Natural radioactivity measurement and radiological hazard evaluation in surface soils in a gold mining area and surrounding regions in Bolikhamxay province, Laos

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Abstract

Measurement of natural radioactivity in surface soils in a gold mining area and surrounding regions in Bolikhamxay province, Laos has been conducted using an HPGe detector. Soil samples were collected at 65 locations distributed widely in Bolikhamxay province, including 25 samples in the gold mining area in Khamkheut district. The average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K are obtained as 44.4 ± 3.2, 63.3 ± 5.2 and 523 ± 18 Bq kg^{-1}, respectively. The calculated average radium equivalent activity is 175 ± 20 Bq kg^{-1}. Radiological hazard indices in the gold mining area are higher than the average values in the province by 15–20%.

Keywords Soil sample · Activity concentration · Radiological hazard · Gold mining

Introduction

Primordial radionuclides incorporated in surface soils contribute mostly to the natural terrestrial gamma exposure [1]. Soils are considered as the main sources to distribute radioactive nuclides to other environments such as water, air, sediments and biological systems. The radioactivity in food grains is also dependent on that in surface soils. Hence, surface soils are considered as essential sources to assess the radiological exposure, and to evaluate the environmental radiological contamination. For environmental protection purpose, measurement of radioactivity in surface soils is considerably important to assess the change of natural radioactivity and to evaluate the effect on environment in case of radioactive release [2].

The decay series of ^{238}U, ^{232}Th and ^{40}K contribute mostly to natural radioactivity in soils. ^{238}U decay series is also referred to as ^{226}Ra series because the contribution of ^{226}Ra subseries in the external gamma dose is about 98.5% [3]. Radioactivity at mining areas is usually higher than surrounding regions because mining activities expose natural occurring radioactive materials (NORMs) to the earth's surface, and therefore increasing the background gamma radiation levels [1]. Mining is a major technological concern of the enhancement of NORM concentrations [1, 4]. Consequently, it is essential to measure the radioactivity concentrations of the major primordial radionuclides in the soil mine tailings and assess the gamma radiation exposure of humans and living systems. It is because long-term exposure to radiation can cause harmful health effects, such as chronic lung diseases, anemia and different cancers [1, 4, 5]. The high concentrations of natural radioactivity and ^{226}Ra/^{238}U disequilibrium were indicated as the main cause of cancers in Penang, Malaysia [5]. Thus,

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many attempts have been done to assess the natural radioactivity and radiation exposure in mining areas [4, 6–10]. It is noticed that in some places the activity concentrations of NORMs in mining areas are relatively high compared to the world average.

The world average radioactivity concentrations of [226]Ra, [232]Th and [40]K in soils are 35, 30 and 400 Bq kg^{-1}, respectively [1]. Though the values are relatively low, they may vary in a large range at different places. The variation of activity concentrations can be up to 1000, 360 and 3200 Bq kg^{-1} for [238]U, [232]Th and [40]K, respectively [11]. There has been increasing interest in assessing and establishing baseline data of the natural activity concentrations and related radiological hazards in soils in many countries [2, 3, 12–17]. Many research activities on natural radioactivity levels have also been conducted in neighboring countries of Laos in Southeast Asia such as Vietnam [17–19], Thailand [20–22], Malaysia [5, 10, 13, 23], and so on. It is noticed that the concentrations of natural radioactivity in soils in several places in Malaysia are in wide variation and relatively high compared to neighboring countries. In particular, the activity concentrations of main radioactive nuclides in soils in Kinta district in Perak state, Segamat district in Johor state and Penang state, Malaysia were reported about few times higher than the world average values [5, 10, 23]. This may be resulted from geological formations and soil types of the regions. In Laos, several attempts have been done to assess the activity concentrations of NORMs in surface soils and building materials, however the studies are still very limited until present [24, 25]. Therefore, it is of high important to perform the measurement of natural radioactivity in surface soils, and to establish the baseline data in Laos for evaluating the radiological impact to population and for the purpose of environmental protection.

In the attempt for establishing the baseline data of the natural radioactivity in soils in the middle of Laos, a previous work conducted the measurement of the radioactivity concentrations and associated radiological hazard indices in surface soils in Savannakhet province, one of the three provinces in the middle of Laos [24]. The present work presents the assessment of the natural radionuclide concentrations and radiological hazards in surface soils in a gold mining area and surrounding regions in Bolikhamxay province in continuation of the establishment of a baseline data in the middle of Laos. Moreover, the mining activities in Laos have just been officially recorded since 2003, and the mining activity in the study region was started in 2015. This assessment would be of beneficial and can be considered as the first monitor of natural radioactivity levels in this mining area. Comparison of the data obtained in Bolikhamxay province with neighboring and worldwide regions has also been presented.

Materials and methods

Study area and sample collection

Laos is a Southeast Asian country located on the latitude of 14.117°–23.684°N and the longitude of 100.413°–108.832°E. Bolikhamxay province locates in the middle of Laos on the latitude of 18.43°N and the longitude of 104.47°E. The area of Bolikhamxay province is about 15,977 km^2, and the population is about 273,000. The altitude of the province is in the range of 140–1588 m. Bolikhamxay province has the same borders with Xiangkhouang province to the northwest, Thailand to the west, Vietnam to the east, and Khammouan province to the south. Bolikhamxay province consists of seven administrative districts of Pakkan, Thaphabat, Pakkading, Borikhan, Viengthong, Khamkheut, and Xaichamphon. Bolikhamxay is known as a rich place of natural and cultural resources with three national protected areas of PhouKhaoKhouay, Nam Ka Ding and a part of Theun-Nakai. The climate of Bolikhamxay is tropical monsoon with average temperature of 21–31°C. Rainy season lasts from May to September, and from October to April is the dry season. Khamkheut district is a mountainous region in the south of the province with average temperature of about 11°C during winter. A gold mining area locates in Khamkheut district, which is close to agricultural fields and about 3 km from Pakxan city. Therefore, it is of high important to assess the natural radioactivity around the gold mining area in comparison with other regions in the province.

Figure 1 displays the geological map of Bolikhamxay province with the sampling locations. The geological formations of Bolikhamxay province could be zoned in three parts from East North to South West (EN–SW). All formations have a similar tendency with the strike of West North–South East (WN–NS). The EN part includes intrusive and volcanic rocks which compose of granitoid gneiss, granite, mica gneiss, arenite, marble, and mafic volcanic rocks. This zone forms the gold mining area in Khamkheut district. The middle part is sedimentary rocks, which include red clyed arenite, gravel, and limestone with some clay, coal, silt, and conglomerate. The last one is dominated by arenite, limestone with some clay, coal, weathering rocks, and the south and north of this part exist some granite intrusive rocks.

Soil samples were collected at 65 locations (S1–S65) distributed widely in Bolikhamxay province, in which 25 samples (S21–S45) were collected in the gold mining area in Khamkheut district and 40 samples were collected around populated areas and agricultural fields as shown in Fig. 1. In Khamkheut district, five other samples (S16–S20) were also collected outside the gold mining
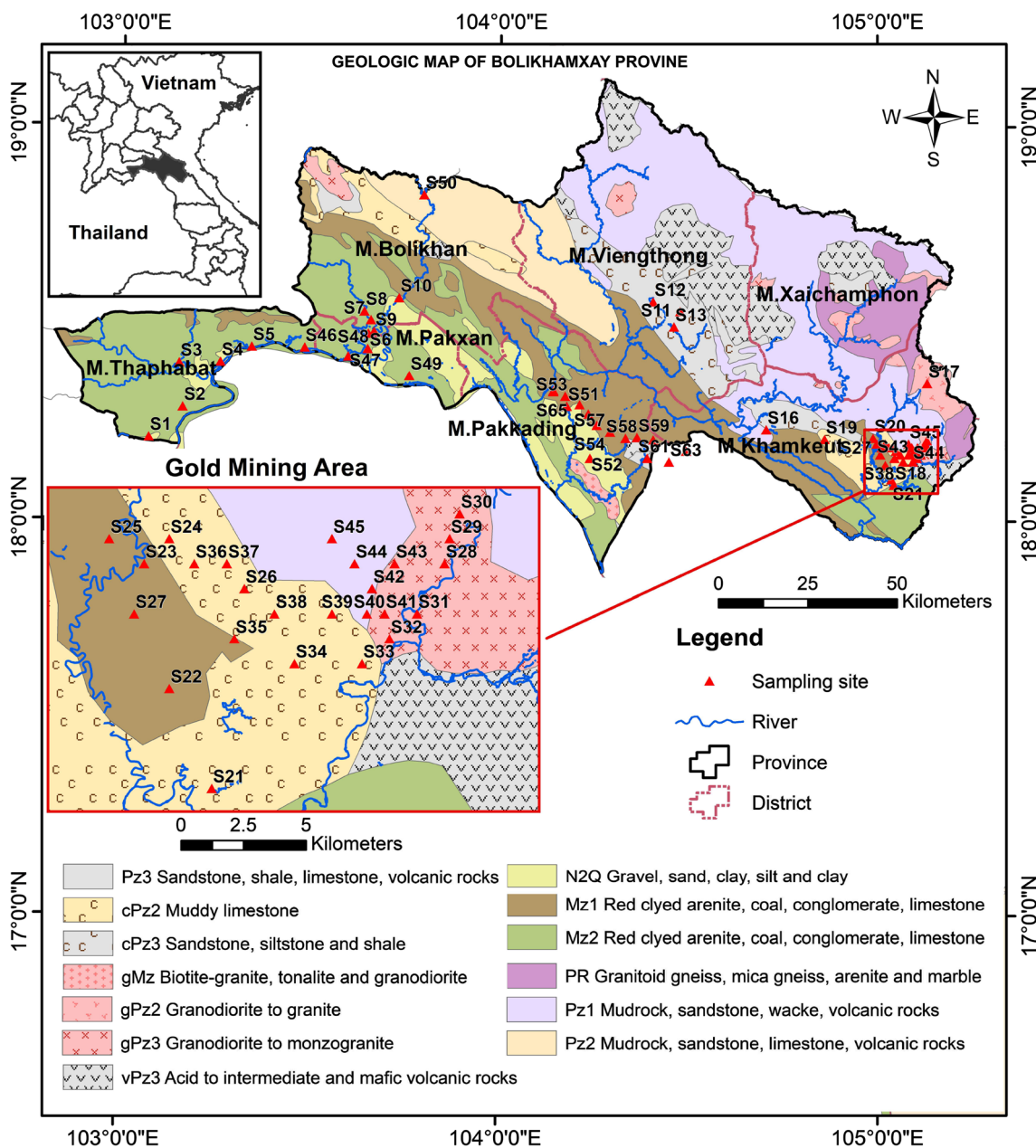
Fig. 1 Geologic map of Bolikhamxay province and the locations of soil samples

area, and thus, the total number of samples collected in this district was 30. The soil samples were collected in January 2019. This time period was the dry season with the outdoor temperature of about 25–30°C. The soils were collected at the depth of 5–30 cm from the surface. At each location, a square of 60 cm × 60 cm was determined. The square surface was then flattened for collecting soils. Five topsoil samples, i.e., one at the center and four at the corners of the square, were collected and mixed up. An amount of about 1–2 kg was collected based on a quartile method to transport to the laboratory. At the

laboratory, organic materials and pieces of stone in soils were removed, and the soils were air dried for 24–48 h. After that, the soils were dried at the temperature of 110°C for about 10 h for obtaining unchanged mass. The soils were then crushed and served into 0.2 mm-diameter samples using a mesh. The samples were then put in a polyethylene cylinder with 75-mm diameter and 30-mm height. The samples were stored for a month to obtain secular equilibrium between ^{226}Ra with ^{214}Bi and ^{214}Pb before measurements.

Calibration of detector efficiency

The radioactivity of the soil samples was measured using the Canberra low background gamma spectrometer with an HPGe detector (Model-BE6530) connected to a PC–based 8192 channel analyzer. In the measurement of the gamma ray spectrum, the soil sample was put on the top of the detector. The spectra were then analyzed using Genie 2000 software. Calibration of the detector for determining the efficiency curve with gamma ray energy was performed using the IAEA RGU-1 and RGTh-1 reference materials. The reference materials RGU-1 and RGTh-1 was measured for about 60,000 s, while the standard sample IAEA–375 and the soil samples were measured during a period of 86,400 s to reduce the statistical errors. Background measurement was also conducted during a period of 160,000 s. The detector efficiency curve was constructed based on the efficiency at the peaks of 46.5 keV of ^{210}Pb, 63.3 keV of ^{232}Th, 186.2 keV of ^{226}Ra, 295.22 keV and 351.93 keV photopeaks of ^{214}Pb, 609.31 keV, 1120.29 keV and 1764.49 keV peaks of ^{214}Bi, and 1460 keV peak of ^{40}K. The detector has a relative efficiency of 60% and resolution of 1.9 keV at 1333 keV photopeak of ^{60}Co. Figure 2 shows the efficiency curve of the HPGe detector as a function of gamma ray energy.

To evaluate the detector efficiency curve, the detector was used to measure the radioactivity of the IAEA-375 reference material and compared with the reported values. Table 1 shows the radioactivity concentrations of ^{228}U, ^{232}Th, ^{40}K and ^{137}Cs measured by the HPGe detector and the reported values of the IAEA-375 reference material. The deviations of the activity concentrations are within 3.4%, which is less than the uncertainty of the measurement and is acceptable for further use in the measurement of soil samples. Figure 3 displays a typical gamma spectrum of
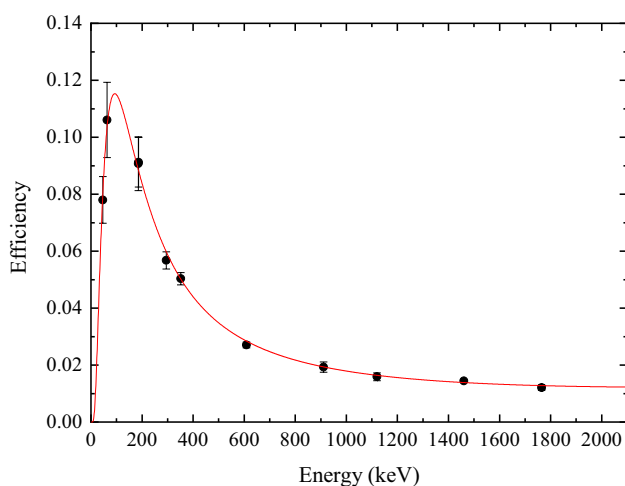
Fig. 2 Detector efficiency curve as a function of gamma ray energy
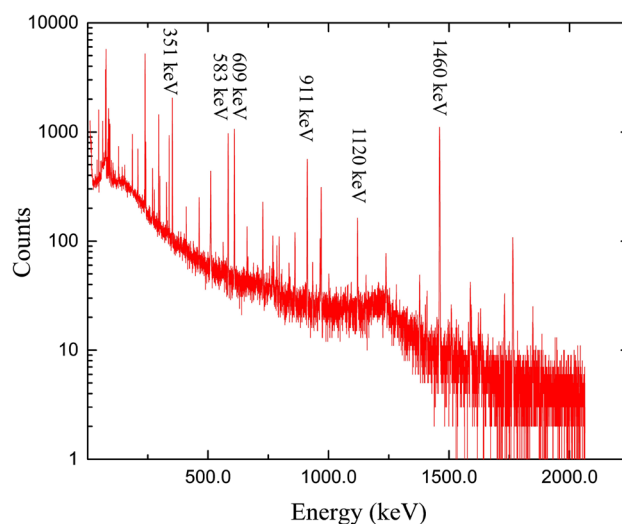
Fig. 3 Gamma ray spectrum of soil sample S53 measured by the HPGe detector

sample S53 collected in the gold mining area in Khamkheut district.

Radioactivity measurement

Measurement of gamma ray spectrum of a soil sample was conducted during 86,400 s to reduce the statistic errors (1σ) of important peaks within 5%. For instance, ^{226}Ra activity concentration is evaluated via the 295.57 keV (with the branching ratio of 0.1841) and 351.9 keV (0.3560) of ^{214}Pb, and the 609.3 keV (0.4549) and 1120.3 keV (0.1491) peaks of ^{214}Bi. ^{232}Th activity concentration is evaluated from the 338.6 keV (0.1127) and 911.1 keV (0.258) peaks of ^{228}Ac and the 583.19 keV (0.3055) peak of ^{208}Tl. While, ^{40}K activity concentration is evaluated based on its gamma line of 1460 keV (0.1066). The branching ratios and their uncertainties were taken from Ref. [26]. The activity concentration of a radionuclide is denoted as A in Bq kg^{-1} unit, and is calculated as [27]:

Table 1 Comparison of the radioactivity concentrations of ^{228}U, ^{232}Th, ^{40}K and ^{137}Cs of IAEA-375 reference material measured by the HPGe detector

Radionuclides	This measurement (Bq kg^{-1})	Reference (Bq kg^{-1})	Difference (%)
^{228}U	19.6 ± 2.3	20 ± 2	− 2.0
^{232}Th	19.8 ± 2.1	20.5 ± 2.7	− 3.4
^{40}K	416.2 ± 20.9	424.2 ± 7.0	− 1.9
^{137}Cs	2874 ± 198	2905.2 ± 187.4	− 1.1

$$A(\mathrm{Bq\,kg^{-1}}) = \frac{n}{\epsilon \times I_{eff} \times m_s},\tag{1}$$

where n is the net counting rate (cps) for a peak at a specific energy; ϵ is the detector efficiency; I_{eff} is the gamma emission probability; and m_s is the mass of soil sample. Together with the activity concentrations, 2σ standard uncertainties are also evaluated based on the uncertainties of related quantities such as the counting rate n, the detector efficiency ϵ, the branching ratios and the mass of soil sample m_s.

Calculation of radiological hazards

In order to evaluate the effect of natural activity concentrations of the radioactive nuclides, radiological hazard indices have been calculated, such as radium equivalent activity (Ra_{eq}), absorbed gamma dose rate (D), annual effective dose equivalent ($AEDE$), and external and internal hazard indices (H_{ex} and H_{in}). The formula of Ra_{eq} is written as [28, 29]:

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \tag{2}$$

where A_{Ra}, A_{Th} and A_K stand for the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively.

The value of D at 1 m above the ground is calculated as [30]:

$$D(\mathrm{nGy.h^{-1}}) = 0.46A_{Ra} + 0.62A_{Th} + 0.042A_K, \tag{3}$$

where the conversion factors of 0.46, 0.62, and 0.042 nGy h^{-1} are used for ^{226}Ra, ^{232}Th and ^{40}K, respectively.

The formula of $AEDE$ is written as [1]:

$$AEDE(\mathrm{mSv\,y^{-1}}) = D \times DCF \times OF \times T \tag{4}$$

where D (nGy h^{-1}) is obtained in Eq. (3); $DCF = 0.7$ Sv Gy^{-1} is the dose conversion factor; $OF = 0.2$ is the

outdoor occupancy factor, and $T = 8760$ h is the time factor [1, 31].

The H_{ex} and H_{in} are calculated as follows [29, 32]:

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810}, \tag{5}$$

and

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810}. \tag{6}$$

Results and discussion

Activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K

Table 2 shows the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the six districts of Bolikhamxay province. The activity concentration of ^{226}Ra are obtained in the range of 13.0–90.0 Bq kg^{-1} with the average value of 44.4 ± 4.6 Bq kg^{-1}. The ^{232}Th activity concentrations are within the range of 11.1–99.4 Bq kg^{-1}, and the average value is 63.2 ± 5.2 Bq kg^{-1}. Whereas, the activity concentrations of ^{40}K vary in the range of 37.5–999 Bq kg^{-1} with the average value of 523 ± 18 Bq kg^{-1}. Compared to the world average values, the average activity concentrations in Bolikhamxay are higher by factors of 1.3–2.0 [1].

Khamkheut and Viengthong districts, where the geological formation is dominated by intrusive and volcanic rocks, are recorded with higher average activity concentrations compared to the whole province. Some samples with higher activity concentrations are also found in Thaphabat and Bolikhan districts, where the geological formation of arenite, limestone with some clay, coal and weathering rocks is expected with high variation of radioactivity level. The

Table 2 Activity concentrations of radionuclides in soil samples in Bolikhamxay province

| District name | Samples | Activity concentration (Bq kg^{-1}) | | | | | | | |
| | | ^{226}Ra | | ^{232}Th | | ^{40}K | | Ra_{eq} | |
		Average	Range	Average	Range	Average	Range	Average	Range
Thaphabat	S1–S5	47.4 ± 6.4	41.3–52.6	69.6 ± 9.6	51.3–85.3	505 ± 23	141–980	186	126–245
Bolikhan	S6–S10	57.7 ± 6.5	31.8–90.0	58.9 ± 5.5	32.2–93.2	483 ± 33	164–730	179	90.6–279
Viengthong	S11–S15	50.6 ± 5.7	36.9–65.4	66.1 ± 8.1	57.2–79.5	476 ± 25	339–602	183	145–224
Khamkheut	S16–S45	48.8 ± 4.2	22.9–73.3	72.1 ± 4.2	38.6–99.4	617 ± 16	307–999	199	123–277
Pakxan	S46–S49	29.3 ± 3.7	13.0–58.4	36.6 ± 4.9	11.1–73.9	206 ± 13	134–341	97.4	39.2–190
Pakkading	S50–S65	33.1 ± 4.2	17.9–65.6	51.9 ± 4.7	32.4–95.7	455 ± 16	37.5–715	142	83.8–205
Gold mining area	(S21–S45)	48.5 ± 3.6	22.9–71.8	72.6 ± 3.2	38.6–99.4	642 ± 14	339–999	202	145–277
Average		44.4 ± 3.2	13.0–90.0	63.2 ± 5.2	11.1–99.4	523 ± 18	37.5–999	175	39.2–279
World average		35	–	30	–	400	–	89	–

highest [226]Ra activity concentration of 90.0 ± 12.8 Bq kg^{-1} is found at sample S7 in Bolikhan. The highest [232]Th activity concentration of 99.4 ± 3.5 Bq kg^{-1} is determined at sample S40 in the gold mining area in Khamkheut district. Khamkheut also corresponds to the highest [40]K activity concentration of 999 ± 16 Bq kg^{-1}. The average activity concentrations in the gold mining area are higher than that in the whole province by factors of 1.1–1.2 as shown in Table 2.

It is noticed that the activity concentrations are smaller in the soil samples in Pakxan and Pakkading districts, where the geological formation is dominated by arenite, limestone with some clay, coal and weathering rocks. For example, samples S46, S48 and S49 in Pakxan correspond to the lowest [226]Ra and [232]Th activity concentrations. The values are about 13.0–24.0 Bq kg^{-1} for [226]Ra and 11.1–31.6 Bq kg^{-1} for [232]Th, respectively. Pakxan and Pakkading are also noticed with the lowest [40]K activity concentrations, e.g., the lowest value of 37.5 ± 2.7 Bq kg^{-1} is determined at sample S52 in Pakkading.

Table 3 compares the activity concentrations of NORMs in surface soils in Bolikhamxay province with that in neighboring and worldwide regions. Comparing with neighboring regions, the values obtained in Bolikhamxay province are about 2.0 times greater than that obtained in Savannakhet province and approximate and slightly higher than that in neighboring provinces in Viet Nam such as Nghe An, Ha Tinh, and Quang Binh [17, 24]. However, as reported in Ref. [17], only a few soil samples were collected in each province in Viet Nam. As shown in Table 3, Bolikhamxay is among the regions with radioactivity concentrations at medium levels compared to worldwide regions, but still much lower compared to Penang, Perak and Johor states in Malaysia [5, 10, 23]. The high activity concentrations in surface soils in several states in Malaysia are ascribed to the geological formations of these regions. In particular, the high activity concentrations in Penang state correspond mainly to some areas underlain by granite bedrocks. It is worth mentioning that the data reported for Perak state were taken at an old tin mining region in Kinta district. Whereas, the highest activity concentrations of [226]Ra and [232]Th in Johor state correspond to the soil samples at the locations with the tertiary geological formation. The highest concentrations of [40]K was obtained at the locations with the triassic geological formation.

Table 3 Activity concentrations of radionuclides in Bolikhamxay province in comparison with other worldwide regions

Region	Activity concentration (Bq kg^{-1})			References
	[226]Ra	[232]Th	[40]K	
Bolikhamxay, Laos	44[a] (13–90)[b]	63 (11–93)	523 (38–999)	This work
Savannakhet, Laos	22[a] (7–74)[b]	31 (4–114)	212 (14–906)	[24]
Nghe An, Vietnam	55	75	438	[17]
Ha Tinh, Vietnam	45	63	488	[17]
Quang Binh, Vietnam	39	48	319	[17]
Southern Thailand	29 (4–122)	44 (6–170)	344 (5–1422)	[20]
Perak, Malaysia	112 (12–426)	246 (19–1377)	277 (19–2204)	[10]
Johor, Malaysia	162 (12–968)	261 (11–1210)	300 (12–2450)	[23]
Penang, Malaysia	396	165 (16–667)	835 (87–1827)	[5]
Xi'an, China	36 (28–49)	51 (44–61)	733 (640–992)	[36]
Japan	33 (6–98)	28 (2–88)	310 (15–990)	[1]
India	29 (7–81)	64 (14–160)	400 (38–760)	[1]
Iran	28 (8–55)	22 (5–42)	640 (250–980)	[1]
Turkey	21 (10–44)	25 (9–37)	299 (144–401)	[35]
Denmark	17 (9–29)	19 (8–30)	460 (240–610)	[1]
Switzerland	40 (10–900)	25 (4–70)	370 (40–1000)	[1]
Poland	26 (5–120)	21 (4–77)	410 (110–970)	[1]
Greece	25 (1–240)	21 (1–190)	360 (12–1570)	[1]
Romania	32 (8–60)	38 (11–75)	490 (250–1100)	[1]
Spain	32 (6–250)	33 (2–210)	470 (25–1650)	[1]
Niger Delta, Nigeria	18 (11–40)	22 (12–46)	210 (69–530)	[34]
World average	32	45	412	[1]

[a]Average activity concentration

[b]Range of activity concentration

Radium equivalent activity, absorbed gamma dose rate, annual effective dose equivalent, and external and internal radiological hazard indices

Radium equivalent activity

Since NORMs are distributed non-uniformly in soils, the Ra_{eq} is used to quantify the total activity. Figure 4 shows the calculated Ra_{eq} of 65 soil samples in Bolikhamxay province. The Ra_{eq} values are obtained in a wide range of 39–279 Bq kg^{-1}. The average value is 175 ± 20 Bq kg^{-1}, which is higher than the world average value by a factor of 2.0. The contributions of the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the Ra_{eq} are about 25, 52 and 23%, respectively. Analysis of the relationship between the Ra_{eq} and the activity concentrations of the radioactive nuclides shows strong correlation of the quantities as shown in Fig. 5. The correlation coefficients (R^2) of the Ra_{eq} and the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K are 0.7718, 0.9036 and 0.6339, respectively. The average Ra_{eq} of Khamkheut district, where the gold mining area locates, is 199 ± 22 Bq kg^{-1}. This value is higher than the average value in the whole province by 14%. The highest Ra_{eq} of 279 ± 19 Bq kg^{-1} is still lower than the safety limit of 370 Bq kg^{-1} [1].

Absorbed gamma dose rate

Table 4 presents the average and range of the calculated radiological hazard indices. Figure 6 displays the calculated D (nGy h^{-1}) of the terrestrial gamma radiation in 65 soil samples in Bolikhamxay. The values are obtained in the range of 18.5–130.6 nGy h^{-1} with the highest value of 130.6 nGy h^{-1} determined at sample S41 in the gold mining area in Khamkheut district. The average value of D in Bolikhamxay province is 81.6 ± 6.1 nGy h^{-1}, which is about 1.38 times greater than the world average value as shown in Table 4. It is also noticed that the D value in the gold mining area is about 16% higher than the average value in the province. The contributions of ^{226}Ra, ^{232}Th and ^{40}K to the calculated D are 25, 48 and 27%, respectively.

Annual effective dose equivalent

The calculated *AEDE* values associated with the soil samples are obtained in the range of 0.02–0.16 mSv y^{-1} as shown in Fig. 7 and Table 4. The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K contribute about 25, 48 and 27% to the calculated *AEDE*, respectively. The highest *AEDE* value of 0.16 mSv y^{-1} is obtained in the gold mining area in Khamkheut district. The average *AEDE* in Bolikhamxay province is 0.10 mSv y^{-1}, while the average value in the gold mining area is 0.12 mSv y^{-1}. These values are smaller than the world average value [1], and are much lower than the safety limit of 1.0 mSv y^{-1} for humans living in the area [33].

External and internal radiological hazards

Calculated H_{ex} and H_{in} of the soil samples in Bolikhamxay province show that the H_{ex} varies from 0.10 to 0.76 with the average value of 0.47. Whereas, the H_{in} index varies from 0.14 to 1.00 with the average value of 0.59. The
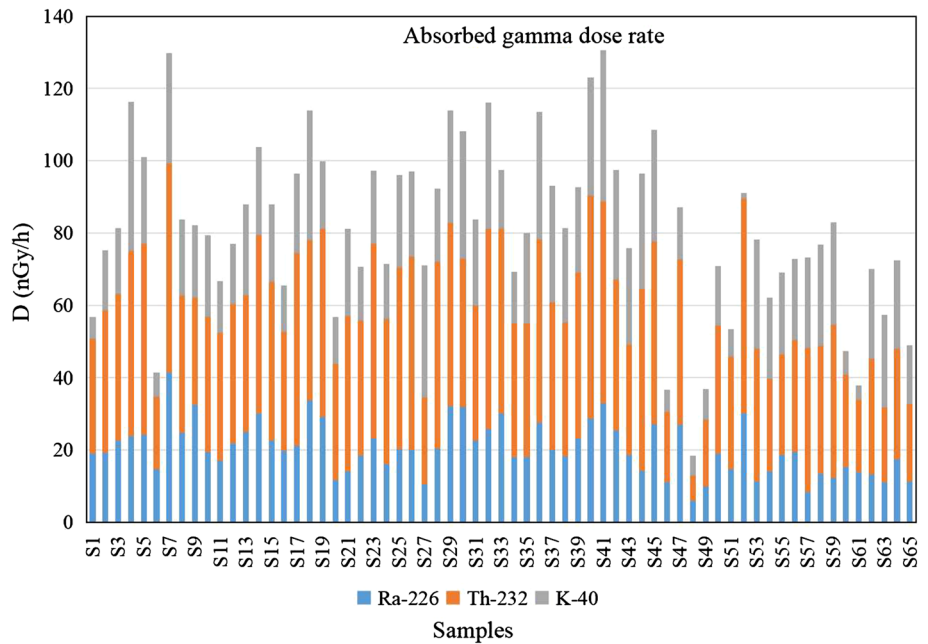
Fig. 4 Radium equivalent activity in soil samples in Bolikhamxay province
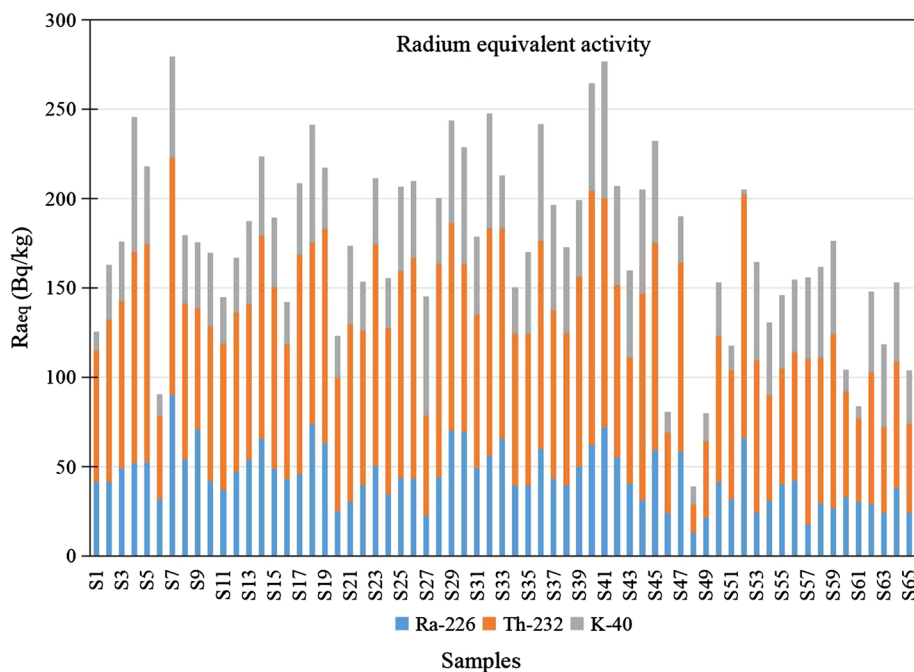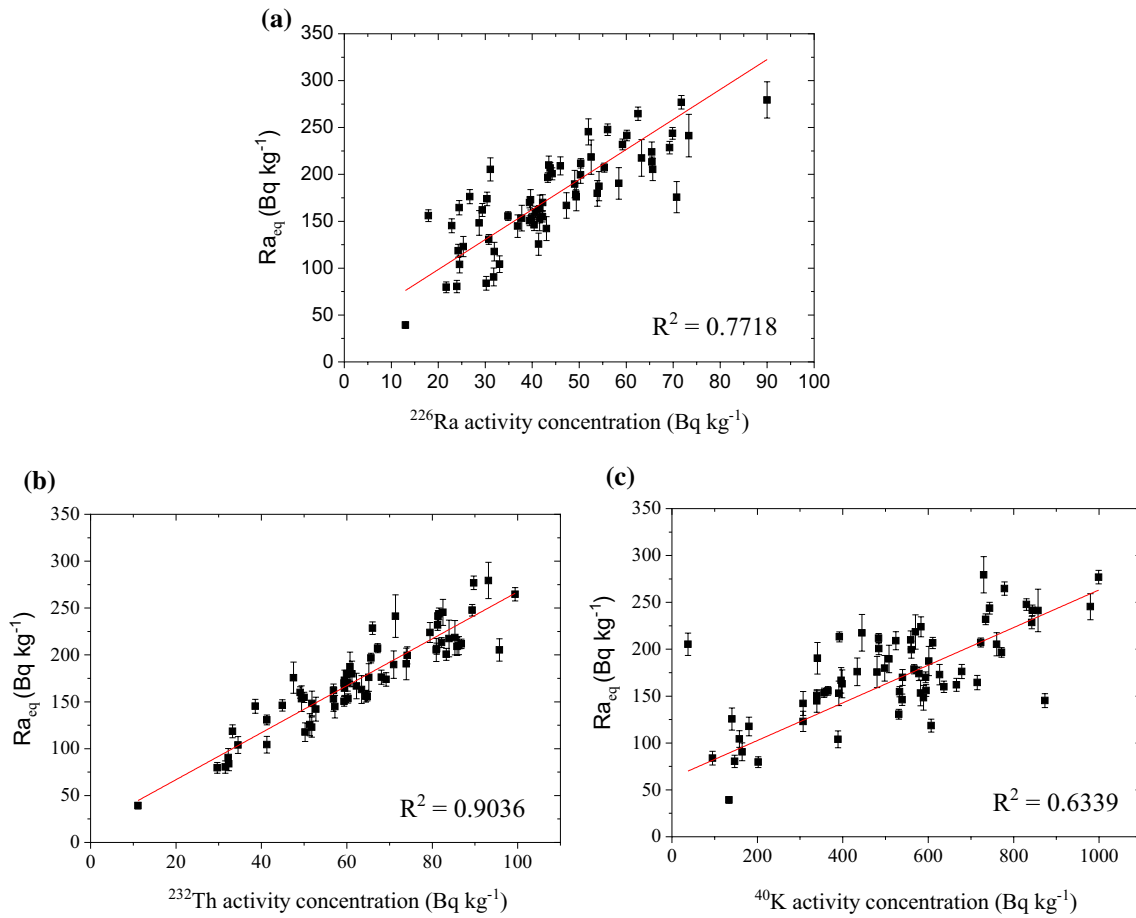
Fig. 5 Correlation between the Ra_{eq} and the activity concentrations of ^{226}Ra (**a**), ^{232}Th (**b**) and ^{40}K (**c**)


Fig. 6 Absorbed gamma dose rate in soil samples in Bolikhamxay province

Table 4 Calculated radiological hazard indices in soil samples in Bolikhamxay province

District name	Samples	D		AEDE		H_{ex}		H_{in}	
		Average	Range	Average	Range	Average	Range	Average	Range
Thaphabat	S1–S5	86.1	56.7–116.2	0.11	0.07–0.14	0.50	0.34–0.66	0.63	0.45–0.80
Bolikhan	S6–S10	83.3	41.5–129.8	0.10	0.05–0.16	0.48	0.24–0.75	0.64	0.33–1.00
Viengthong	S11–S15	84.7	66.7–103.9	0.10	0.08–0.13	0.49	0.39–0.60	0.63	0.49–0.78
Khamkheut	S16–S45	93.0	56.7–130.6	0.11	0.07–0.16	0.54	0.33–0.75	0.67	0.40–0.94
Pakxan	S46–S49	44.8	18.5–87.0	0.05	0.02–0.11	0.26	0.11–0.51	0.34	0.14–0.67
Pakkading	S50–S65	66.5	37.9–91.1	0.08	0.05–0.11	0.38	0.23–0.55	0.47	0.31–0.73
Gold mining area	(S21–S45)	94.3	69.2–130.6	0.12	0.08–0.16	0.55	0.39–0.75	0.68	0.45–0.94
Average		81.6	18.5–130.6	0.10	0.02–0.16	0.47	0.10–0.76	0.59	0.14–1.00
World average		59	–	0.7	–	–	–	–	–
Limit		–	–	1.0	–	1.0	–	1.0	–

Fig. 7 Annual external effective dose rate in soil samples in Bolikhamxay province
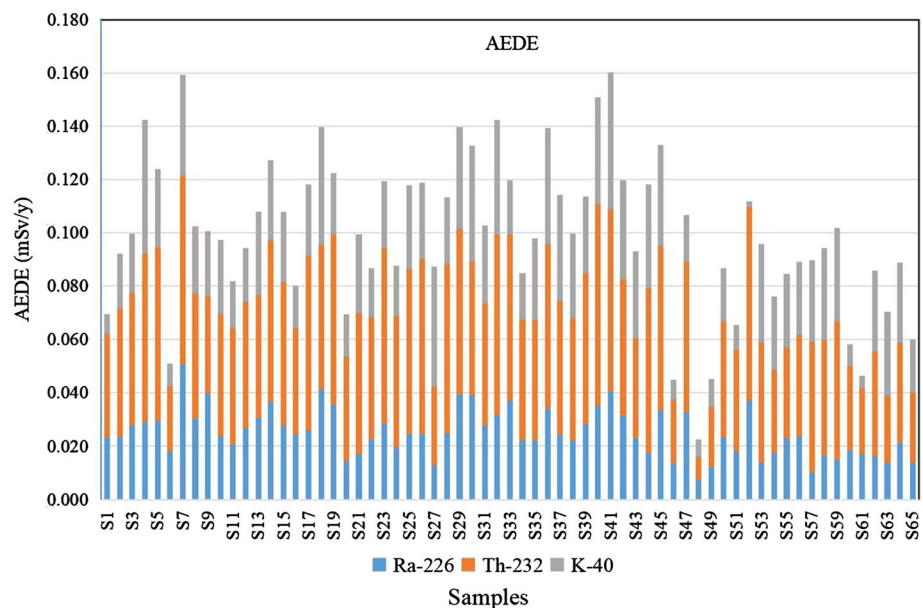
contributions of ^{226}Ra, ^{232}Th and ^{40}K to the H_{ex} are about 25, 52 and 23%, and the contributions to the H_{in} are 41, 41 and 18%, respectively. The values of H_{ex} and H_{in} in all soil samples are less than unity. The results imply no significant effect to human health.

Table 5 compares the radiological hazards in surface soils in Bolikhamxay province with that of neighboring and worldwide regions. The radium equivalent activity and other radiological hazards obtained in Bolikhamxay are almost two times greater than that of Savannakhet province, and are approximate the values of the neighboring provinces in Viet Nam (Nghe An and Ha Tinh) as displayed in Table 5. The values are among medium group, but much smaller than that in Penang, Perak and Johor states in Malaysia [5, 10, 23].

Conclusions

Natural radioactivity measurement and radiological hazard evaluation in surface soils in the gold mining area and surrounding regions in Bolikhamxay province, Laos have been performed for establishing the baseline data in the middle of Laos. Soil samples were collected at 65 locations distributed widely in Bolikhamxay province, including 25 samples in the gold mining area in Khamkheut district and 40 samples around populated areas and agriculture fields. The average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in Bolikhamxay province vary are 44.4 ± 3.2, 63.2 ± 5.2 and 523 ± 18 Bq kg^{-1}, respectively. Whereas, the values in the gold mining area underlain mainly by intrusive and volcanic rocks are about 20% greater than that of the whole province.

Table 5 Comparison of radiological hazard indices in soil samples in Bolikhamxay province and other regions

Region	Ra_{eq} (Bq kg^{-1})	D (nGy h^{-1})	$AEDE$ (mSv y^{-1})	H_{ex}	H_{in}	References
Bolikhamxay, Laos	175[a] (39–279)[b]	82 (18–130)	0.10 (0.02–0.16)	0.47 (0.10–0.75)	0.59 (0.14–0.99)	This work
Savannakhet, Laos	83[a] (17–300)[b]	37 (8–137)	0.05 (0.01–0.17)	0.22 (0.05–0.81)	0.28 (0.07–1.01)	[24]
Nghe An, Vietnam	196	87	–	0.53	–	[17]
Ha Tinh, Vietnam	173	78	–	0.47	–	[17]
Quang Binh, Vietnam	134	60	–	0.36	–	[17]
Perak, Malaysia	478 (52–2227)	222 (39–1039)	–	–	–	[10]
Penang, Malaysia	696 (268–1103)	315 (125–496)	–	1.78 (0.72–2.98)	2.9 (1.07–5.08)	[5]
Southern Thailand	126 (14–446)	58 (6–203)	0.07 (0.01–0.25)	0.34 (0.04–1.20)	–	[20]
Xi'an, China	166 (148–199)	79 (71–96)	0.10 (0.09–0.12)	–	–	[36]
China	(230–676)	(86–237)	(0.10–0.29)	(0.60–1.80)	–	[37]
Nigeria	(50–110)	(23–52)	(0.03–0.06)	(0.14–0.29)	(0.18–0.37)	[34]
Jordan	(12–702)	(45–73)	(0.05–0.08)	(0.87–4.0)	–	[12]

[a]Average value

[b]Range of the values

Compared to the world average values, the average activity concentrations in Bolikhamxay province are greater by factors of 1.3–2.0. The average Ra_{eq} is 175 ± 20 Bq kg^{-1}, which is greater than the world average value by a factor of 2.0. The contributions of ^{226}Ra, ^{232}Th and ^{40}K in the Ra_{eq} are about 25, 52 and 23%, respectively. Strong correlation between the Ra_{eq} and the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K has also been obtained. Associated radiological hazard indices such as D, $AEDE$, H_{ex} and H_{in} are calculated as 81.6 nGy h^{-1}, 0.10 mSv y^{-1}, 0.47 and 0.59, respectively, of which the activity concentration of ^{232}Th contributes about 40–50%. These values are still less than the safety limits. This means that there is no significant effect to humans living in the area.

Compliance with ethical standards

Conflict of interest There is no prohibition regarding the collection of surface soil samples in the study area. The authors declare that they have no conflicts of interest regarding the publication of this paper.

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