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Determination of the Radiological Risk from the Natural Radioactivity in Irrigation at Selected Areas of Peninsular Malaysia

(Penentuan Risiko Radiologi daripada Keradioaktifan Semula Jadi dalam Pengairan di Kawasan Terpilih di Semenanjung Malaysia)

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ABSTRACT

This study involves a comprehensive analysis of ^{226}Ra, ^{232}Th, and ^{40}K concentration from irrigation water samples. Water samples were obtained, and the physical parameters were examined. Subsequently, the corresponding radiological risks to human health were estimated. The concentration levels of ^{226}Ra, ^{232}Th, and ^{40}K in water samples amounted to 1.51 ± 0.30, 0.17 ± 0.09, and 7.67 ± 3.07 Bq L^{-1}, respectively, which were within the concentration levels reported in the literature from Malaysia and other countries worldwide. Based on the food intake rate by MoH and UNSCEAR, the annual ingestion effective dose (ID) and the cancer risks corresponding to radionuclide intake in irrigation were below the recommended maximum values. Meanwhile, the average hazard indices and annual outdoor effective dose (ED) amounted to 0.01 and 1.39 mSv $year^{-1}$, respectively. It was inferred from the findings of this study that the water used as the sample does not have any significant radiological impacts to human body and is safe to be used as irrigation in the related area.

Keywords: Gamma spectrometry; hazard indices; health risk; irrigation water; radionuclide concentration

ABSTRAK

Kajian ini melibatkan analisis komprehensif terhadap kepekatan radionuklid ^{226}Ra, ^{232}Th dan ^{40}K daripada sampel air pengairan. Sampel air telah diperoleh, dan parameter fizikal telah dinilai. Seterusnya, risiko radiologi berikutan dedahan sinaran terhadap kesihatan manusia telah dianggar. Aras kepekatan ^{226}Ra, ^{232}Th dan ^{40}K dalam sampel air adalah masing-masing 1.51 ± 0.30, 0.17 ± 0.09 dan 7.67 ± 3.07 Bq L^{-1}, masih berada dalam lingkungan aras kepekatan yang dilaporkan di dalam kepustakaan sama ada dari Malaysia atau negara-negara lain di seluruh dunia. Berdasarkan kepada kadar pengambilan makanan oleh MoH dan UNSCEAR, dos pemakanan berkesan tahunan (ID) dan risiko kanser berikutan pengambilan radionuklid dalam air siraman masih berada di bawah nilai maksimum yang disarankan. Sementara itu, purata indeks bahaya luaran dan dos luaran berkesan tahunan (ED) adalah berjumlah 0.01 dan 1.39 mSv $tahun^{-1}$ masing-masing. Ia disimpulkan daripada hasil kajian ini bahawa air daripada sampel kajian ini tidak mempunyai kesan radiologi yang ketara kepada tubuh badan manusia, dan selamat untuk digunakan sebagai pengairan di kawasan yang berkaitan.

Kata kunci: Air pengairan; indeks bahaya; kepekatan radionuklid; risiko kesihatan; spektrometri gama

INTRODUCTION

Agriculture appears to involve the highest water use at the global level due to the major role of the irrigation of agricultural lands in food production. The intensity of irrigation varies depending on the climate, crops cultivated, and farming methods. Although cultivated plants consist of a small internal ‘water warehouse’, which allows them to survive through low water availability within the dry and hot climate, the water content of the plants is reduced by 20 to 30% of the optimum value due to their possibility to wither at a fast rate. As a result, lower rate of photosynthesis takes place, which leads to slower plant development and production (Mavrogianopoulos 2016). In achieving better crop production, as a country located near the equator and surrounded by hot and humid climate throughout the year, Malaysia demands approximately 9.0 billion m^3 of water for irrigation purposes. However, higher irrigation use for crops productions in Malaysia would lead to higher radiological health risk among the Malaysians. Radioactivity in irrigation leads to exposure to radiation among vegetable consumers. Suzuki et al. (2015) reported that the radionuclide concentration in brown rice irrigated with 10 Bq L^{-1} was seven times higher compared to the crops irrigated with 1 Bq L^{-1}. The presence of radionuclides in vegetables also increases the risk of radionuclide contamination when irrigated by water source with high concentration of radionuclide.

The increasing evidence of radionuclide contamination in irrigation and water sources was reported by several researchers (Agbalagba & Onoja 2011; Alfatih et al. 2008; Almayahi et al. 2012; Carvalho et al. 2009; Ehsanpour et al. 2014; El-Gamal et al. 2019; El-Mageed et al. 2013; Kpeglo et al. 2014; Saqan et al. 2001). Most publications provided complete individual datasheets for a wide range of distributed radionuclide, which was then classified into different groups as the functions of risk level. These studies also focused on investigating the places predicted with high radiation levels, emitted from rocks, soils, and surrounding materials either naturally or through human activities. Subsequently, most studies evaluated the exposure of the population to radiation through the consumption of radionuclide in water. Various international organisations, such as World Health Organization (WHO), International Commission on Radiological Protection (ICRP), International Atomic Energy Agency (IAEA), and International Agency for Research on Cancer (IARC) recommend the guidelines to determine the quality of water for human consumption. The recommended reference level of committed effective dose is < 0.1 mSv from 1-year consumption of radionuclide by drinking and < 2.4 mSv from 1-year of exposure to natural radiation. The water samples should comprise lower health hazard indices compared to the unity value (H_{ex} and $H_{in} < 1$) for safe outdoor use (IAEA 2004; IARC 1988; ICRP 2012; WHO 2011).

Radioactive contamination consists of terrestrial radionuclide, which involves long-term exposure of gamma radiation including radium (^{226}Ra), thorium (^{232}Th), and potassium (^{40}K). Although the process for evaluation of potential radiological risks to the human body is less formal compared to the chemical hazard assessment, the background radiation remains an issue which should be addressed as potential site-related impacts (Meyers-Schöne et al. 2003). Several water treatment projects have been implemented in order to remove radiological and chemical substance from water. However, difficulties always arise during the process because of the water physical parameters, such as the continuous changing of the pH (Zainol et al. 2017). Furthermore, the primary similarities and some important differences between radiological and chemical risk assessments were identified (Mercat-Rommens et al. 2005), which were due to unsealed sources of radiation. These sources can be easily dispersed to the atmosphere and reach the human body, leading to the risk of radionuclide intakes in organ's tissues and cell retention (Dominguez-Gadea & Cerezo 2011). Although terrestrial radiation contamination is generally not involved in immediate life-threatening radiological hazard, long-term radiation exposure may lead to health effects. In this case, the signs and symptoms of radiation illness might not be detected within a short period of time (Delacroix et al. 2002). With the intake of radium in the human body, an appreciable fraction is deposited into the bone, along with the almost uniform distribution of the remaining fraction into the soft tissues. A long-term exposure of radium to human body leads to an increase in the risk of bone and nasal cavity cancer (Ahmed 2004). Meanwhile, if thorium is swallowed as food, most of it would be discharged from the body as faeces. However, a small amount of thorium left in the body will enter the bloodstream and be deposited into the bones, increasing the risk of pancreatic and bone cancer and liver disease (Environmental Protection Agency). According to human health fact sheet by Argonne National Laboratory (2005), potassium which is deposited into the human body would flow at a fast rate from the gastrointestinal tract to the bloodstream. It is then distributed throughout the body, causing cell damage and increasing potential for subsequent cancer induction. Based on the Malaysian National Cancer Registry (MNCR) report on cancer incidences from 2007 to 2011, cancer is one of the leading causes of death, with 103,507 new cases being reported within the period. Colorectal cancer, stomach cancer, nasopharynx cancer, and liver cancer are among the ten most common cancer types in Malaysia. Therefore, studying the possible substances associated with cancer risk especially upon the ingestion of radionuclides may be a beneficial action to local authorities and the general public.

In this study, the level of radionuclide in irrigation was examined, followed by the estimation of the corresponding radiological health risk at the selected vegetable farm in the central zone of Peninsular Malaysia. To observe the relationship between the physicochemical properties of irrigation water and radionuclide concentration, linear regression analysis was carried out. Overall, this study will be significant in the research field of environmental radiation, especially among Malaysian vegetable consumers. Besides, the results would assist the involvement of the government in the development of irrigation water system and provision of safe water source to the farmers or vegetable growers.

Materials and Methods

STUDY AREA

Three main locations in Peninsular Malaysia were chosen as the study area namely Cameron Highlands in Pahang, Kinta in Perak and Sekinchan in Selangor. Cameron Highlands is located on the Titiwangsa Range and the irrigation water supply for crop's farming is obtained from three rivers, namely Sungai Bertam, Sungai Telom, and Sungai Lumoi. Kinta is known as a former mining area. Most of the vegetable farm use the former mining pond as the water source for crop irrigation. It has been reported that in Kinta district, Perak has high activity concentration of U and Th up to 426 and 1377 Bq/kg, repectively (Lee et al. 2009). Irrigation of the farms in Sekinchan is supplied by Sungai Tengi, a nearby river connected to Selat Melaka. All sampling locations were selected as they are the main areas for vegetable supply to the locals. Table 1 illustrates the coordinate of each sampling area.

SAMPLE COLLECTION AND PREPARATION

Irrigation water samples were collected from retention ponds built by the farm owner and located near the crop plantation. A plastic container was used to collect 6 L of the water in the ponds, originated from the nearby water sources, at the depth of 0.5 m. Nitric acid was then dropped into the sample container to prevent microbial growth and the attachment of the sample to the container's wall (Norbert et al. 2019). Water sampling was preceded by the measurement of several physical parameters, namely pH, Dissolve Oxygen (DO), and Conductivity, C through PH400S portable pH meter, HI98193 waterproof portable DO and Biochemical Oxygen Demand (BOD) meter, and Milwaukee 801 multiparameter connected to Consort C933 electrochemical analyser. The samples were then brought to the laboratory and cleaned from any dirt using plasma membrane filter.

Afterward, water samples were heated until the volume decreased from 2000 to 200 mL. Following that, the water was packed into a Marinelli beaker, which was air tightly sealed, weighed, and stored for a minimum of 30 days to achieve radioactive secular equilibrium. Prior to the radiometric analysis, the sample beaker was shaken for 30 s to gain a homogenised distribution of the radionuclides. One type of vegetable for each sampling point was brought to the laboratory to conduct an analysis of the proportion of irrigation intake into the human body through vegetable ingestion. The vegetable samples were dried, crushed, sieved, stored in Marinelli beakers for 30 days, and evaluated in terms of radionuclide concentration through HPGe gamma spectrometry (Priharti & Samat 2017). Overall, this study was conducted according to the standard sample preparation, as mentioned in the IAEA technical report series no. 295 (IAEA 2004).

INSTRUMENTATION

Detection and measurement of radionuclides were performed using gamma spectrometry with High Purity Germanium (HPGe) detector. The HPGe detector is enclosed inside CANBERRA 747 shielding with 10 cm thickness lead coated with 1 and 1.6 mm of tin and copper, respectively, in order to reduce the background radiation from building and cosmic rays. Energy resolution for the 1332.5 keV energy peak was 1.80 keV and the relative efficiency of the detector was 30% (Idris et al. 2017). The existing background radiation inside the system was measured using an empty Marinelli beaker. Each sample was specified to have three replicates to reduce errors at the energy peak as the calculation took place. Moreover, the concentration of radionuclides ^{226}Ra and ^{232}Th for each sample was determined from the respective gamma lines emitted by the radionuclides' progenies, namely 214Bi (609 keV) and 212Pb (238.6 keV) (Priharti & Samat 2017; Solehah & Samat 2018). Meanwhile, the gamma-ray energy peak, which amounted to 1460 keV, was used to determine the concentration of radionuclide ^{40}K prior to the calculation of the radionuclide concentration through equation (1). To conceal the minor peaks for each sample, the minimum detectable activity (MDA) was identified based on Curie's derivation. Subsequently, the average MDAs with the counting time 43,200 s amounted to 0.13, 0.13 and 1.47 Bq kg^{-1} for 609, 238 and 1460 keV, respectively.

RESULTS AND DISCUSSION

PHYSICAL PARAMETERS: pH, DISSOLVE OXYGEN, AND CONDUCTIVITY OF WATER SAMPLES

The results of physical parameters are shown in Table 2 where the pH values of the irrigation water samples ranged from 4.60 to 6.71, while the dissolve oxygen and conductivity ranged from 2.64 to 6.90 g L^{-1}, and 4.34 to 7.55 µs cm^{-1}, respectively. The pH value indicated that the water is moderately acidic, with its pH range exceeding the range approved by WHO for agricultural purposes, which is from 6.5 to 8.4. This may be due the nutritional imbalance or the presence of toxic elements. In some cases low salinity, with conductivity < 2.0 µs cm^{-1}, leads to water pH level to exceed the range for agricultural purpose. Further evaluation may be conducted for total dissolved solids and water element content, such as magnesium, chlorine, calcium, and sodium (Ayers & Westcot 1985). According to Sanchez-Gonzales et al. (2014) high pH value of water in certain areas is possibly due to industrial sewage materials, such as polymer, while low pH value is possibly due to chemical and mining industry waste with acid contents.

pH of water source, which was affected by salinity and conductivity, might vary between neighbouring water sources due to geological factor or the separate inflow of the water source (Fondriest Environmental). The pH level depends on the mineral components and weathering of the existing parent rock. Volume of rainfall and the rate of evaporation at the retention ponds may also lead to the changes in chemical properties of water, which influences the pH, dissolved oxygen, and conductivity (Clean Water Team 2004). Therefore, the lower water conductivity in our study was possibly affected by the surrounding pollution, leading to significantly lower pH values compared to the pH values 7.32 to 7.94 that was reported by Al-Nafiey et al. (2014) in Cameron Highlands, Malaysia. They reported that the conductivity ranged from 27.5 to 10.9 μs cm^{-1}. The pH values in this study also differ from those in a water quality study by Isiyaka and Juahir (2015) at Sungai Kinta, Malaysia, where the pH and conductivity ranged from 4.54 to 8.29 and 6.00 to 327.00 μs cm^{-1}, respectively.

CORRELATION ANALYSIS OF PH, DISSOLVE OXYGEN, AND CONDUCTIVITY OF WATER SAMPLES WITH RADIONUCLIDE CONCENTRATION

The graphic demonstration of the relationship between physical parameters and radionuclide concentration is shown in Figures 1 to 3. Based on a literature studies on physical and radiological properties of water sources, there was no significant correlation between radionuclide concentration and physical parameters (Al-Nafiey et al. 2014; Elkamel et al. 2012). Similarly, it is found that the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K had a moderate positive correlation with the conductivity of water, namely R = 0.24, R = 0.04, and R = 0.16, respectively. Conversely, a significant negative correlation was observed statistically between the concentration of ^{40}K and pH value, R = -0.91, while moderate negative correlations were observed between ^{226}Ra and ^{232}Th concentrations and the water pH values, namely R = -0.46 and R = -0.18, respectively. These correlations indicated that the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K have an inverse relationship with the pH of the acidic oxidising water. Although similar negative correlation was found between pH and the concentrations of radium and thorium in a previous study by Ahmad et al. (2019a), it might be different if the variables were tested in alkaline and anoxic water (pH > 6, DO ≤ 1 mg L^{-1}). This difference was due to the concentration of radionuclide, which was affected by the chemical reaction between the existing ions (Szabo et al. 2011). It could be seen from Figure 2 that dissolve oxygen had a moderate positive correlation with the concentrations of ^{226}Ra and ^{40}K, while it had a moderate negative correlation with the concentration of ^{232}Th. Therefore, it was indicated that there is an increase in ^{232}Th concentration with the absence of DO, while its concentration is either low or absent when DO is abundant.

NATURAL RADIOACTIVITY CONCENTRATION

The radionuclide activity concentration, A (Bq L^{-1}) in irrigation water samples was calculated using the following equation (Priharti & Samat 2017):

$$A = \frac{N}{\varepsilon \times t \times P_\gamma \times V} \quad (1)$$

Accordingly, N refers to the net count rate of γ-rays for time t, which is equal to 43 200 s, while ε refers to the absolute efficiency of the detector, with P_γ is probability of gamma ray emission and V representing the volume of sample (200 mL).. The average activity concentrations for three sampling sites are illustrated in Table 2. The values of ^{226}Ra, ^{232}Th, and ^{40}K ranged from ND to 2.38 ± 0.80, ND to 0.24 ± 0.16 and ND to 12.82 ± 2.33 Bq L^{-1}, respectively. Notably, several samples comprised of significantly low radionuclide concentration, which was below the detection limit were recorded as ND. As a result, the highest ^{226}Ra and ^{232}Th concentrations for W1 were recorded in Cameron Highland, while the highest ^{40}K concentration was obtained from sample W6 in Kinta. It was also found that there was a high concentration of radionuclide in the irrigation from Kinta compared to Sekinchan. The high concentrations of these radionuclides in irrigation were possibly due to the leaching process from the soil, which then accumulated to the sediment and water of retention ponds. Solehah and Samat (2018) reported that the soil of Kinta possesses a high concentration of radionuclide in soil compared to Sekinchan. Overall, the results of this study were in agreement with the previous report, which concluded that geological factors were the main factors which affected the radionuclide concentration in terrestrial.

Besides that, there were several factors which influenced the radionuclide concentration in irrigation water. Specifically, the changes in land usage, especially in the urban area, led to the increment of soil erosion rate. As a result, the eroded sediments would be deposited along river channels, and the diversion tunnels would increase the rate of radionuclide accumulation in the surface water due to farther contact distance (Raj 2002). According to Mazlin Mokhtar et al. (2019), the toxicity of sediment arose due to the phosphorus fertilisers from cultivated soil, atmospheric depositions, animal manures, extent liming agents, sewage sludge, and biowaste. The irrigation originating from water reservoir treatment was found to exhibit less radiological risk compared to the irrigation from natural resources (Yusof et al. 2001). It exhibited lower levels of ^{226}Ra compared to the raw water samples originating from the rivers. The ^{226}Ra radionuclide level in water samples decreased by 10% of the original activities after treatment as the incorporation of the suspended particles with the radionuclide would take sufficient time to settle to the bottom of the reservoir, leading to less activity concentration in the surface water. In addition, the change in soil type from light sandy loam to loamy sand and sand increased the irrigation requirements by 17 and 3%, respectively. Similarly, climate change from high humidity to dry atmosphere led to an increase in irrigation volume (Talal & Neil 2016).

RADIOLOGICAL RISK ANALYSIS

In this study, both the internal and external radiological hazards resulted from the exposure of radionuclide in water irrigation were estimated, either through ingestion or outdoor exposure. Ingestion dose was calculated with the perception that the radionuclide in water was transferred to the crops. The radionuclide was then deposited to the human body through the food chain. The intake of radionuclide from irrigation was calculated from a fraction of annual vegetable intake by adults and the effective dose was estimated from the vegetable intake rate provided by the Ministry of Health (MoH), Malaysia and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Due to the ingestion of radionuclide from the vegetable intake, the annual effective dose, D (μSv year^{-1}) was calculated using equation (2) below:

$$D = A \times I \times F_C \qquad (2)$$

with *I* refers to the intake of irrigation in the human body; while *Fc* refers to the effective dose coefficient from Becquerel unit to Sievert unit. Furthermore, the cancer risk, *R*, for a lifespan of 70 years was also estimated using the following equation:

$$R = D\ (mSv\ year^{-1}) \times 70\ years \times 5 \times 10^{-5} (mSv^{-1}) \quad (3)$$

Table 3 illustrates the annual effective dose and estimated cancer risk due to the annual ingestion of radionuclide ^{226}Ra, ^{232}Th, and ^{40}K among adults. Based on the results shown, the amount of effective dose due to the ingestion of radionuclide in the vegetables irrigated with W1 - W11 ranged from ND to 9.61 μSv year^{-1} (MoH) and ND to 38.99 μSv year^{-1} (UNSCEAR), with average values of 9.61 and 14.83 μSv year^{-1}, respectively. However, these values remained significantly lower than the permissible limit of water consumption, which is 0.1 mSv year^{-1}, and the recommended dose limit for total radiation exposure, which is 2.4 mSv year^{-1}. In a study on the groundwater of Bangalore by Ravikumar and Somashekar (2017), higher amount of effective dose was found for all age groups, especially among male individuals. Similar results were found in the annual effective dose as the ingestion of radionuclide in water at Sik, Malaysia was lower compared to the dose recommended by WHO (Ahmad et al. 2019b; WHO 2011). In this study, the corresponding cancer risk estimated from annual effective dose was found to be 3.36 × 10^{-5} and 5.19 × 10^{-5}, indicating that within one million adult population who consume vegetables irrigated with W1 - W11, approximately 34 to 52 individuals are probably faced with the risk of cancer. The estimations of individuals with cancer risk were found to be lower than 8400. This number was found to match the prediction from UNSCEAR and set apart from the threshold value. However, if the estimated cancer risk was found exceed or be close to the threshold value, proper attention and remedial actions were required in the contaminated areas (Sar et al. 2017).

Another approach was implemented by Cohen and Lee (1991), who estimated the risk of cancer through the reduction of life expectancy of an individual who was exposed to a certain dose of radiation within a year. If an individual of the age of 18 to 65 years old was exposed to 3 mSv year^{-1} radiation, their lifespan would decrease by an average of 15 days. This indicated that with the exposure of the human body to a dose of 9.61 and 14.83 μSv year^{-1}, their lifespan is predicted to decrease by 1 h 12 min and 1 h 41 min, respectively. Subsequently, it was found that the consumption of vegetables irrigated with W1 - W11 had no significant radiological impact on human health.

The external radiological hazards were assessed by determining the radium equivalent activity, Ra_{eq} (Bq L^{-1}), annual effective dose, *ED* (mSv year^{-1}), external hazard index, H_{ex}, and internal hazard index, H_{in}. As shown in the equations, A_{Ra}, A_{Th}, and A_K represented the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in water samples respectively. Meanwhile, Ra_{eq} refers to an index used to represent the specific activities of ^{226}Ra, ^{232}Th, and ^{40}K through one quantity. It could be calculated through the estimation of the weighed amount of each radionulide activity, with 370 Bq L^{-1} of ^{226}Ra, 259 Bq L^{-1} of ^{232}Th, and 4810 Bq L^{-1} of ^{40}K produced the same gamma radiation dose rate as follows:

$$Ra_{eq} = A_{Ra} + (1.43)\,(A_{Th}) + (0.077)\,(A_K) \quad (4)$$

Meanwhile, the annual outdoor effective dose, *ED* was calculated using the following equation:

$$ED = 1.23 \times 10^{-3} \times [(0.462)(A_{Ra}) + (0.621)(A_{Th}) + (00.041)(A_K)]\ (5)$$

The external hazard index, H_{ex}, and the internal hazard index, H_{in} for the samples under investigation were calculated using the following equation defined by Ehsanpour et al. (2014):

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (6)$$

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (7)$$

Notably, the maximum values of H_{ex} and H_{in} were equal to unity (≤ 1) for radiation hazard to be negligible (Diab et al. 2007). All results are displayed in Table 4, including previous data from Malaysia and other countries. Compared to previous studies and similar to the outdoor effective dose, *ED*, the estimation of Ra_{eq} by this study from the concentration of ^{226}Ra, ^{232}Th, and ^{40}K in the irrigation amounted to 2.37 Bq L^{-1}, which was one-fold less than the lower bound limit of the world average. The estimated effective dose in this study was 1.39 mSv year^{-1}, which was lower than the effective dose of Iran although this country exhibited the lowest *ED* compared to other previous studies. The H_{ex} and H_{in} amounted to 0.01. These values were within the range of previous international record, which was from 0.01 to 0.14 for the H_{ex} and from 0.01 to 0.28 for H_{in}. However, the indices presented in this study remained lower than the unity value of 1. Therefore, the irrigation water in the study area exhibited low radiation exposure and could be used for agricultural purposes without risking any significant radiological threats to the general population. However, monitoring and remedial actions are required to avoid the increase in radiological risks in the future.

TABLE 1. Coordinates of sampling locations and codes of collected irrigation sample from central zone of Peninsular Malaysia

Sampling area	Coordinate		Sample code	Number of samples
	Latitude (N)	Longitude (N)		
Cameron Highlands, Pahang	4º29’00.9”	101º23’53.1”	W1	3
(Altitude: 1442 m)	4º30’39.0”	101º25’55.6”	W2	3
	4º31’40.7”	101º24’40.0”	W3	3
Kinta, Perak	4º43’52.5”	101º07’04.5”	W4	3
(Altitude: 72 m)	4º43’52.6”	101º06’22.7”	W5	3
	4º43’57.9”	101º06’23.0”	W6	3
	4º40’04.7”	101º06’46.8”	W7	3
Sekinchan, Selangor	3º31’47.3”	101º09’01.5”	W8	3
(Altitude: 3 m)	3º31’46.5”	101º08’28.3”	W9	3
	3º31’37.2”	101º09’05.0”	W10	3
	3º31’47.7”	101º09’20.2”	W11	3
Total number of samples				33

TABLE 2. Physical parameter and radionuclide concentration in irrigation sample

Sample code	Physical parameter			Activity concentrations, A (Bq L^{-1})		
	pH	DO (g L^{-1})	C (μS cm^{-1})	^{226}Ra	^{232}Th	^{40}K
W1	6.19 ± 0.08	3.04 ± 0.26	4.50 ± 0.08	2.38 ± 0.80	0.24 ± 0.16	3.23 ± 5.77
W2	6.20 ± 0.14	3.99 ± 0.33	5.25 ± 0.12	ND	ND	ND
W3	5.66 ± 0.04	4.06 ± 0.22	4.74 ± 0.14	2.17 ± 0.01	0.10 ± 0.02	ND
Average CH	6.01 ± 0.26	3.70 ± 0.81	4.83 ± 0.11	2.28 ± 0.40	0.17 ± 0.09	3.23 ± 5.77
W4	5.25 ± 0.08	3.18 ± 0.01	4.66 ± 0.04	1.07 ± 0.44	0.21 ± 0.00	17.49 ± 0.00
W5	5.20 ± 0.01	3.21 ± 0.09	4.51 ± 0.07	2.11 ± 0.66	ND	11.54 ± 3.03
W6	4.62 ± 0.01	6.41 ± 0.50	7.52 ± 0.02	1.88 ± 0.03	0.18 ± 0.00	12.82 ± 2.33
W7	6.52 ± 0.02	6.13 ± 0.06	7.20 ± 0.03	2.00 ± 0.22	ND	4.86 ± 1.32
Average K	5.40 ± 0.12	4.73 ± 0.66	5.97 ± 0.04	1.77 ± 0.34	0.20 ± 0.00	11.68 ± 1.67
W8	6.59 ± 0.06	3.44 ± 0.28	4.86 ± 0.05	0.74 ± 0.14	ND	6.57 ± 0.74
W9	6.64 ± 0.06	2.97 ± 0.19	4.93 ± 0.04	0.67 ± 0.03	0.19 ± 0.00	4.43 ± 0.00
W10	6.53 ± 0.03	4.26 ± 0.17	4.79 ± 0.06	1.16 ± 0.42	0.08 ± 0.00	ND
W11	6.61 ± 0.04	3.37 ± 0.16	4.88 ± 0.02	0.88 ± 0.28	ND	ND
Average S	6.59 ± 0.19	3.51 ± 0.20	4.87 ± 0.04	0.86 ± 0.22	0.14 ± 0.00	5.50 ± 0.74
Average all	6.00 **± 0.05**	4.01 **± 0.21**	5.25 **± 0.06**	1.51 ± 0.30	0.17 ± 0.09	7.96 ± 3.07
Range	4.60 – 6.71	2.64 – 7.55	4.34 – 7.55	ND – 3.44	ND – 0.57	ND – 17.45

*ND = Not Detectable, CH = Cameron Highland, K = Kinta, S = Sekinchan

TABLE 3. Annual effective dose due to ingestion of radionuclide from water

Sample code	Intake of radionuclide, *I* (Bq year^{-1})						Effective Dose, D (µSv year^{-1})		Estimated Cancer Risk (×10^{-5})	
	MoH			UNSCEAR			MoH	UNSCEAR	MoH	UNSCEAR
	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K				
W1	25.70	9.24	0.12	39.67	14.26	0.18	17.64	27.22	6.17	9.53
W2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
W3	27.39	3.01	ND	42.27	4.65	ND	16.71	25.79	5.85	9.03
Average CH							17.18	26.51	6.01	9.28
W4	22.01	8.08	0.28	33.97	12.48	0.44	7.01	10.81	2.45	3.78
W5	42.73	ND	0.34	65.94	ND	0.52	25.27	38.99	8.84	13.65
W6	36.01	10.60	0.89	55.57	16.36	1.38	19.46	30.04	6.81	10.51
W7	11.22	ND	0.22	17.32	ND	0.33	6.29	9.71	2.20	3.40
Average K							14.51	22.39	5.08	7.84
W8	10.94	ND	0.46	16.88	ND	0.72	2.29	3.53	0.80	1.23
W9	0.05	12.11	0.26	0.07	18.69	0.40	0.55	0.84	0.19	0.29
W10	19.36	7.41	ND	29.87	11.43	ND	6.42	9.91	2.25	3.47
W11	16.61	ND	ND	25.63	ND	ND	4.09	6.32	1.43	2.21
Average S							3.34	5.15	1.17	1.80
Mean effective dose							9.61	14.83	3.36	5.19

*ND = Not Detectable, CH = Cameron Highland, K = Kinta, S = Sekinchan

TABLE 4. Comparison of radium equivalent, Ra_{eq} (Bq L^{-1}), outdoor effective dose, *ED* (mSv year^{-1}), external hazard index, H_{ex} and internal hazard index, H_{in}

Country	Activity concentration, A (Bq L^{-1})			Ra_{eq} (Bq L^{-1})	*ED* (mSv year^{-1})	H_{ex}	H_{in}	Reference
	^{226}Ra	^{232}Th	^{40}K					
Malaysia	1.51	0.17	7.96	2.37	1.39	0.01	0.01	Present Study
Malaysia	2.86	3.78	152.00	19.97	12.18	0.05	0.06	Almayahi et al. (2012)
Malaysia	2.70	3.79	148	19.52	11.89	0.05	0.06	Agbalagba & Onoja (2011)
Nigeria	12.00	12.00	97.00	36.63	20.88	0.10	0.13	El-Mageed et al. (2013)
Yemen	3.50	1.26	17.00	6.61	3.81	0.02	0.03	Saqan et al. (2001)
Sudan	2.44	3.94	118.00	17.16	10.35	0.05	0.05	Alfatih et al. (2008)
Iran	0.67	1.65	4.72	3.39	1.88	0.01	0.01	Ehsanpour et al. (2014)
Ghana	13.70	1.20	NR	15.42	8.70	0.04	0.08	Kpeglo et al. (2014)
Egypt	3.05	1.39	NR	5.04	2.79	0.01	0.02	El-Gamal et al. (2019)
Portugal	51.59	0.15	NR	51.80	29.43	0.14	0.28	Carvalho et al. (2009)
Range of previous studies				3.39-51.80	1.88-29.43	0.01-0.14	0.01-0.28	

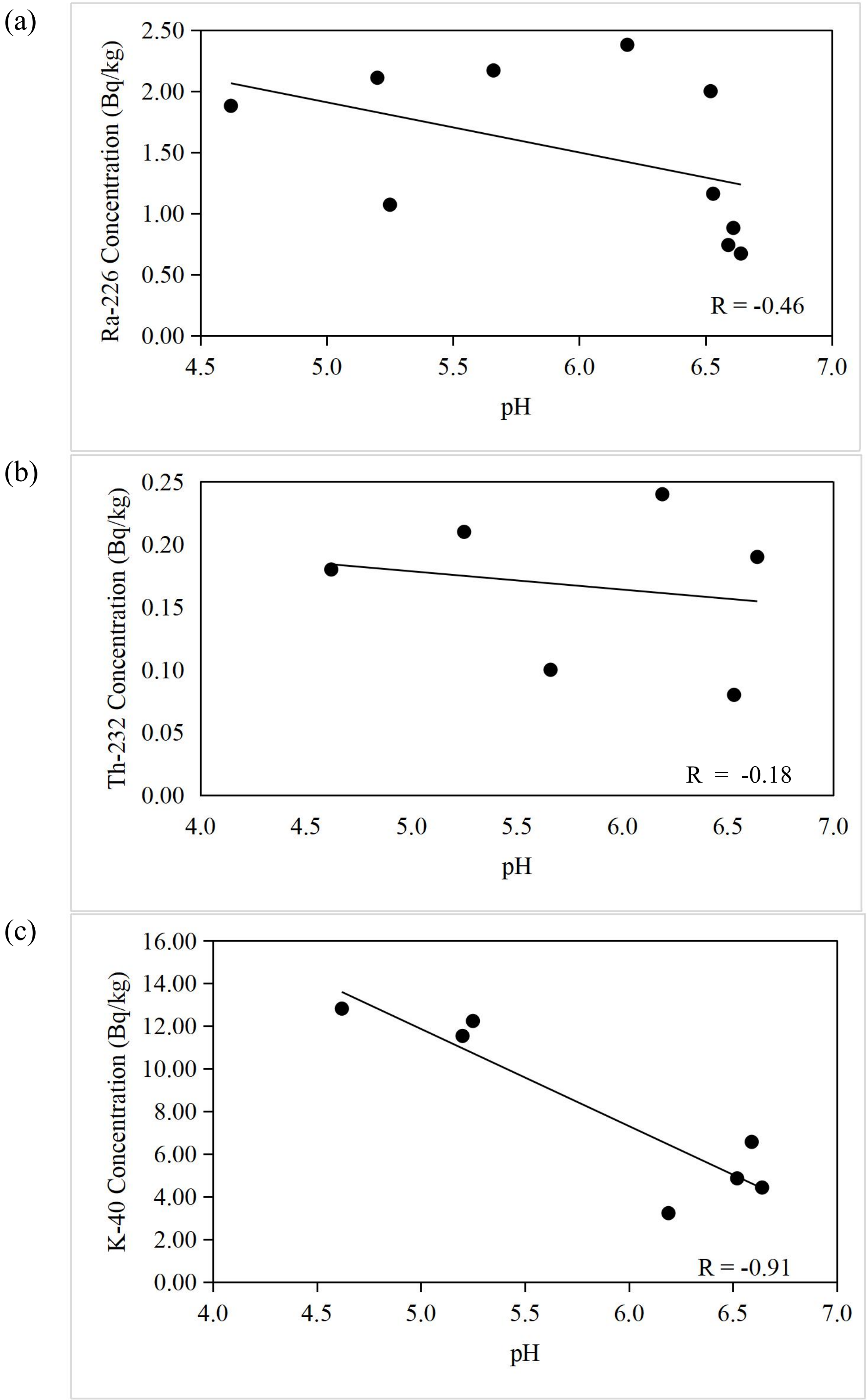

FIGURE 1. Relation between concentration of radionuclide (a) ^{226}Ra, (b) ^{232}Th and (c) ^{40}K with pH

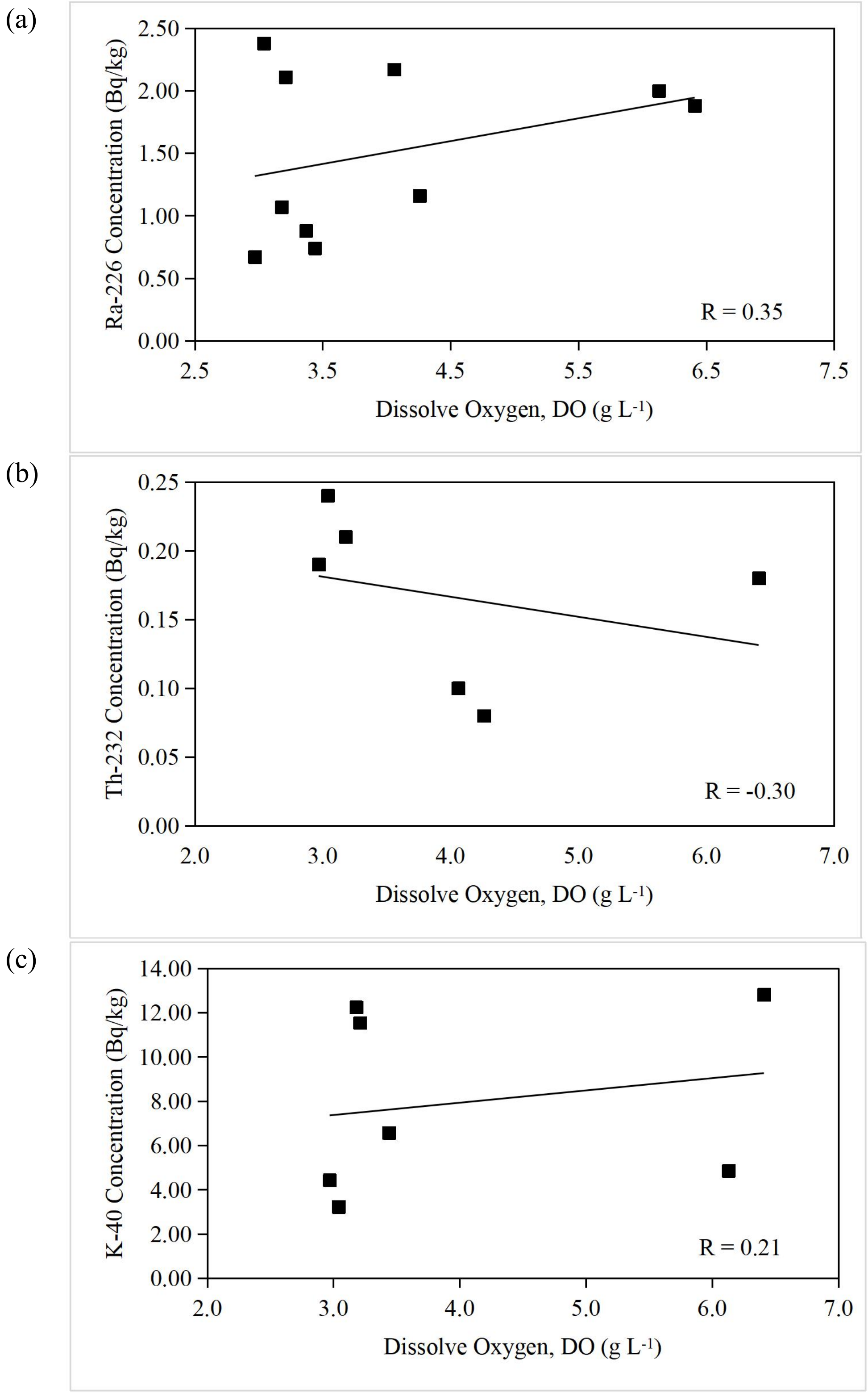

FIGURE 2. Relation between concentration of radionuclide (a) ^{226}Ra, (b) ^{232}Th and (c) ^{40}K with dissolve oxygen

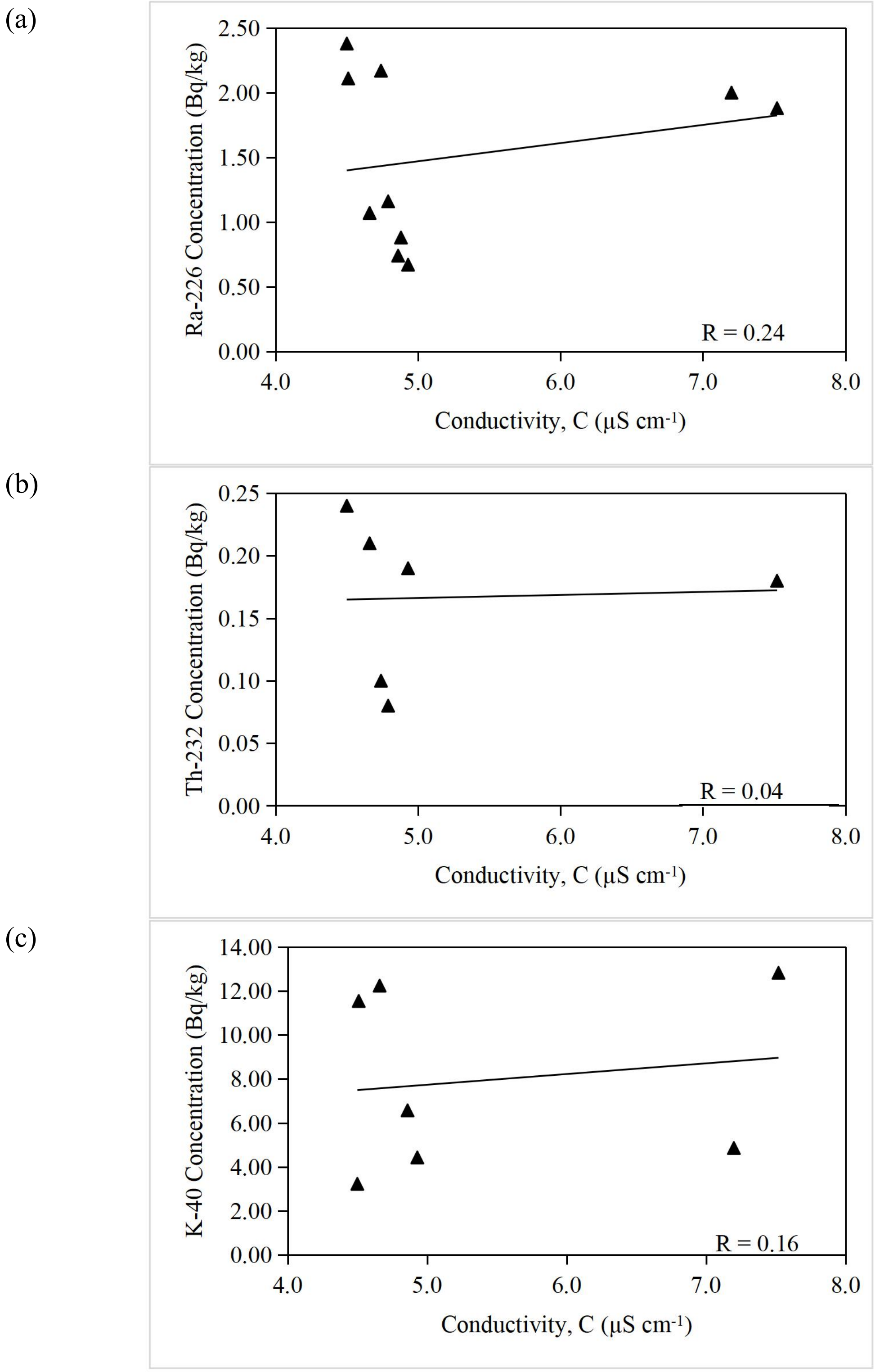

FIGURE 3. Relation between concentration of radionuclide (a) ^{226}Ra, (b) ^{232}Th and (c) ^{40}K with conductivity

CONCLUSION

In this study, the ^{226}Ra, ^{232}Th, and ^{40}K concentrations in irrigation water were measured using gamma-ray spectroscopy and HPGe detector. This was followed by further evaluation of the activity concentrations for possible radiological health hazard by assessing the annual effective dose. The hazard was due to the ingestion of radionuclide in the vegetables irrigated with the examined water sample. By taking the food intake rate by MoH and UNSCEAR into account, the annual effective doses were found to be lower than the recommended maximum limit of 0.1 mSv year^{-1} for the ingestion of radionuclide in irrigation water and 2.4 mSv for total radiation exposure within a year. Besides, the annual outdoor effective dose and radiological hazard indices were estimated from the ^{226}Ra, ^{232}Th, and ^{40}K concentrations. Overall, the results were in agreement with the results from previous studies, including the representative values reported by international organisations of radiation protection. Based on this study results, it was indicated that there was no potential internal and external radiation hazard encountered by individuals through the irrigation in the areas. However, further actions need to be performed to improve water quality and provide safer water source for irrigation.

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