014 mSv year^{-1}, significantly lower than the worldwide average value of 0.07 mSv year^{-1} for the annual outdoor effective dose as reported by UNSCEAR (2000). Some other representative radiation indices such as activity utilization index (AUI), H_{ex}, H_{in}, excess lifetime cancer risk (ELCR), and annual gonadal dose equivalent (AGDE) were derived and also compared with the world average values. Statistical analysis performed on the obtained data showed a strong positive correlation between the radiological variables and ^{226}Ra and ^{232}Th.

Keywords LAMP · HPGe detector · Statistical analysis · External absorbed dose rate · Radiological hazard and excess lifetime cancer risk

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Introduction

Lynas Advanced Material Plant (LAMP) is acclaimed as the largest rare earth refinery project in the world. It is an Australian rare earth refining industry located in Malaysia, with the sole responsibility of production and recovery of rare earth elements (REEs) from the concentrated raw materials supplied from Australia. REEs are metals, which by virtue of their unique physical and chemical properties, find great demands in the ever-expanding technological market all around the world (Rim et al. 2013). The citing of this processing plant in Malaysia has become a boost to the efforts of Malaysian government in turning the country into a manufacturing nerve centre and a more attractive environment for further domestic businesses.

Whereas the REEs have become an indispensable integral of green technology, their extraction and processing can pose serious environmental challenge and health risk to plant workers and the entire public in terms of radiation exposure. Although REEs are not, in themselves, radioactive, they exist in the earth crusts in mixture with naturally occurring radioactive materials (NORM). Schmidt (2013) reported that the raw materials and the rare earth ore imported from Australia for processing at LAMP are a concentrated mixture of REEs and radioactive thorium, uranium, and their decay products. The processing of the ore can therefore concentrate these NORMs in the wastes (TENORM), which, if not handled effectively, can become a channel of public exposure. Thorium dust, which is a known cancer-inducing agent, is easily blown by wind and carried by water over long distances, thereby create radiation hazards over large span of areas. Thus, all the steps of REE production, from mining through transportation, processing and waste disposal stages, are potential pathways for contamination of soil and water by radioactive and hazardous chemicals.

Soil has become the principal component of our ecosystem that is constantly exposed to and/or contaminated by numerous radioactive and hazardous materials due to continuous urbanizations, increasing agricultural practices, and ongoing industrial and technological developments, etc. (Omoniyi et al. 2013). According to UNSCEAR (2000) report, man spends an average of 20 % of his time outdoors, and through this period, he gets continuous exposure by gamma radiations originating from ^{238}U, ^{232}Th and ^{40}K in soil within the upper 30 cm of the earth surface (Al-Jundi et al. 2003; Chikasawa et al. 2001; Dabayneh et al. 2008; Mandić et al. 2010; Tzortzis et al. 2004). This has therefore made soil radioactivity studies of paramount importance, both for public dose rate assessments and for epidemiological studies (Asgharizadeh et al. 2013; Mandić et al. 2010), in addition to establishing reference baseline data for studies of subsequent radiation impact assessments of any eventual radioactivity changes that may occur due to human activities in the environment.

All around the world, studies have been conducted on environmental radioactivity, majority of which is centered on radioactivity in soils. Saleh et al. (2013) assessed the natural radioactivity levels and associated dose rates from surface soils in Pontian district, Johor, Malaysia. Results of natural radioactivity in surface soil samples from dwelling areas in Tehran city, Iran were documented by Asgharizadeh et al. (2013). Wang et al. (2012) conducted similar research in Eastern Sichuan Province of China. Agbalagba and Onoja (2011) evaluated the natural radioactivity in soil, sediment, and water samples of Niger Delta flood plain lakes in Nigeria. Analysis of terrestrial naturally occurring radionuclides in soil samples from some areas of Sirsa district of Haryana, India was carried out by Mehra et al. (2010), while Aznan et al. (2009) documented the results of similar studies in Malaysia. All of these studies bring to focus the necessity for continuous assessment of radiation dose distribution in soils so as to accurately evaluate the radiation risk to a population and to effectively monitor the contributions of anthropogenic activities to terrestrial gamma dose rates for any outdoor occupation (Obed et al. 2005; Singh et al. 2005).

The strategic location of LAMP within about 2-km radius of residential areas raises a deep concern among the local communities of environmental contamination and public health challenge from hazardous and radioactive wastes that may be generated over long period of time. Continuous processing activity by LAMP may put the surrounding lands and water bodies at risk of enhanced radiation dose and high-toxic chemical perturbation which does not augur well for the health, safety and economic well-being of the local communities. The risk of soil and groundwater contamination should therefore be evaluated to so as to assess the level of exposure and to ascertain if precautionary measures are needful for the public from the point of radiation protection. This therefore forms the main objective of this study.

Materials and methods

Sample collection and preparation

LAMP is located at E 103° 22′ 34″, N 4° 0′ 21″ in Gebeng Industrial Estate (GIE), Kuantan, Pahang, Malaysia (Fig. 1). It is a refining plant responsible for producing rare earth oxides in Malaysia.

In order to have a preliminary survey of the radiological situation of LAMP environment, 15 soil samples were collected at random outside the LAMP from 5 to 10 cm of the upper soil surface. About 2.0 kg of each composite soil sample collected from level, undisturbed grass-covered areas using a hand auger, was packed into well-labeled and well-secured polyethylene bags to prevent sample contamination. Similarly, six water samples were collected in the same manner into well-secured water bottles. All of the samples were finally transported to the laboratory for analysis.

At the laboratory, all stones, foreign particles and organic materials were removed from the soil samples, and the samples were left open to dry at room temperature for about 3 days after which they were oven-dried at 100 °C for another 24 h to ensure completely moisture-free samples (Asgharizadeh et al. 2013; Singh et al. 2005; Sroor et al. 2001). This becomes necessary because, according to IAEA (2003), moisture content constitutes error in the desired spectrum. The dried samples were pulverized, screened through 2-mm-mesh sieve and homogenized. About 270 g (±0.05 %) of the soil samples was packed into well-labeled marinelli beakers, tightly sealed and stored for about 6 weeks to allow the daughter radionuclides attain radioactive equilibrium with their respective long-lived parents (Agbalagba and Onoja 2011; Amekudzie et al. 2011; Mehra et al. 2010). The water samples were also prepared likewise and stored in the same manner.

Gamma spectrometric measurements

The radiometric analysis of all the samples was done at the radiation laboratory of physics department, University of Malaya, Malaysia. The assessment of the activity concentrations of ^{226}Ra(^{238}U), ^{228}Ra(^{232}Th) and ^{40}K in all the samples was done using a P-type Coaxial ORTEC, GEM-25 HPGe gamma-ray detector with 57.5-mm crystal diameter and 51.5-mm thickness. The detector was set at operating voltage of +2800 V, with a relative efficiency of 28.2 % and 1.67 keV FWHM energy resolution at 1.33-MeV peak of ^{60}Co. The detector, which is coupled to ADCM data acquisition system with PCAII multichannel analyzer, is housed in a good cylindrical lead shield with a fixed bottom in order to reduce the interference of background radiation from terrestrial and extra-terrestrial sources with the measured spectrum (Asaduzzaman et al. 2014; Khandaker et al. 2012). Before the measurement, the detector was calibrated for energy and efficiency using a cylindrical multinuclide

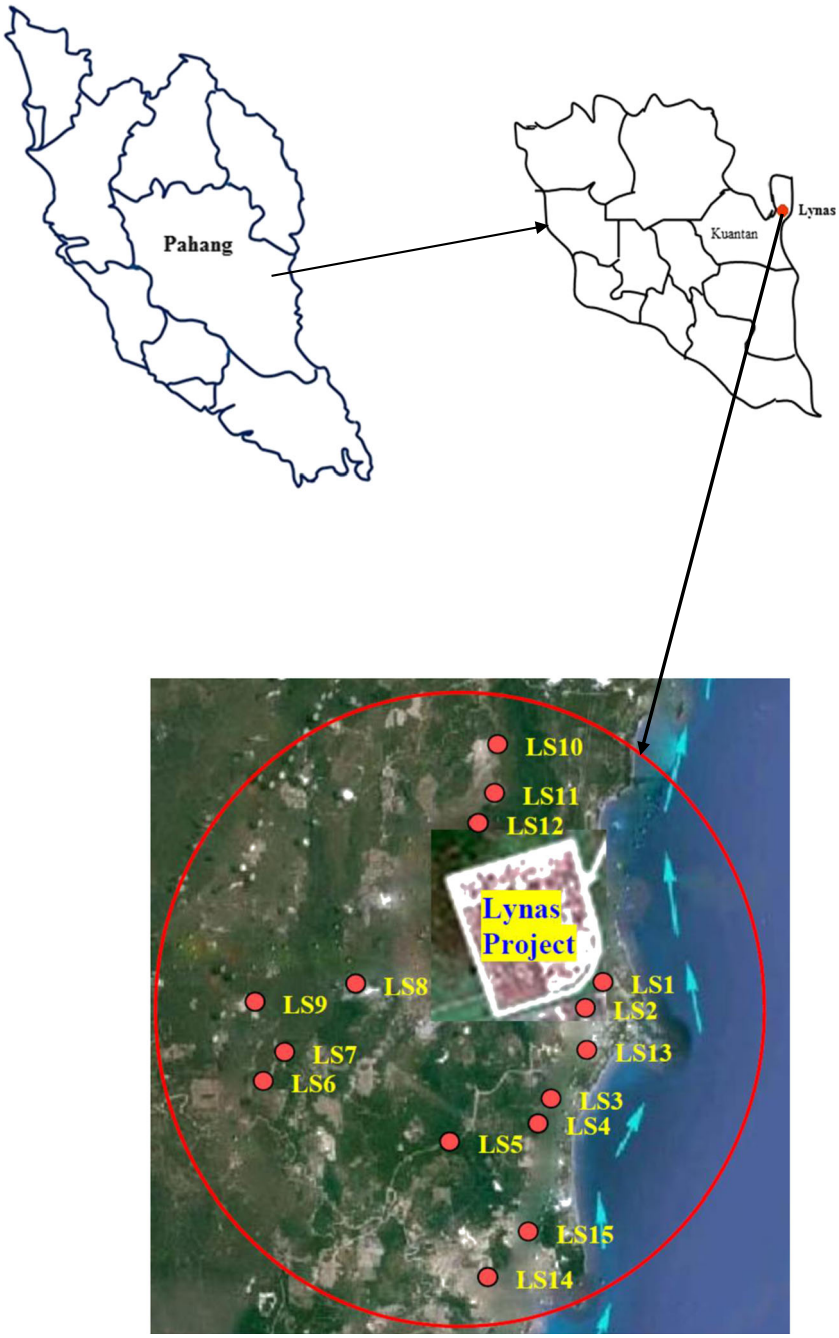

Fig. 1 Location of LAMP (E 103° 22′ 34″, N 4° 0′ 21″) in Gebeng Industrial Estate (GIE), Kuantan, Pahang, Peninsular Malaysia

gamma-ray source with homogenously distributed activity in the same container geometry as the samples. The calibration source with an initial activity of 5.109 μCi was supplied by Isotope Products Laboratories, Valencia, CA 91355, USA, in October 2013. The nuclides contained in the calibration along with their respective energies are as follows: ^{241}Am (59.541 keV), ^{109}Cd (88.040 keV), ^{57}Co (122.061 keV, 136.474 keV), ^{203}Hg (279.195 keV), ^{113}Sn (391.698 keV), ^{85}Sr (514.007 keV), ^{137}Cs (661.657 keV), ^{88}Y (898.042 keV, 1836.063 keV) and ^{60}Co (1173.22 keV, 1332.492 keV).

The activity concentration of ^{226}Ra was estimated from the weighted average gamma peaks of ^{214}Pb (351.93 keV, 35.6 %) and ^{214}Bi (609.32 keV, 45.49 %), while that of ^{232}Th was estimated from the weighted average gamma peaks of ^{212}Pb (238.63 keV, 46.6 %) and ^{208}Tl (583.19 keV, 99.2 %). The ^{40}K activity concentration was determined from its 1460.822-keV (10.66 %) single characteristic gamma line. The minimum detectable activity (MDA) at 95 % confidence level for the detector was estimated following the equation (Khandaker et al. 2012):

$$\mathrm{MDA}\left(\mathrm{Bq}/\mathrm{kg}\right) = \frac{K_\alpha \sqrt{N_\mathrm{B}}}{\eta(E) P_\gamma T_\mathrm{c} M} \quad (1)$$

where K_α is the statistical coverage factor equivalent to 1.645, N_B is the background count (cps), η (E) is the photo-peak efficiency, P_γ is the probability of gamma emission, T_c is the counting time(s) and M is the sample mass (kg). Using the above Eq. (1), the MDA for the respective radionuclides of interest was calculated to be 0.70 Bq/kg for ^{226}Ra, 0.80 Bq/kg for ^{232}Th and 2.40 Bq/kg for ^{40}K.

Each sample was counted for 86,400 s, a long enough counting period to minimize the counting errors. This analysis considered that the statistical errors of the gamma-ray counting (2–9.5 %), detection efficiency errors (~3 %) and errors from gamma-ray intensity (~1 %) accounted for the overall errors of the measured activities found to be in the range of 3.74–10.01 %. The net count rate of the primordial radionuclides was obtained by subtracting the respective count rate from the background spectrum acquired for the same counting time. The specific activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in all the samples investigated were calculated using the following expression (Amekudzie et al. 2011; Dabayneh et al. 2008; Khandaker et al. 2012);

$$A\left(\mathrm{Bq}/\mathrm{kg}\right) = \frac{\mathrm{CPS} \times 1000}{\varepsilon_\gamma \times I_\gamma \times W} \tag{2}$$

where A (Bq/kg) is the specific activity, CPS is the net counts per second for each sample investigated, ε_γ (E) is the detector photo-peak efficiency at respective gamma-ray peak, I_γ is the corresponding gamma-ray intensity and W is the mass of sample in gram.

Radiation indices

Radium equivalent activity (Ra_{eq})

Due to nonuniform distribution of ^{226}Ra, ^{232}Th and ^{40}K in soils, a single parameter is defined with respect to radiation exposure which compares the activity of materials containing different elements of these primordial radionuclides. This single entity, called the radium equivalent activity (Ra_{eq}) is measured in becquerel per kilogram, and defined based on the assumption that 370 Bq/kg of ^{226}Ra or 259 Bq/kg of ^{232}Th or 4810 Bq/kg of ^{40}K produces the same gamma-ray dose (Agbalagba and Onoja 2011; Dabayneh et al. 2008). It is quantitatively expressed as follows (UNSCEAR 2000):

$$\mathrm{Ra_{eq}} = A_{\mathrm{Ra}} + 1.43A_{\mathrm{Th}} + 0.077A_{\mathrm{K}} \tag{3}$$

where Ra_{eq} is the radium equivalent activity measured in becquerel per kilogram, and A_{Ra}, A_{Th} and A_K are the respective specific activities of ^{226}Ra, ^{232}Th and ^{40}K.

Absorbed dose rate (D_R)

The absorbed dose rates (D_R) due to gamma radiations in air, 1 m above the ground, are estimated with an assumption that ^{226}Ra, ^{232}Th and ^{40}K are uniformly distributed, and that other radionuclides outside these three contribute insignificantly to the total environmental background dose (Jacob et al. 1986; Leung et al. 1990). D_R is calculated using the conversion factor of 0.462 nGyh^{-1}/Bqkg^{-1} for ^{226}Ra, 0.604 nGyh^{-1}/Bqkg^{-1} for ^{232}Th and 0.0417 nGyh^{-1}/Bqkg^{-1} for ^{40}K, published by UNSCEAR (2008) as

$$D_{\mathrm{R}}\left(\mathrm{nGy}/\mathrm{h}\right) = 0.462A_{\mathrm{Ra}} + 0.604A_{\mathrm{Th}} + 0.0417A_{\mathrm{K}} \tag{4}$$

where D_R is the absorbed dose in nanogray per hour and A_{Ra}, A_{Th}, and A_K are the specific activities measured in Bq/kg for ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

Annual effective dose equivalent

Two radiation parameters have been provided by UNSCEAR (2000), which are critical in the estimation of annual effective dose in air. These are the conversion coefficient from absorbed dose in air to effective dose given to be 0.7 Sv/Gy, and the outdoor occupancy factor given to be 0.2, with the view that an individual spends an average of 80 % of his time indoors. The annual effective dose equivalent (AEDE) in outdoor air, measured in millisievert per year, is therefore calculated as follows (UNSCEAR 2000):

$$\begin{aligned}\mathrm{AEDE}\left(\frac{\mathrm{mSv}}{\mathrm{year}}\right) &= D_{\mathrm{R}}\left(\frac{\mathrm{nGy}}{\mathrm{h}}\right) \times 8760\left(\frac{\mathrm{h}}{\mathrm{year}}\right) \times 0.7\left(\frac{\mathrm{Sv}}{\mathrm{Gy}}\right) \\ &\quad \times 0.2 \times 10^{-6}\left(\frac{\mathrm{mSv}}{\mathrm{year}}\right) \\ &= D_{\mathrm{R}} \times 1.21 \times 10^{-3}\ \mathrm{mSv}/\mathrm{year}\end{aligned} \tag{5}$$

Annual gonadal dose equivalent

The genetic relevance of the dose equivalent received each year by the reproductive organs (gonads) of the exposed population is represented by the annual gonadal equivalent dose (Morsy et al. 2012). Within this context also, the activity bone marrow and the bone surface cells are inclusive by UNSCEAR (1988) as organs of interest. Thus, the annual gonadal dose equivalent (AGDE), due to the specific activities of ^{228}Ra, ^{232}Th and ^{40}K in the studied samples, was estimated using the formula (Chandrasekaran et al. 2014; Ravisankar et al. 2014):

$$\mathrm{AGDE}\left(\mu\mathrm{Sv}/\mathrm{year}\right) = 3.09A_{\mathrm{RA}} + 4.18A_{\mathrm{Th}} + 0.314A_{\mathrm{K}} \tag{6}$$

Activity utilization index

The dose rates in air from different combinations of the three primordial radionuclides in soil samples are expressed by the activity utilization index (AUI). By applying the appropriate conversion factors along with the activity concentrations of the respective radionuclides, AUI is calculated from the following equation (Ramasamy et al. 2011; Ravisankar et al. 2014):

$$\mathrm{AUI} = \left(\frac{A_{\mathrm{Ra}}}{50\ \mathrm{Bq/kg}}\right) f_{\mathrm{U}} + \left(\frac{A_{\mathrm{Th}}}{50\ \mathrm{Bq/kg}}\right) f_{\mathrm{Th}} + \left(\frac{A_{\mathrm{K}}}{500\ \mathrm{Bq/kg}}\right) f_{\mathrm{K}} \quad (7)$$

where A_{Ra}, A_{Th} and A_{K} are the measured activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively, and f_{K} (0.041), f_{Th} (0.604) and f_{U} (0.462) are the respective fractional contributions from the actual activities of these radionuclides to the total gamma radiation dose rate in air (Chandrasekaran et al. 2014). Typical activities per unit mass of ^{40}K, ^{232}Th and ^{226}Ra in soils A_{K}, A_{Th} and A_{Ra} are reported by NEA-OECD (1979) to be 500, 50 and 50 Bq/kg, respectively.

Hazard indices (H_{ex} and H_{in})

Radiation hazard incurred due to external exposure to gamma rays from the studied soil samples is quantified in terms of the external hazard index (H_{ex}) given by UNSCEAR (2000):

$$H_{\mathrm{ex}} = \frac{A_{\mathrm{Ra}}}{370} + \frac{A_{\mathrm{Th}}}{259} + \frac{A_{\mathrm{K}}}{4810} \quad (8)$$

Similarly, respiratory organs are in danger of radiation exposure from radon and its short-lived daughter radionuclides. The internal radiation exposure is quantified by the internal hazard index (H_{in}) given by UNSCEAR (2000):

$$H_{\mathrm{in}} = \frac{A_{\mathrm{Ra}}}{185} + \frac{A_{\mathrm{Th}}}{259} + \frac{A_{\mathrm{K}}}{4810} \quad (9)$$

where A_{Ra}, A_{Th} and A_{K} are the specific activities of ^{226}Ra, ^{232}Th and ^{40}K, respectively.

UNSCEAR (2000) provided that the value of the above index must be less than unity for the radiation hazard to be regard as insignificant.

Representative gamma index ($I_{\gamma r}$)

The gamma radiation hazard due to the respective concentrations of the investigated natural radionuclides in the soil samples is assessed by the representative gamma index ($I_{\gamma r}$). This

Table 1 Location coordinates, natural radioactivity concentrations and radiation hazard indices for water samples outside the LAMP environment

S_ID	Location	Coordinates		Sampling distance	Activity concentrations (Bq/l)			Radiation hazard indices				
		Long.	Lat.	from LAMP (m)	^{226}Ra	^{232}Th	^{40}K	Ra_{eq} (Bq/l)	D (nGy/h)	ED (mSv/year)	$H_{ex} \leq 1$	$H_{in} \leq 1$
LW 1	River water 1	103° 22′ 52″	3° 59′ 55.9″	953	0.21±0.03	0.06±0.02	4.65±0.32	0.65	0.33	4.01E−04	1.77E−03	2.33E−03
LW 2	River water 2	103° 21′ 29.8″	3° 59′ 34.4″	2446	0.38±0.06	0.68±0.06	4.99±0.34	1.74	0.79	9.75E−04	4.69E−03	5.72E−03
LW 3	Drainage water 1	103° 21′ 21.2″	4° 0′ 1.7″	2321	0.21±0.03	0.08±0.04	4.71±0.28	0.69	0.34	4.19E−04	1.86E−03	2.42E−03
LW 4	Drainage water 2	103° 21′ 21.9″	4° 0′ 2.2″	2296	0.38±0.06	0.06±0.02	4.64±0.28	0.82	0.41	4.97E−04	2.22E−03	3.25E−03
LW 5	Drainage water 3	103° 21′ 14.2″	4° 0′ 25.6″	2463	0.56±0.07	0.14±0.04	4.36±0.24	1.10	0.53	6.44E−04	2.96E−03	4.47E−03
LW 6	Tap water	103° 22′ 23.9″	3° 58′ 37.6″	3209	0.24±0.04	0.07±0.07	4.97±0.25	0.72	0.36	4.42E−04	1.95E−03	2.60E−03
Min					0.21±0.03	0.06±0.02	4.36±0.24	0.65	0.33	4.01E−04	1.77E−03	2.27E−03
Max					0.56±0.07	0.68±0.06	4.99±0.34	1.74	0.79	9.75E−04	4.69E−03	6.69E−03
Mean					0.33±0.05	0.18±0.04	4.72±0.29	0.95	0.48	5.65E−04	2.57E−03	3.47E−03

index, according to Jibiri and Okeyode (2012), is a screening parameter for materials of possible radiation health challenge. It is calculated using the following equation (El-Gamal et al. 2007; NEA-OECD 1979; Ravisankar et al. 2014):

$$I_{\gamma r} = \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500} \quad (10)$$

where A_{Ra}, A_{Th} and A_K are the specific activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in becquerel per kilogram. Manigandan and Chandar Shekar (2014) stated that to satisfy the dose criteria, the value of representative gamma index should be ≤1 which corresponds to an annual effective dose of ≤1 mSv (Ravisankar et al. 2014).

Excess lifetime cancer risk

Consequent upon the evaluation of AEDE, the excess lifetime cancer risk (ELCR) was estimated using the equation (Ravisankar et al. 2014; Taskin et al. 2009):

$$\mathrm{ELCR} = \mathrm{AEDE} \times \mathrm{DL} \times \mathrm{RF} \quad (11)$$

where AEDE, DL and RF are the annual effective dose equivalent, duration of life (70 years) and risk factor (0.05 Sv^{-1}), respectively. Ravisankar et al. (2014) defined the risk factor as fatal cancer risk per sievert, which according to Taskin et al. (2009) and also by ICRP (1991), is assigned to a value of 0.05 for the public for stochastic effects.

Results and discussion

Table 1 shows the values of activity concentration of ^{226}Ra, ^{232}Th and ^{40}K along with the radiation indices for the water samples collected outside the LAMP environment. The calculated average Ra_{eq} value is 0.95 Bq/l, with a corresponding mean external dose of 0.48 nGy/h for the water samples. The estimated average annual effective dose of 5.65×10^{-4} mSv/year is found to be far below the 0.1 mSv/year safety limit provided by WHO (1978). Therefore, the contribution to overall radiation dose outside the LAMP environment from water samples is insignificant. Thus, the discussions in this study will be centered mostly on the soil samples.

The location coordinates and activity concentrations (measured in Bq/kg) of ^{226}Ra, ^{232}Th and ^{40}K for all the investigated soil samples are presented in Table 2. Spatial variations are noticed among the values which may be due to the physicochemical and geochemical properties of the respective radionuclides along with their presence in the soil samples (El Mamoney and Khater 2004; Sam et al. 1998).

Table 2 Location coordinates and activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K of soil samples outside the LAMP environment

S_ID	Location	Coordinates		Sampling distance	Activity concentrations (Bq/kg)		
		Long.	Lat.	from LAMP (m)	^{226}Ra	^{232}Th	^{40}K
LS 1	Garbage dump site 1	103° 22′ 53″	3° 59′ 58″	921	9.99±0.17	8.85±0.27	27.05±0.60
LS 2	Garbage dump site 2	103° 22′ 54″	3° 59′ 59″	917	7.44±0.20	12.41±2.33	11.58±0.74
LS 3	Processing plant 1	103° 22′ 51″	3° 59′ 56″	933	7.04±0.20	19.28±0.36	16.35±0.63
LS 4	Processing plant 2	103° 22′ 52″	3° 59′ 56″	951	12.14±0.31	24.85±0.45	32.98±0.72
LS 5	Construction area	103° 22′ 6″	3° 59′ 43″	1457	5.46±0.22	7.84±0.23	121.21±0.95
LS 6	Road junction 1	103° 21′ 30″	3° 59′ 33″	2467	6.16±0.27	7.28±0.22	92.94±0.90
LS 7	Road junction 2	103° 21′ 28″	3° 59′ 36″	2463	6.08±0.19	8.00±0.27	33.72±0.60
LS 8	Lynas gate 1	103° 22′ 53″	4° 0′ 3″	807	2.90±0.14	3.25±0.15	6.28±0.39
LS 9	Lynas gate 2	103° 21′ 23″	4° 0′ 2″	2265	6.56±0.18	7.47±0.23	59.64±0.76
LS 10	Opposite Lynas 1	103° 22′ 34″	4° 0′ 57″	1112	6.65±0.18	7.55±0.24	60.33±0.76
LS 11	Opposite Lynas 2	103° 22′ 39″	4° 0′ 49″	878	1.76±0.04	6.12±0.27	1.05±0.01
LS 12	Nondisturbed areas 1	103° 22′ 53″	4° 0′ 25″	598	4.95±0.19	6.48±0.28	12.21±0.93
LS 13	Nondisturbed areas 2	103° 22′ 53″	3° 59′ 42″	1339	7.66±0.20	10.66±0.26	7.71±0.46
LS 14	Suburban 1	103° 22′ 53″	3° 58′ 37″	3265	6.11±0.21	11.48±0.33	58.76±0.74
LS 15	Suburban 2	103° 22′ 53″	3° 58′ 40″	3174	7.56±0.28	17.78±0.35	73.54±0.89
Min					1.76±0.04	3.25±0.15	1.05±0.01
Max					12.14±0.31	24.85±0.45	121.21±0.95
AM±SD					6.57±2.5	10.62±5.8	41.02±35.6
Skew					0.26	1.34	0.91
Kurt					1.41	1.38	0.14

AM arithmetic mean, *SD* standard deviation, *Skew* skewness, *Kurt* kurtosis

Table 3 Radiation hazard indices for soil samples outside the LAMP environment

S_ID	Ra_{eq} (Bq/kg)	D_R (nGy/h)	AEDE (mSv/year)	AGDE (μSv/year)	AUI=1	$H_{ex}\leq 1$	$H_{in}\leq 1$	$I_{yr}\leq 1$	ELCR×10^{-3}
LS 1	24.73	11.09	0.01	76.36	0.20	0.07	0.09	0.17	0.05
LS 2	26.08	11.42	0.01	78.50	0.22	0.07	0.09	0.18	0.05
LS 3	35.87	15.58	0.02	107.48	0.30	0.10	0.12	0.25	0.07
LS 4	50.21	21.99	0.03	151.74	0.42	0.14	0.17	0.35	0.10
LS 5	26.00	12.31	0.02	87.70	0.16	0.07	0.08	0.20	0.05
LS 6	23.73	11.12	0.01	78.65	0.15	0.06	0.08	0.18	0.05
LS 7	20.12	9.05	0.01	62.82	0.16	0.05	0.07	0.14	0.04
LS 8	8.03	3.56	0.00	24.52	0.07	0.02	0.03	0.06	0.02
LS 9	21.85	10.04	0.01	70.28	0.16	0.06	0.08	0.16	0.04
LS 10	22.09	10.15	0.01	71.05	0.16	0.06	0.08	0.16	0.04
LS 11	10.59	4.55	0.01	31.35	0.09	0.03	0.03	0.07	0.02
LS 12	15.16	6.71	0.01	46.22	0.13	0.04	0.05	0.11	0.03
LS 13	23.60	10.35	0.01	70.98	0.20	0.06	0.08	0.16	0.05
LS 14	27.05	12.21	0.01	85.32	0.20	0.07	0.09	0.19	0.05
LS 15	38.65	17.30	0.02	120.77	0.29	0.10	0.12	0.28	0.08
Min	8.03	3.56	0.00	24.52	0.07	0.02	0.03	0.06	0.02
Max	50.21	21.99	0.03	151.74	0.42	0.14	0.17	0.35	0.10
Mean	24.92	11.16	0.01	77.58	0.19	0.07	0.09	0.18	0.05

The activity concentrations of ^{226}Ra and ^{232}Th (12.14±0.31 and 24.85±0.45 Bq/kg, respectively) are found to be the highest in the sample LS4, 951 m from the processing plant. This should be expected, owing to the effects of little heaps of unused thorium-rich raw material that are deposited within the region. Indiscriminate dumping of contaminated factory waste within the region is another likely activity enhancement index. Sample LS5 collected from a construction area 1400 m away showed the highest activity concentration value for ^{40}K (121.21±0.95 Bq/kg). This is likely due to constant soil turnover effects as a result of the ongoing construction activity and the presence of other construction aggregates within the site. Though there are variations in the activities of these naturally occurring radionuclides, their values are generally below the safety limits provided by UNSCEAR (2000) and so reflect a general radiation background trend.

The calculated Ra_{eq}, D_R, AEDE, AGDE, ELCR and other hazard indices for the soil samples outside the LAMP environment are presented in Table 3. A general overview of the results indicates that all of the calculated radiation parameters have mean values below the safety limits set by UNSCEAR (2000) for radiation protection.

A comparison with similar studies from many parts of the world as presented in Table 4 below further confirms the low trend. Additionally, the estimated mean value of ELCR is 0.049×10^{-3}, which is far below the world average value of 0.29×10^{-3} for soils (UNSCEAR 2000) and also lower than the limit of 0.05 for low-level radiations prescribed by ICRP. Hence, the risk of cancer among the population living outside LAMP environment is insignificant.

In general, therefore, Lynas processing plant does not pose any radiological threat to the outside environment neither the

Table 4 Comparison of Ra_{eq}, D_R and AEDE of the present study with other parts of the world

Location	Ra_{eq} (Bq/kg)	D_R (nGy/h)	AEDE (mSv/year)	Reference
Western Ghats, India	208	91.54		Maniganan and Shekar (2014)
Northern Pakistan	190.89	87.47	0.11	Qureshi et al. (2014)
Saudi Arabia	68.1	35.2	0.04	El-Taher and Al-Zahrani (2014)
Tehran city, Iran	143.6	69.1	0.08	Asgharizadeh et al. (2013)
Eastern Sichuan, China	130	60	0.074	Wang et al. (2012)
Niger Delta, Nigeria	76	30	0.037	Agbalagba and Onoja (2011)
West Bank, Palestine	185.8	88.2	0.11	Dabayneh et al. (2008)
Kuantan, Malaysia	24.92	11.16	0.014	Present study

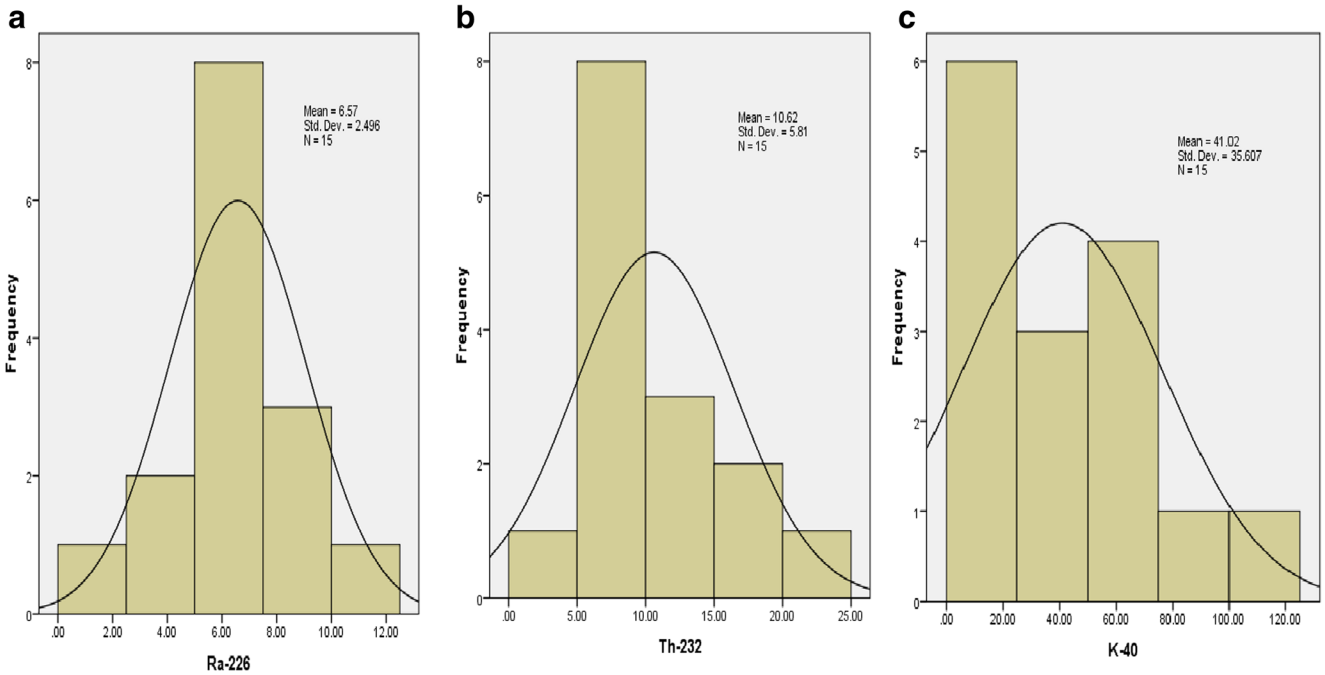

Fig. 2 Frequency distribution histograms of **a** ^{226}Ra, **b** ^{232}Th, and **c** ^{40}K

general public nor the factory workers under any radiological burden that demands urgent intervention.

Statistical analysis

Descriptive statistical analysis

The statistical properties of the measured activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the studied soil samples, which comprises the minimum and maximum values, the arithmetic mean (AM), standard deviation (SD), skewness and kurtosis are presented in Table 2.

The basic statistical data shows a higher value of AM for ^{40}K within the SD compared to the AM values of ^{232}Th and ^{226}Ra. The skewness, which defines the degree of asymmetry of real-valued random variables around its mean, has positive values for the studied nuclides. This implies an asymmetric distribution of the radionuclides outside the LAMP environment (Table 2). Kurtosis, on the other hand, is a comparative parameter that shows the relative peakedness or flatness of any given distribution relative to the normal distribution. Relatively peaked distribution is represented by positive kurtosis while negative kurtosis connotes a relatively flat distribution. The results presented in Table 2 for the present investigation recorded positive values of kurtosis, which indicate a relatively peaked distribution of the radionuclides in the studied soil

Table 5 Pearson correlation coefficients among radioactive parameters for soil samples outside the LAMP environment

Variables	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	D_R	AEDE	AGDE	H_{ex}	H_{in}	$I_{\gamma r}$	AUI	ELCR
^{226}Ra	1											
^{232}Th	0.721	1										
^{40}K	0.093	−0.017	1									
Ra_{eq}	0.822	0.946	0.266	1								
D_R	0.818	0.924	0.328	0.998	1							
AEDE	0.616	0.854	0.304	0.890	0.890	1						
AGDE	0.810	0.915	0.354	0.996	1.000	0.891	1					
H_{ex}	0.829	0.949	0.233	0.996	0.991	0.901	0.988	1				
H_{in}	0.874	0.931	0.228	0.991	0.987	0.847	0.984	0.991	1			
$I_{\gamma r}$	0.801	0.921	0.345	0.996	0.999	0.896	0.999	0.989	0.982	1		
AUI	0.836	0.982	0.046	0.975	0.958	0.855	0.950	0.978	0.975	0.952	1	
ELCR	0.821	0.943	0.245	0.992	0.989	0.874	0.986	0.984	0.980	0.989	0.971	1

samples. The normal (bell-shaped) distribution illustrated by the frequency distribution histograms of ^{226}Ra, ^{232}Th and ^{40}K (shown in Fig. 2) further confirms the even distribution of these radionuclides in the studied soil samples.

Pearson's correlation coefficients

The radiological data generated in this study were subjected to multivariate analysis using the Statistical software package: Statistical Program for Social Science (SPSS 22.0). The essence is to understand the interdependency and natural relationships between the samples and/or determined variables that will enable valid judgments of the nature and significance of radionuclide distributions in environmental matrices from the point of view of radiation protection (Laaksoharju et al. 1999; Liu et al. 2003). The relationships and degree of association that may exist among the measured radiological variables were assessed using Pearson's correlation analysis. The calculated linear Pearson's correlation coefficients among the variables for the studied soil samples are given in Table 5. Based on the strength of the relationship between the radiological variables, the correlation coefficient values in this study are grouped as "very weak" ($r<0.36$), "weak" ($0.36<r<0.49$), "strong" ($0.50<r<0.75$), and "very strong" ($r>0.75$), while maintaining the alpha testing level at $p<0.05$ for samples ($n=15$). As seen in Table 5, there exists a strong positive correlation ($r=0.72$) between ^{232}Th and ^{226}Ra, while a very weak negative correlation is observed between ^{40}K and these two ($r=0.093$ for ^{40}K and ^{226}Ra; −0.018 for ^{40}K and ^{232}Th). These degrees of association among the radionuclides may be because radium and thorium decay series come from the same origin and exist together in nature, whereas potassium is from a different origin (Tanasković et al. 2012). Furthermore, the measured absorbed dose rates have a very strong positive correlations with ^{226}Ra and ^{232}Th ($r=0.82$ and 0.92, respectively). This may not be unconnected with the fact that the processed raw material is a concentrated mixture of REEs, and radioactive uranium and thorium (Schmidt 2013). On the other hand, a very weak correlation ($r=0.33$) is observed between ^{40}K and the absorbed dose rate which makes its contribution to dose insignificant. In general, therefore, nearly all of the measured radioactive variables are very strongly correlated with one another, and very strongly positively correlated ($r>0.75$) with ^{226}Ra and ^{232}Th, but very weakly with ^{40}K ($r<0.36$). Hence, ^{226}Ra and ^{232}Th have been identified as the basic contributors to emission of gamma radiation in soil samples outside LAMP environment.

Conclusion

The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in water, and soil samples outside the LAMP environment were assessed using gamma radiometric technique. Radiation hazard indices were also determined to quantify the exposure level of the environment. The calculated mean activities of 6.57±0.2, 10.62±0.4 and 41.02±0.7 Bq/kg for soil samples, and 0.33±0.05, 0.18±0.04 and 4.72±0.29 Bq/l for water samples, respectively, for ^{226}Ra, ^{232}Th and ^{40}K were found to be within the normal background levels. Furthermore, the average value for each of the assessed radiation hazard parameter was found to be below the world safety limit set by UNSCEAR. There is therefore no harmful radiation effect posed to the public or factory workers, neither does Lynas processing plant constitute any potential radiological environmental or health challenge. Statistical analysis of the obtained data not only showed that ^{226}Ra and ^{232}Th are principally responsible for the radioactivity levels outside LAMP environment because of the strong positive correlation between them and the radiation parameters, but also confirmed the safety of the environment with respect to gamma radiation effects. These assertions are, however, only valid within the scope of the present investigation and the analyzed samples. Since Lynas operations are continuous and progressive, constant radiological studies are recommended to mitigate the health effects of radioactive thorium and radium especially in the factory's wastes so as to keep the radiation effects as low as reasonably achievable (ALARA) within the economic, social, and health framework. The results of this study can be used as baseline data and reference platform for further investigations.

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