

# Measurement of radionuclides in surface soil and beach sand samples from Rayong Province (Thailand) and the evaluation of excess lifetime cancer risk

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**ABSTRACT:** Specific activities of natural ( $^{40}\text{K}$ ,  $^{226}\text{Ra}$ , and  $^{232}\text{Th}$ ) and anthropogenic ( $^{137}\text{Cs}$ ) radionuclides in 230 surface soil and beach sand samples collected from the densely populated areas of industrial activities in Rayong Province, Thailand, were analyzed. Experimental results were obtained using a high-purity germanium detector and gamma spectrometric analysis system. The frequency distributions of the four radionuclides were investigated and calculated as suitable medium values of all distributions. According to asymmetrical distribution, medium values of the specific activities of all required radionuclides should be median values. Furthermore, the median values of the three natural radionuclides were also used to evaluate absorbed dose rates in the air ( $D$ ), radium equivalent ( $Ra_{\text{eq}}$ ), external hazard index ( $H_{\text{ex}}$ ), annual effective dose rate ( $AED_{\text{out}}$ ), and excess lifetime cancer risk (ELCR) in the studied areas. The results were compared with data obtained from the annual report of Thailand's Office of Atoms for Peace, the global radioactivity measurements, and the evaluations and recommended values proposed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). It was found that most of the results were significantly lower than the recommended values of UNSCEAR except for the median value of specific activity of  $^{226}\text{Ra}$ . Moreover, the radioactive contour map for the investigated areas was constructed.

**KEYWORDS:** radionuclides, high-purity germanium detector, gamma-ray spectrometry, radiological hazard index, excess lifetime cancer risk

## INTRODUCTION

Rayong Province, located in Eastern Thailand, has played an important role as part of the Eastern Seaboard Development Project since 1982. It is a gateway for the Northeast region to send products to foreign countries without passing through Bangkok. The Thai government has prepared a complete basic utility system and designated Map Ta Phut, Mueang District, Rayong Province as a location of the industrial estate. The primary industries in Rayong Province are natural gas separation plants, petrochemical industry, and chemical fertilizer industry. Hence, the province comprises industrial estates jointly operated with many private individuals, industrial areas, industrial communities, and industrial parks, thus having a high potential for industrial investment and rapid industrial development [1, 2]. It creates a total annual value of almost one-third of Thailand's Gross Domestic

Product (GDP). Moreover, Rayong Province has been recently selected as one of the three provinces, besides Chonburi and Chachoengsao, promoted for industrial progress in the Eastern Economic Corridor (EEC) Project. As a result, Rayong Province is an area of continuous industrial development, and a significant increase in number of factories in parallel with an increase in accidents in this area is foreseen.

There are seven refineries for crude oil refining industry in Thailand. Almost all are located in the eastern part of the country. Oil refinery is classified as one of fourteen types of high-polluting plants according to the Notification of the Ministry of Industry in the year 2002 [3]. Although oil refining provides enormous benefits to humans, it also causes many environmental pollutants and, in particular, an increase or build-up of radioactive materials in the environment. The existence of radioactive materials coincides with the creation of the Earth. Therefore, rocks and sand on the Earth's

surface and crude oil, caused by the deposition of fossil in the shale beneath the Earth's surface for millions years, are composed of radioactive substances [4, 5]. Measuring the amount of radioactivity in the area where the manufacturing industry is located has been a point of interest worldwide, especially to monitor the concentration of natural and artificial radionuclides in the environment [6–10]. In the United States, State and Federal regulatory agencies have developed guidelines for controlling naturally occurring radioactive materials that will adequately protect health of the public and the environment [11]. The European Union (EU) has also focused on the survey and measurement of radioactive substances from oil and gas productions among the EU member states [12]. In addition, the Safety Report Series 34 of the International Atomic Energy Agency (IAEA) also provides information on the naturally occurring radioactive substances in oil and gas productions [13].

Generally, the geology of Rayong Province is not quite intricate. Two principal rock types, namely sedimentary rocks and igneous rocks, are found in the area. Granitic rock, which is one type of igneous rock mainly Triassic in age, underlines approximately 20% of the area. Hence, some natural radionuclides such as  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  might be accumulated in this area. The distribution of these radionuclides has proved to be important in estimating the level of natural background radiation to which humans are exposed [14].

For this reason, we were interested in the measurement and analysis of background radioactivity of Rayong Province. The aim was to measure and analyze specific activities of natural radioactive nuclides ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ ) and man-made radioactive nuclides ( $^{137}\text{Cs}$ ) in surface soil and beach sand samples collected from eight districts in Rayong Province. The frequency distribution and some medium values of all measured specific activities were investigated. Then, some interesting radiological hazard indices and ELCR value were also evaluated using the suitable medium values from the frequency distribution values. Moreover, the radioactive contour maps (RCM) of all radioactive nuclides were created.

## MATERIALS AND METHODS

### Studied areas

Rayong Province, one of the seven provinces in Eastern Thailand, is located at  $12^{\circ}40'51.4''\text{N}$  latitude and  $101^{\circ}15'28.7''\text{E}$  longitude (Fig. 1) with

neighboring Chonburi Province to the north-west, Chanthaburi Province to the north-east, and the Gulf of Thailand to the south. The province is divided into eight districts: *Mueang, Ban Chang, Nikhom Phatthana, Pluak Daeng, Ban Khai, Wang Chan, Khao Chamao, and Klaeng Districts*. The population of Rayong Province was 723,316 in 2018.

### Surface soil and beach sand sample collection and preparation

Two hundred surface soil samples (yellow color) were collected from populated areas in the eight districts (Fig. 1). At the same time, 30 beach sand samples (blue color) were collected from Mae Ram Phueng Beach located in the south of Mueang District of the studied area. The collected surface soil samples were ground and homogenized and air-dried for several days. In the meantime, the beach sand samples were taken to dry in the ambient environment for 2–3 days. Both the surface soil and the beach sand samples were placed in an oven at  $100^{\circ}\text{C}$  for at least 3 h to eliminate any traces of water and, then, were sieved through a 2 mm mesh-sized. Approximately 420 g of each meshed surface soil and beach sand sample was removed to a PVC ( $8.2\text{ cm} \times 7.5\text{ cm}$ ) cylindrical container. The container was sealed hermetically and externally using cellophane tape and left for about four weeks to ensure equilibrium between  $^{226}\text{Ra}$  and its daughters and  $^{228}\text{Ra}$  and its daughters [15].

### Measurement, analysis, and frequency distribution of specific activities

The specific activities of natural ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ ) and anthropogenic ( $^{137}\text{Cs}$ ) radionuclides in 230 surface soil and beach sand samples were determined using a high-purity germanium detector (HPGe, EG&G ORTEC Model GEM 20 P4) and gamma spectrometric analysis system at the Thailand Institute of Nuclear Technology (Public Organization) (TINT). The detector was enclosed in a massive 10-cm thick lead shielding. The container's geometric efficiency for soil matrices was determined by the IAEA Soil-375 reference materials (International Atomic Energy Agency IAEA, Vienna, Austria). Gamma-ray energies of  $^{214}\text{Pb}$  (351.9 keV),  $^{214}\text{Bi}$  (609.3, 1764.5 keV), and  $^{226}\text{Ra}$  (185.99 keV) were used to estimate the specific activities of  $^{226}\text{Ra}$  [16]. Evaluation of specific activities of  $^{232}\text{Th}$  was from gamma-lines of  $^{212}\text{Pb}$  (238.6 keV) and  $^{228}\text{Ac}$  (338.4, 911.07, 968.90 keV). The specific activities of  $^{40}\text{K}$  and  $^{137}\text{Cs}$  in all samples were evaluated from gamma energies 1460.8 and

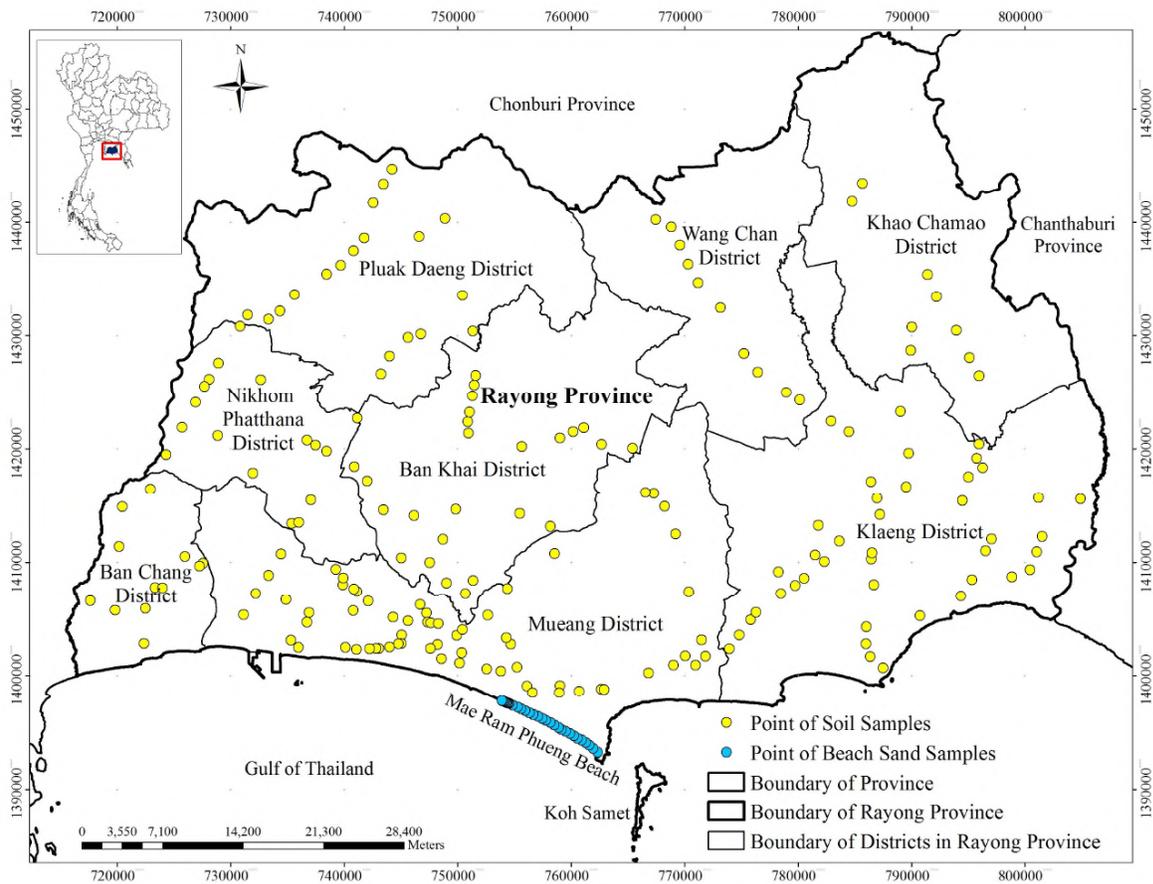


Fig. 1 Geographical map of Rayong Province and sampling locations.

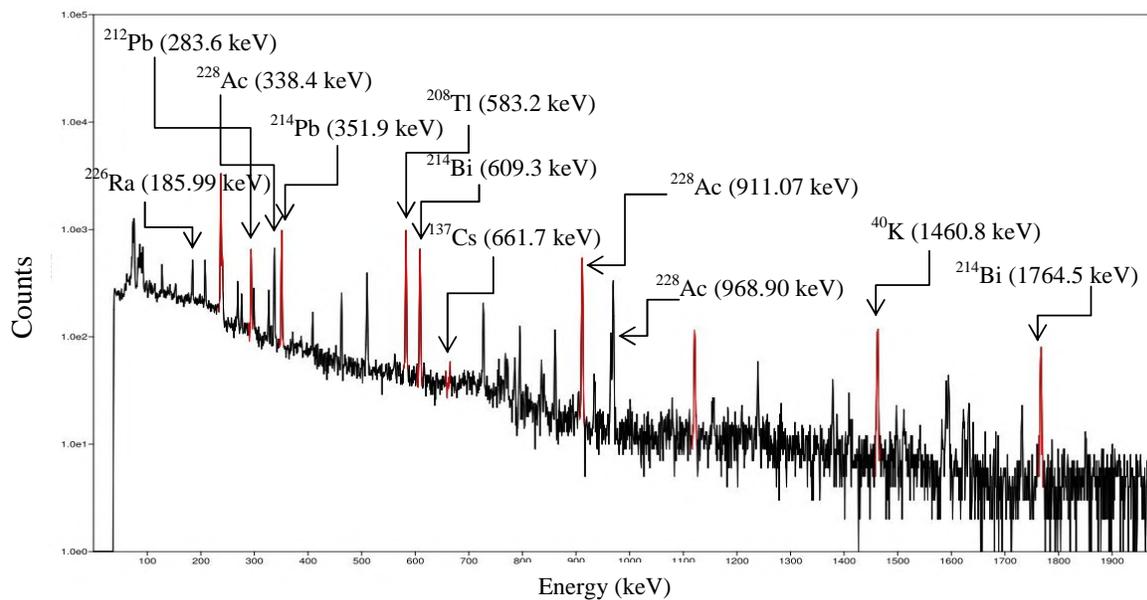


Fig. 2 The gamma-ray energy spectrum of surface soil sample collected from Klang District, Rayong Province.

661.7 keV of themselves, respectively (Fig. 2). The SPSS computer program was employed to analyze the frequency distribution of specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ , and  $^{137}\text{Cs}$  radionuclides. The results were compared with existing data in Thailand and global measurement and evaluation.

### Evaluation of radiological hazard indices and excess lifetime cancer risk

The specific activities of the four radionuclides in the surface soil and beach sand samples [16] were evaluated from Eq. (1):

$$\text{S.A.} = \frac{C}{\epsilon \times P \times m \times t}, \quad (1)$$

where S.A. = specific activity of a radionuclide (Bq/kg); C = count rate under related full energy peak;  $\epsilon$  = detection efficiency at energy E; P = abundance of the gamma line in a radionuclide; m = soil sample mass (kg); and t = counting time. The minimum detectable activity (MDA) of each radionuclide was also evaluated at the 95% confidence level. The average values of MDA for  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ , and  $^{137}\text{Cs}$  were 8.11, 3.77, 63.43, and 0.82 Bq/kg, respectively, for a counting time of 10 800 s and approximately 420 g of the surface soil and the beach sand samples.

By using the conversion factors published [17] and with all selected medium values of specific activity of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  from this study, the absorbed dose rate (D) in outdoor air at 1 m above the ground could be calculated by Eq. (2):

$$D = 0.461C_{\text{Ra}} + 0.623C_{\text{Th}} + 0.0414C_{\text{K}}, \quad (2)$$

where  $C_{\text{Ra}}$ ,  $C_{\text{Th}}$ , and  $C_{\text{K}}$  are suitable medium values of specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  in Bq/kg, respectively. Then, the radium equivalent activity ( $\text{Ra}_{\text{eq}}$ ) [18, 19] could be calculated by Eq. (3):

$$\text{Ra}_{\text{eq}} = C_{\text{Ra}} + 1.43C_{\text{Th}} + 0.077C_{\text{K}} \quad (3)$$

The external hazard index ( $H_{\text{ex}}$ ) [20] was also evaluated by Eq. (4):

$$H_{\text{ex}} = C_{\text{Ra}}/370 + C_{\text{Th}}/259 + C_{\text{K}}/4810 \leq 1. \quad (4)$$

By adoption of a conversion factor of 0.7 Sv/Gy, the calculated D (nGy/h) value in outdoor air was converted to the effective dose received by adults, and by consideration that people in Thailand, on the average, spend approximately 20% of their time outdoors, the annual (8760 h) effective dose rate

( $\text{AED}_{\text{out}}$  (mSv/y)) [17] could be determined by Eq. (5):

$$\text{AED}_{\text{out}} = D \times 8760 \times 0.2 \times 0.7 \times 10^{-6}. \quad (5)$$

Then the excess lifetime cancer risk (ELCR) (outdoor) [21] was also evaluated for the investigated area as shown in Eq. (6):

$$\text{ELCR (outdoor)} = \text{AED}_{\text{out}} \times \text{LF} \times \text{RF} \quad (6)$$

where LF and RF are the life expectancy of Thai people (75 years) [22] and risk factor ( $0.05 \text{ Sv}^{-1}$ ), respectively. All four radiological hazard indices and the ELCR (outdoor) values were calculated and compared with national and international studies, Office of Atoms for Peace (OAP) data, and the recommended values reported by the UNSCEAR [18, 23, 24].

### Construction of radioactive contour maps

The radioactive contour maps (RCM) of specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ , and  $^{137}\text{Cs}$  radionuclides from 230 surface soil and beach sand samples could be created and presented using the ArcGIS computer program.

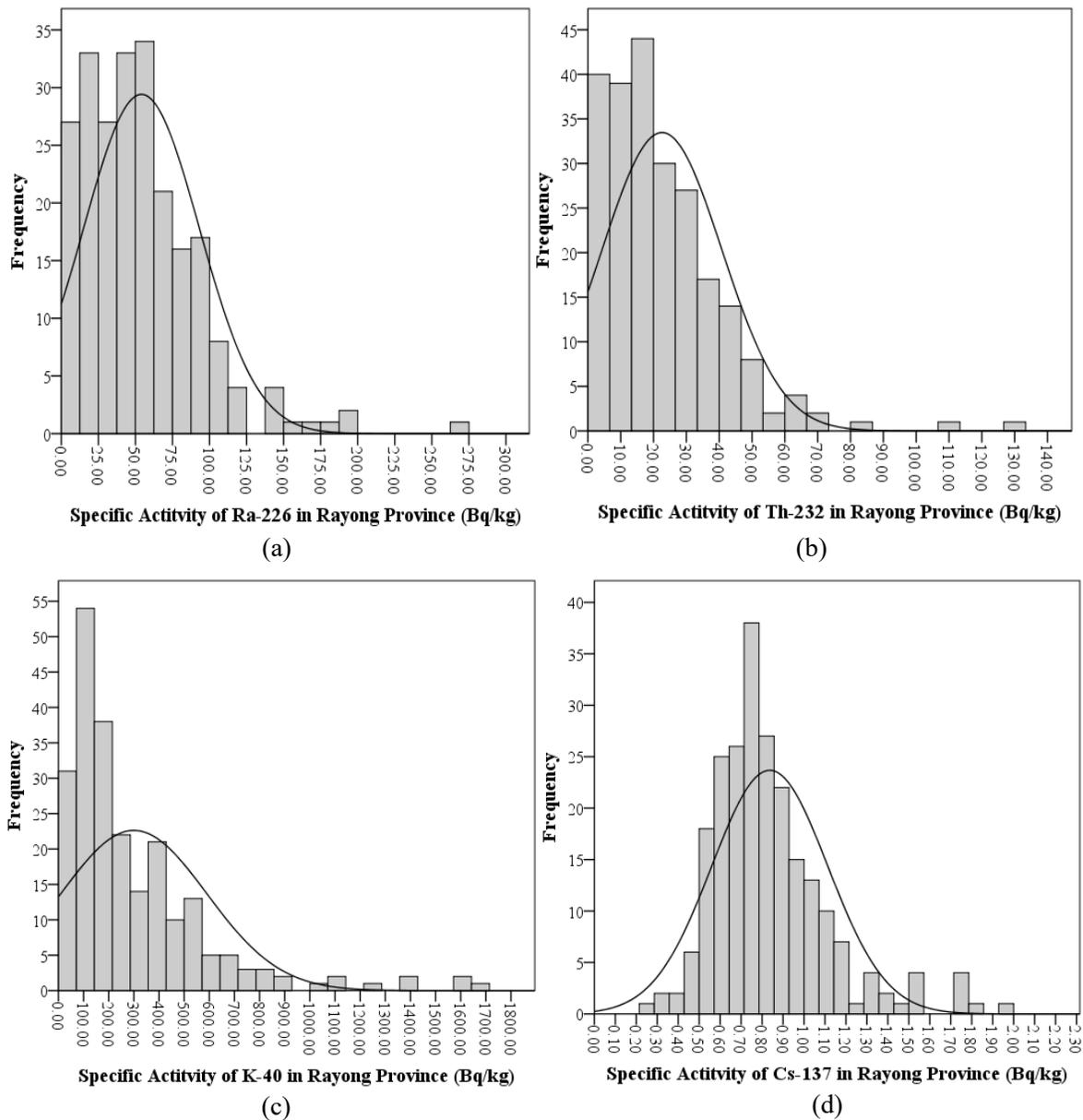
## RESULTS AND DISCUSSION

### Gamma-ray energy spectrum

The gamma-ray energy spectrum of surface soil and beach sand samples in Rayong Province showed the existence of natural ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ ) and anthropogenic ( $^{137}\text{Cs}$ ) radionuclides (Fig. 2). To estimate the terrestrial gamma dose rate for outdoor occupation, it is very important to evaluate the specific activities of natural radionuclides in soils. Since 98.5% of the radiological effects of the uranium series are produced by radium and its daughter products, the natural radioactivity of soil samples is usually determined from the  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  contents. Not only these three natural radionuclides, but also anthropogenic radionuclide ( $^{137}\text{Cs}$ ) may become air-borne, and inhalation of contaminated dust can result in an internal exposure [16, 17, 24].

### Frequency distribution of specific activities and statistic values

The frequency distribution of calculated specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ , and  $^{137}\text{Cs}$  in 230 surface soil and beach sand samples is shown in Fig. 3. Some important statistic values were calculated, and the results are shown in Table 1.



**Fig. 3** Frequency distribution of specific activities of: (a) <sup>226</sup>Ra; (b) <sup>232</sup>Th; (c) <sup>40</sup>K, and (d) <sup>137</sup>Cs in 230 surface soil and beach sand samples collected from Rayong Province.

From Fig. 3 and Table 1, it was found that the frequency distribution of specific activities of <sup>226</sup>Ra, <sup>232</sup>Th, <sup>40</sup>K, and <sup>137</sup>Cs in 230 surface soil and beach soil samples collected from Rayong Province were not symmetrical, with the skewness of 1.57, 1.95, 2.23, and 1.36, respectively. All the distributions were positive skewness or right-skewness of the data set indicating the asymmetric distributions in nature. In addition, these radionuclides showed a normal (bell-shaped) distribution, especially the

<sup>137</sup>Cs. Furthermore, <sup>226</sup>Ra, <sup>232</sup>Th, and <sup>40</sup>K presented some degree of multi-modality [25] exhibiting the complexity of minerals in soil surface and beach sand samples. It also contributed to the emission of gamma radiation in the investigated area. The median values of <sup>226</sup>Ra, <sup>232</sup>Th, <sup>40</sup>K, and <sup>137</sup>Cs were  $47.28 \pm 1.39$ ,  $18.46 \pm 0.70$ ,  $209.03 \pm 8.01$ , and  $< 0.78$  Bq/kg, respectively. Consequently, four radiological hazard indices and ELCR (outdoor) could be evaluated using this study's representative

**Table 1** Statistic values of the frequency distribution of specific activities of natural (<sup>226</sup>Ra, <sup>232</sup>Th, and <sup>40</sup>K) and anthropogenic (<sup>137</sup>Cs) radionuclides in 230 surface soil and beach sand samples collected from the studied areas.

Statistic value	Analyzed value			
	<sup>226</sup> Ra	<sup>232</sup> Th	<sup>40</sup> K	<sup>137</sup> Cs
Mean (Bq/kg)	54.09 ± 1.40	22.57 ± 0.70	299.07 ± 8.22	< 0.84
Median (Bq/kg)	47.28 ± 1.39	18.46 ± 0.70	209.03 ± 8.01	< 0.78
Mode (Bq/kg)	10.55	5.16	340.81	< 0.57
Skewness	1.57	1.95	2.23	1.36
Kurtosis	4.35	6.70	6.14	2.61
Minimum value (Bq/kg)	7.25	1.44	21.30	< 0.26
Maximum value (Bq/kg)	265.58	129.26	1654.53	< 1.95

**Table 2** The values of specific activities of natural (<sup>226</sup>Ra, <sup>232</sup>Th, and <sup>40</sup>K) and anthropogenic (<sup>137</sup>Cs) radionuclides in 12 provinces in Southern Thailand, OAP annual report data, and enlisted worldwide mean compared with the present study.

Location	Specific Activity (Bq/kg)			
	<sup>226</sup> Ra	<sup>232</sup> Th	<sup>40</sup> K	<sup>137</sup> Cs
Rayong <sup>a</sup>	47.28 ± 1.39	18.46 ± 0.70	209.03 ± 8.01	< 0.78
Songkhla P. [26]	107.28 ± 6.74	51.53 ± 5.02	3562.14 ± 223.56	3.05 ± 1.58
Nakhon Si Thammarat P. [27]	108.55 ± 31.19	73.95 ± 4.15	4313.18 ± 148.16	4.84 ± 2.59
Phatthalung P. [28]	135.89 ± 6.71	76.34 ± 5.32	3573.35 ± 203.89	4.00 ± 1.92
Chumphon P. [29]	57.32 ± 5.19	56.98 ± 4.68	2135.69 ± 168.87	2.30 ± 1.38
Surat Thani P. [30]	75.72 ± 5.75	47.77 ± 4.79	2119.10 ± 171.72	3.85 ± 1.67
Ranong P. [31]	71.39 ± 1.66	38.11 ± 1.09	470.80 ± 14.56	N.A.
Trang P. [32]	69.86 ± 3.26	79.22 ± 4.36	382.75 ± 23.45	1.72 ± 0.83
Satun P. [33]	102.54 ± 7.05	124.46 ± 4.52	4146.73 ± 251.13	5.30 ± 2.30
Yala P. [34]	128.94 ± 7.42	85.93 ± 6.13	3607.70 ± 235.48	4.53 ± 2.24
Phuket P. [35]	240.11 ± 10.79	210.68 ± 9.89	4896.45 ± 288.74	5.91 ± 2.94
Phang-Nga P. [35]	165.44 ± 8.44	160.11 ± 7.92	2879.87 ± 225.50	5.76 ± 2.49
Krabi P. [35]	65.75 ± 4.95	40.69 ± 3.96	802.58 ± 115.25	2.96 ± 1.59
South Africa [36]	271.96	47.65	87.17	N.A.
Nigeria [37]	42.95	26.84	111.05	3.56
Saudi Arabia [38]	16.73	10.40	419.78	N.A.
India [39]	30.24 ± 0.53	29.89 ± 0.61	291.06 ± 0.57	N.A.
China [40]	23.25 ± 9.40	26.90 ± 10.22	133.84 ± 42.87	N.A.
OAP (Southern region of Thailand [41])	171.55 ± 3.13	211.19 ± 1.98	511.04 ± 7.04	1.13 ± 0.49
Worldwide mean [18]	35	30	400	N.A.

<sup>a</sup> Present study; P = Province; N.A. = Not available.

median values as follows.

The median values of specific activities of all four radionuclides in 230 surface soil and beach sand samples in the investigated area were used to compare with the Office of Atoms for Peace (OAP) annual report data, some Thailand and global radioactivity measurements and evaluations as shown in Table 2 [18, 26–41].

From the result in Table 2, the median value of specific activity of <sup>226</sup>Ra of the present study was higher than the values of Nigeria, Saudi Arabia, India, China, and the worldwide mean. For

<sup>232</sup>Th, the median value of Rayong Province was only higher than the Saudi Arabia's, while the value for <sup>40</sup>K was higher than the South Africa, Nigeria, and China data. However, the median value of specific activities of <sup>137</sup>Cs was the lowest compared with all locations. It should be noticed that the obtained median value of specific activities of <sup>226</sup>Ra, which might be directly caused by the oil and gas industries [42], was comparable and close to the values of Chumphon, Trang, and Krabi Provinces in Thailand and Nigeria but was about 1.35 times higher than the worldwide mean value.

**Table 3** Comparison of the values obtained for Rayong Province to the national and international studies and evaluations, OAP data, and UNSCEAR recommended values.

Location	D (nGy/h)	Ra <sub>eq</sub> (Bq/kg)	H <sub>ex</sub>	AED <sub>out</sub> (mSv/y)	ELCR (outdoor) (×10 <sup>-3</sup> )
Rayong <sup>a</sup>	41.95 ± 1.41	89.77 ± 3.00	0.24 ± 0.01	0.05 ± 0.01	0.19 ± 0.01
Songkhla P.	229.03 ± 15.49	455.25 ± 31.13	1.23 ± 0.08	0.28 ± 0.02	1.05 ± 0.07
Nakhon Si Thammarat P.	274.68 ± 23.10	546.41 ± 48.53	1.48 ± 0.13	0.34 ± 0.03	1.26 ± 0.11
Phatthalung P.	258.14 ± 14.85	520.20 ± 30.02	1.40 ± 0.08	0.32 ± 0.02	1.19 ± 0.07
Chumphon P.	150.63 ± 12.32	303.91 ± 24.93	0.82 ± 0.07	0.18 ± 0.02	0.69 ± 0.06
Surat Thani P.	152.90 ± 12.81	308.44 ± 25.97	0.83 ± 0.07	0.19 ± 0.02	0.70 ± 0.06
Ranong P.	76.14 ± 2.05	162.14 ± 4.34	0.44 ± 0.01	0.09 ± 0.01	0.35 ± 0.01
Trang P.	202.96 ± 11.35	420.26 ± 22.89	1.13 ± 0.06	0.25 ± 0.01	0.93 ± 0.05
Satun P.	296.48 ± 16.46	599.82 ± 32.85	1.62 ± 0.09	0.36 ± 0.02	1.36 ± 0.08
Yala P.	262.33 ± 16.99	529.61 ± 34.32	1.43 ± 0.09	0.32 ± 0.02	1.21 ± 0.08
Phuket P.	446.92 ± 23.19	922.99 ± 47.37	2.49 ± 0.13	0.55 ± 0.03	2.06 ± 0.11
Phang-Nga P.	295.24 ± 18.16	616.14 ± 37.13	1.66 ± 0.10	0.36 ± 0.02	1.36 ± 0.08
Krabi P.	89.16 ± 9.53	186.35 ± 19.50	0.50 ± 0.05	0.11 ± 0.01	0.41 ± 0.04
South Africa	163.17	N.A.	N.A.	0.19	0.66
Nigeria	40.69	89.49	0.23	0.05	0.17
Saudi Arabia	31.68	63.93	0.17	0.04	0.14
India	44.16	93.41	0.24	0.05	N.A.
China	33.02 ± 12.48	72.02 ± 27.32	0.19 ± 0.07	0.04 ± 0.02	0.15 ± 0.06
OAP Data	231.81 ± 2.97	512.90 ± 6.50	1.39 ± 0.02	0.28 ± 0.01	1.07 ± 0.01
UNSCEAR [18, 23, 24]	55	370	1	0.48	1.80

<sup>a</sup> Present study; P = Province; N.A. = Not available.

### Radiological hazard indices and excess lifetime cancer risk evaluation

Using Eqs. (2)–(6) and the median values of specific activities of <sup>226</sup>Ra, <sup>232</sup>Th, and <sup>40</sup>K in Tables 1 and 2, some radiological hazard indices, including the D, Ra<sub>eq</sub>, H<sub>ex</sub>, AED<sub>out</sub>, and ELCR (outdoor) could be calculated for Rayong Province. All these values were compared with national and international studies and evaluations, OAP data, UNSCEAR recommended values (Table 3).

From Table 3, all calculated values of four radiological hazard indices and the ELCR (outdoor) in the investigated areas were lower than the national studies but comparable with the recent international measurements and studies. All values of the investigated area were lower than the OAP data and UNSCEAR recommended values. In addition, the obtained AED<sub>out</sub> value was about 1.71 times lower than the UNSCEAR recommended values. For this reason, the ELCR (outdoor) was evaluated and found to be about 1.68 times lower than the UNSCEAR recommended values as well. Therefore, it can be said that Rayong Province should be a harmless place from background natural radioactivity and has no jeopardy to people or tourists who come to visit and spend time in the area.

### The radioactive contour maps (RCM) of the investigated area

The radioactive contour maps (RCM) of <sup>226</sup>Ra, <sup>232</sup>Th, <sup>40</sup>K, and <sup>137</sup>Cs radionuclides in 230 surface soil and beach sand samples collected from Rayong Province were created by the ArcGIS computer program (Fig. 4).

The comparison of the maximum values of <sup>226</sup>Ra, <sup>232</sup>Th, and <sup>40</sup>K from Eq. (4), which were 370, 259, and 4810 Bq/kg, respectively, and the maximum value of <sup>137</sup>Cs (5.91 Bq/kg) from Table 2 gave the RCM of the four radionuclides for the investigated area as shown in Fig. 4. The data were created and appeared in green or light green color for the average level with not much different from the background radiation.

### CONCLUSION

In this study, three main results were used to consider level of radioactive contaminants and hazardous index in Rayong Province, i.e., the median values of specific activity of natural (<sup>226</sup>Ra, <sup>232</sup>Th, and <sup>40</sup>K) and anthropogenic (<sup>137</sup>Cs) radionuclides in the surface soil and beach sand samples, the four radiological hazard indices (D, Ra<sub>eq</sub>, H<sub>ex</sub>, and AED<sub>out</sub>) and the ELCR (outdoor), and the constructed RCM.

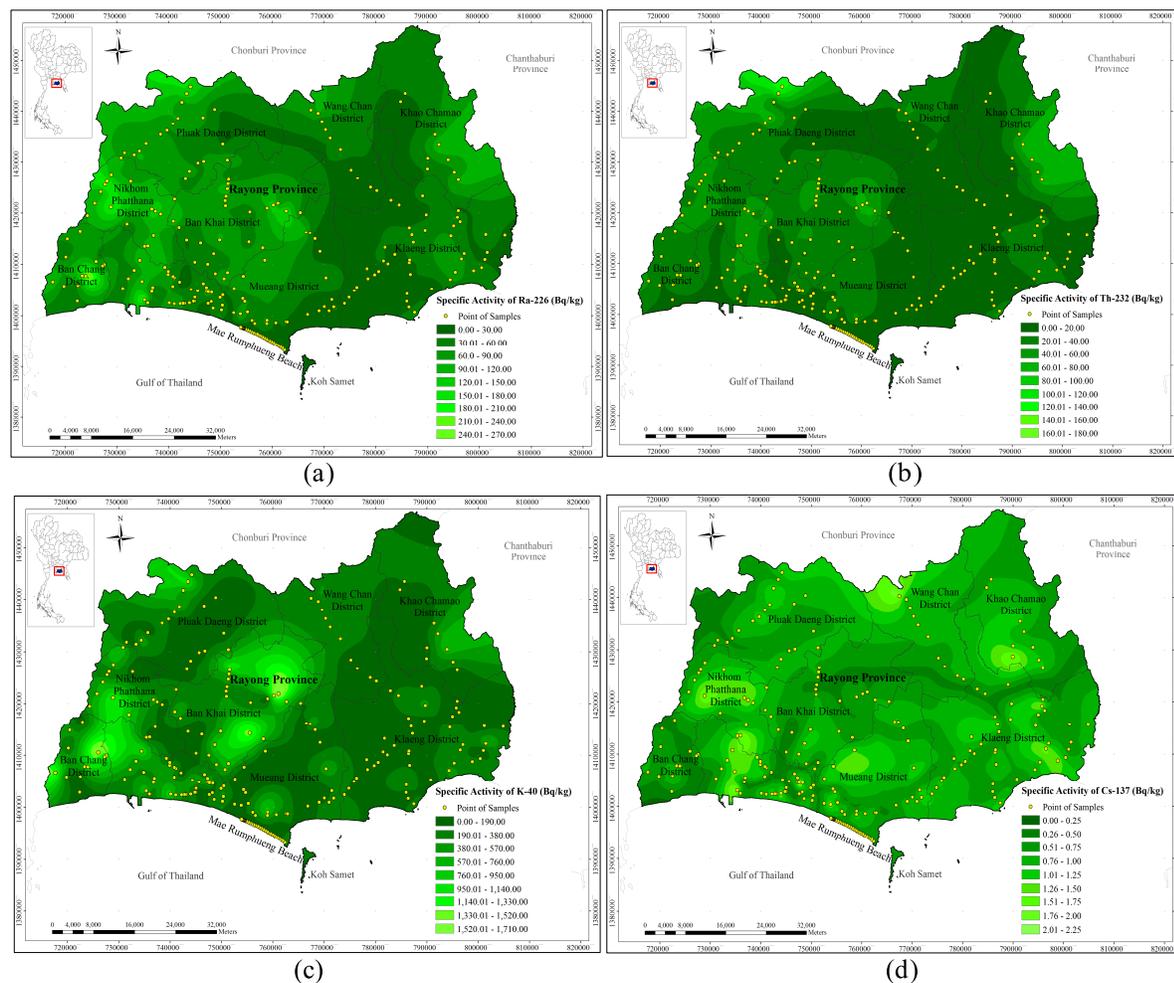


Fig. 4 RCM of: (a)  $^{226}\text{Ra}$ ; (b)  $^{232}\text{Th}$ ; (c)  $^{40}\text{K}$ ; and (d)  $^{137}\text{Cs}$  in surface soil and beach sand samples in Rayong Province.

Most of the values obtained, except for the median value of  $^{226}\text{Ra}$ , were closed to or lower than previous national and international data, especially the OAP data and UNSCEAR recommended values. Moreover, all of the RCMs were in the same background radiation level. For this reason, the radioactive contaminants from the oil and gas extraction industry and human activities would not have a significant effect on surface soil and beach sand in Rayong Province. However, since the distribution of natural radionuclides ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ ) is the multimodal feature, the gamma emission activities in the studied area might be more or less mixed and accumulated. In addition, precaution has to be made from the finding that the median value of  $^{226}\text{Ra}$ , which is the highest concentration of natural radioactive material in the petroleum industry of the present study was higher than the UNSCEAR recommended value. This notification should require

more attention and continuous monitoring during some routine operation in the studied area. For a beneficial aspect, all median values and associated calculations presented in this study can be used as a database to compare, monitor, and quantify possible changes in ecological radioactivity due to nuclear, accident, and other human activities in the future.

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