Journal of Geoscience and Environment Protection, 2025, 13(6), 130-146
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Effect of Irrigation with Thermal Water on Tomato Uptake of Radium-226, Radium-228 and Potassium-40

Amal Alsayaheen[1], Fawwaz I. Khalili[2], Jamal Y. Ayad[3], Ahmad Hussein Alomari[4], Refaat M. Banikhalaf[5]

[1]Ministry of Water and Irrigation, Amman, Jordan
[2]Department of Chemistry, Science Faculty, The University of Jordan, Amman, Jordan
[3]Department of Plant Physiology, Agriculture Faculty, The University of Jordan, Amman, Jordan
[4]Energy and Minerals Regulatory Commission (EMRC), Amman, Jordan
[5]Water Authority of Jordan, Amman, Jordan
Email: amal_sayaheen71@yahoo.com, amal_sayaheen71@yahoo.com

How to cite this paper: Alsayaheen, A., Khalili, F. I., Ayad, J. Y., Alomari, A. H., & Banikhalaf, R. M. (2025). Effect of Irrigation with Thermal Water on Tomato Uptake of Radium-226, Radium-228 and Potassium-40. *Journal of Geoscience and Environment Protection, 13,* 130-146.
https://doi.org/10.4236/gep.2025.136010

Received: May 7, 2025
Accepted: June 15, 2025
Published: June 18, 2025

Abstract

The uptake of Radium-226, Radium-228 and potassium-40 by tomato plants as the effect of irrigation with thermal water was studied as pot experiments. Tomato seedlings were grown in 7 L pots filled with four different soil textural classes collected from different locations; silt clay soil (SZ1) and sandy clay loam (SZ2) collected from Zara area at Jordan Valley with ^{226}Ra activity 392 (SZ2) and 5350 (SZ1) Bq·kg^{-1}. Two control soils also were used; clay loamy soil (SW) and sandy soil (SSa) were collected from Amman with ^{226}Ra activity about 20 Bq·kg^{-1} for SW 8.3 Bq·kg^{-1}. Half of the treatments were irrigated with thermal water while the other half were irrigated with non-thermal water. The average Transfer Factor (TF) for ^{226}Ra values ranged from 0.002 to 0.91 in tomato fruits while in vegetative parts ranging from 0.003 to 2.54 (stems) and from 0.014, to 4.96 (leaves) as a response to irrigation with thermal water. Radium-228 was just detected in tomato leaves that were grown in sandy soil (SSa). High TF was observed for ^{40}K in tomato fruits (8.2 to 133.7) as compared to leaves (1.2 to 16.0) and in stems (1.9 to 11.3). The highest TF values for both ^{226}Ra and ^{40}K were observed in sandy soil. Analysis indicated that source of irrigation water and soil factors affects ^{226}Ra activity in plant tissues while ^{40}K is only affected by its concentration in soil. Although the pot experiment offers controlled conditions for testing, it does not fully replicate field conditions where root depth, soil heterogeneity, and environmental interactions may influence radionuclide uptake. Therefore, the findings should be interpreted with this limitation in mind.

Keywords

Transfer Factor, Thermal Water, Tomato, Soil Texture, Radium-226, Radium-228, Potassium-40, Dose, Radionuclide Uptake, Environmental Radioactivity, Soil-Water-Plant Interactions, Soil-Plant Transfer, Radioactive contamination in Agriculture

1. Introduction

Jordan is considered an arid and semi-arid country, where 90% of its area receives less than 200 mm of rainfall annually (Abu Hamad, 2017); therefore, it suffers from the limited water resources, especially fresh water for human consumption. Meantime, the demand for water had increased as a result of the rapid socioeconomic development and the substantial population increase. Due to the water scarcity in Jordan; it is believed that water resources can be developed by adaptation of non-conventional water sources such as thermal water or hot springs that can provide extra water for irrigation.

Thermal water resources are in effect considered as part of the water supply-demand budget of the country, and the thermal springs and wells which spread along the Jordan Rift Valley, in addition to the thermal wells in the central and eastern plateau, are considered to be part of the water resources in Jordan. The total discharge of the major hot springs in Jordan is about $4.2*10^{10}$ $m^3 \cdot y^{-1}$ (Schaffer & Sass, 2012) while discharge of Zara springs was about $1.8*10^6$ $m^3 \cdot y^{-1}$ which represents about 12% of the total discharge recorded during the study period. The highest discharge (nearly $1.6*10^7$ $m^3 \cdot y^{-1}$) was recorded at Hammamat Ma'in hot springs, which corresponds to 39% of the total recorded discharge.

Presence of radionuclides in thermal, as a part of groundwater, depends on many factors, mainly including the concentration and distribution of the parent element in the rock matrix and solubility of the parent element and the nuclide itself in water. Other factors encompass the rate of release of the radionuclide by weathering relative to the rate of geochemical reactions controlling or limiting its mobility, and the residence time of the water (Szabo et al., 2012). There are important factors that contribute to the presence of Radium in water (Vengosh et al., 2009), such as adsorption/desorption exchange with Ra adsorbed on the surface coating clays and oxides, and co-precipitation with, and/or dissolution of, secondary minerals such as barite.

High radiation doses were reported by Al-Okour et al. (2013) in Al Hammah hot springs in the north of Jordan. These researchers employed gamma radiation to assess radiation doses using a portable Geiger-Muller counter and Sodium Iodide Detector. The study results revealed that the measured doses in air ranged from 70 to 580 nano Gray per hour ($nGyhr^{-1}$). The maximum radiation dose was detected nearby the main hot water source for the cooling pool there, while gamma doses outside the spa region ranged from 30 to 70 $nGyhr^{-1}$.

Radium is the only known radioactive alkaline earth element and is the heaviest one. Isotopes of Ra are consequently found at measurable concentrations, both in soil and groundwater, as a decay product in the thorium and uranium series. ^{228}Ra and ^{226}Ra have half-lives of 5.7 and 1607 years, respectively (IAEA, 2014). Both isotopes are widely used in assessment of water and soil radioactivity because of their relatively high specific activity (the activity per quantity of a radionuclide and is a physical property of that radionuclide).

Plant's uptake of the main natural radionuclide and heavy metals is due to its demand for nutrients. The plants take up radionuclide via the same mechanism by which they take up the essential nutrients due to their similar chemical and physical characteristics (Pallavicini, 2011). Through the mineral uptake process, the plants may absorb and transfer radionuclides to their different parts.

Some radionuclide activities concentrations were determined in some vegetable crops in Jordan Al-Absi et al. (2015). Some collected samples of potatoes, tomatoes, cucumber, radish, spinach, and cabbage from local markets in different places in Amman, Jordan were analyzed by HPGe Gamma Spectroscopy to measure the activities of ^{226}Ra, ^{228}Ra, and ^{40}K were determined. The ranges of the activities of ^{226}Ra, ^{228}Ra, and ^{40}K in the selected vegetables were from 7.1 to 11.7, ND to 3.3 Bq·kg^{-1}, and from 201 to 684 Bq·kg^{-1}, respectively.

The transfer factor (TF) is an important factor that can be used to quantify effect of soil radioactivity on that in plants and is defined as concentration of the radionuclide per unit weight (dry or wet) of the plant organ (Bq·kg^{-1}) divided by concentration of the radionuclide per unit weight of dry soil (Bq·kg^{-1}). Radioactivity and Transfer factors were calculated by some researchers in Jordan Valley. The mean activity in vegetables ranged from 698 to 1439 Bq·kg^{-1} for ^{40}K while the mean concentrations of ^{226}Ra and ^{228}Ra ranged from <0.61 to 2.56 and from <0.69 to 3.35 Bq·kg^{-1}, respectively. Moreover, they found that the transfer factors for ^{40}K were high and ranged from 5 to 8, while those for ^{226}Ra and ^{228}Ra ranged from <0.01 to 0.07 and from <0.09 to 0.42, respectively (Ababneh et al., 2009).

In Saudi Arabia, (El-Taher & Al-Turki, 2014) also studied soil-to-plant TFs of naturally-occurring radionuclides using pot experiment that was carried out in a greenhouse in Qassim University in the Kingdom of Saudi Arabia, in order to examine the effect of contaminated irrigation water on migration and retention of radioactive elements in two soil types (sandy and sandy loam soils) and seven selected plants (not specified in the paper). The levels of ^{226}Ra ranged from below the detection limit to 22.9 Bq·kg^{-1}, with an average of 13.1 Bq·kg^{-1}. Furthermore, it was found that the levels of ^{228}Ra varied from below the detection limit to 31.7 Bq·kg^{-1}. On the other hand, the levels of ^{40}K ranged from 221 to 1212 Bq·kg^{-1}. Additionally, it was found that there were statistically significant, high, and positive correlations between the specific activities of ^{226}Ra and ^{228}Ra in the plant samples and their corresponding specific activities in the irrigation water.

The hypothesis of this research is that irrigation with thermal water, by the effect of its radioactive content, will cause additional transfer of ^{226}Ra, ^{228}Ra and ^{40}K to different plant tissues than other irrigation sources. The objective of this study is to study the levels of these three radioactivity elements in various tissues of tomato plants and to calculate the transfer factor from soil to plants as effect of irrigation of thermal water.

2. Materials and Methods

This study was conducted as pot experiment using four types of soil; two soil types were collected from Zara area, SZ1 and SZ2, which was typically under cultivation with vegetable crops. Soils in Zara area can be divided mainly into two main categories. Soil SZ1 is deeply dissected quaternary deposits with very high radioactive elements concentration (about 5350 Bq·kg^{-1} of ^{226}Ra), very fine silt clay soil. The other soil, SZ2 is deeply dissected sandstone escarpment (activity of ^{226}Ra is about 380 Bq·kg^{-1} of ^{226}Ra). These two soils are under cultivation of vegetable crops and irrigated with thermal water (Zara hot springs). Farmers usually use small pools to allow water to cool and to dissolute fertilizers before using irrigation.

The other two types of soil, SW and SSa were chosen as control soils (activity of ^{226}Ra is about 20 and 8.3 Bq·kg^{-1} of ^{226}Ra, respectively) out of Zara area. Both soils were not exposed before to irrigation with thermal water, in addition to the distinction in their properties; Soil SW is clay loam that was collected from Wadi Essir (Amman) while the SSa soil is sand culture (diameter from 0.05 to 0.25 mm) that is washed with tab water and with 2 molar HCl reagent for 24 h. After that, it was washed with tap water until the water was neutral.

Two water sources were used in this study. The first one was selected to be taken from thermal water (spring 2, **Figure 1**), because it is actually used for irrigation of vegetable crops at site and contains some radioactive elements such as ^{226}Ra, ^{228}Ra, ^{40}K, ^{212}Bi and other elements with different activities. The second one was selected as a control (non thermal) irrigation water source. Wadi Essir spring water was chosen for this purpose as non radioactive water. Water of the two sources were subjected to chemical analysis of Major cations, major anions and heavy metals in addition to radioactive analysis for ^{226}Ra, ^{228}Ra and ^{40}K.

The Mayer variety of tomato was selected for this experiment because of its suitability for saline soils as suggested by nursery engineers. Single seedling of 10 to 12 cm length and 3 to 5 leaves was transplanted into each pot. Combinations of different treatments comprising soil category and irrigation water source had been arranged in a factorial, randomized-block experimental design. A total of 40 pots representing all potential treatment combinations (2 water sources * 4 soil categories × 5 replicates) were used.

Experiment was started on the 4th of March 2016 and ended on 15th of July 2016. Water, soil and tomato samples were collected and analyzed; samples from irrigation water were collected and in polyethylene bottles, soil samples were collected in plastic bags before and after planting while mature fruits of tomatoes were collected and stored in fridge (5˚C - 6.5˚C) for each of the treatments under investigation.

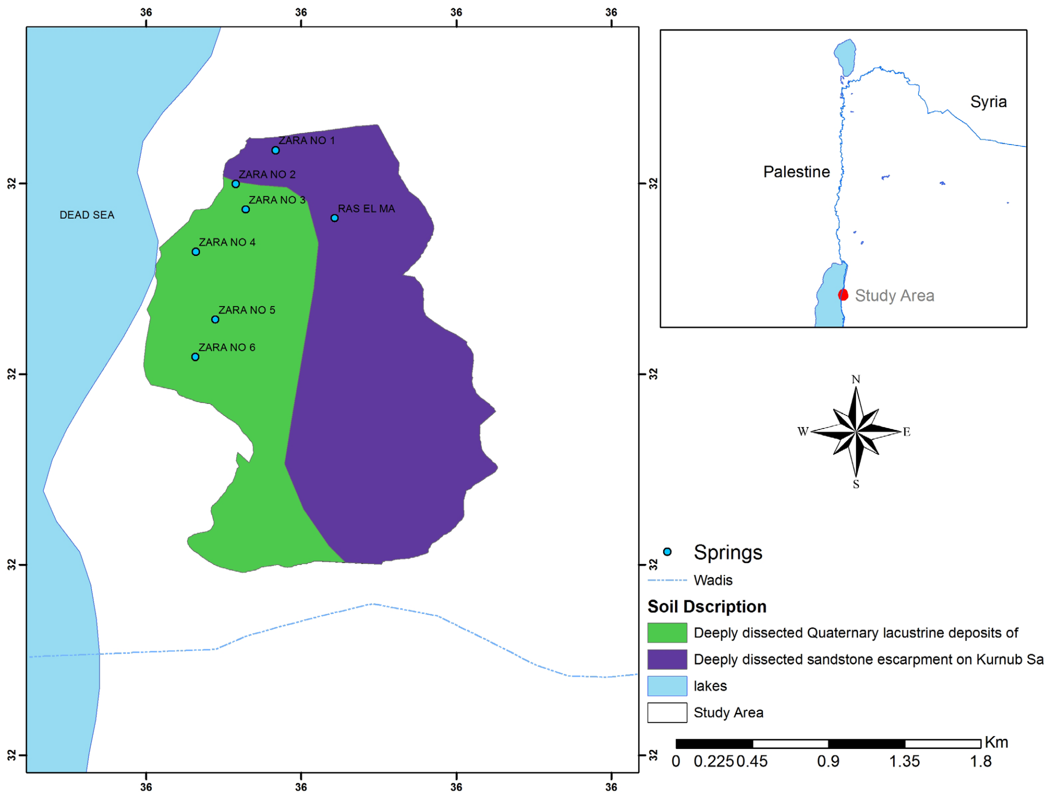

Figure 1. Location of Zara Soil (SZ1 and SZ2) and Zara Hot Springs.

Water samples were enriched by evaporation and kept in one liter Marinelli beakers for Gama spectrometer analysis. Soil samples were oven dried at 105˚C, blended and sieved with 2 mm mesh diameter prior to being packed in containers recommended for gamma spectrometric measurements. These containers were polyethylene cans with 7.8 cm diameter and 1.9 cm height. Vegetative samples were chopped separately into small pieces, weighed and dried in an electrical oven at 105˚C. The dried samples were weighed, crushed into powder and filled in same containers that were used for soil. All samples were tightly sealed and labeled with name, weight and filling date. All samples were left for at least 25 days in order to ensure secular equilibrium for ^{226}Ra and daughters (^{214}Bi and ^{214}Pb) prior to measurement by gamma spectrometer.

Dionex ICS-1000 and ICS-2000 ion chromatography had been used to measure concentrations of major cations and anions in water samples and soil extracts samples. The analysis of ^{226}Ra, ^{228}Ra and ^{40}K was carried out by HPGe gamma spectrometer, Canberra model no B.E3050. The instrument has a shielded detector with 43% efficiency and an energy resolution of 2 Kev. Samples were analyzed for radium after secular equilibrium and the activity was calculated as the average activity obtained from the gamma lines of 351.9 Kev and 609.3 Kev of ^{214}Pb and ^{214}Bi, respectively (Usikalu et al., 2011). Activity of ^{228}Ra was taken as the activity of ^{228}Ac at the 911.2 Kev energy line while ^{40}K activity was determined using the direct gamma line of 1460.7 Kev. Other isotopes that were detected in soil; ^{92}Sr,

^{97}Zr ^{109}Cd, ^{126}I, ^{133}Xe, ^{210}Pb, ^{211}Bi and ^{210}Pb were determined via gamma lines 1383.94, 743, 88.03, 388.63, 258.3, 351.1, 238.6 and 46.5 Kev, respectively. Activity was determined and calculated by Genie 2000 software after applying efficiency and energy calibration.

Gramma spectrometer was calibrated using NIST multiple radionuclide standard, source number 1815-59, from Eckert & Ziegler and was used for energy and efficiency calibration. This standard contains a mixture of radioactive materials having gamma energies in the range of 88 to 1936 Kev in Marinelli beaker with one liter volume. Efficiency curves for two geometries were used in the current study. Marinelli beaker of one-liter SRM with source number 1815-59 from Eckert & Ziegler, and can container standard with certificate number 1035-SE-40320-15 from Check Metrology Institute. Each curve was applied to the samples filled in vessel with the same geometry.

3. Results and Discussion

3.1. Water Characterization

Figure 2 shows concentrations of major cations and anions in irrigation water (thermal and non-thermal). Sulfate, Chloride and Sodium ions concentration in thermal water are higher than non-thermal with concentrations of 93.1, 298.1 and 167.7 mg·L^{-1} compared to 37.4, 76.8 and 46 mg·L^{-1} for non-thermal.

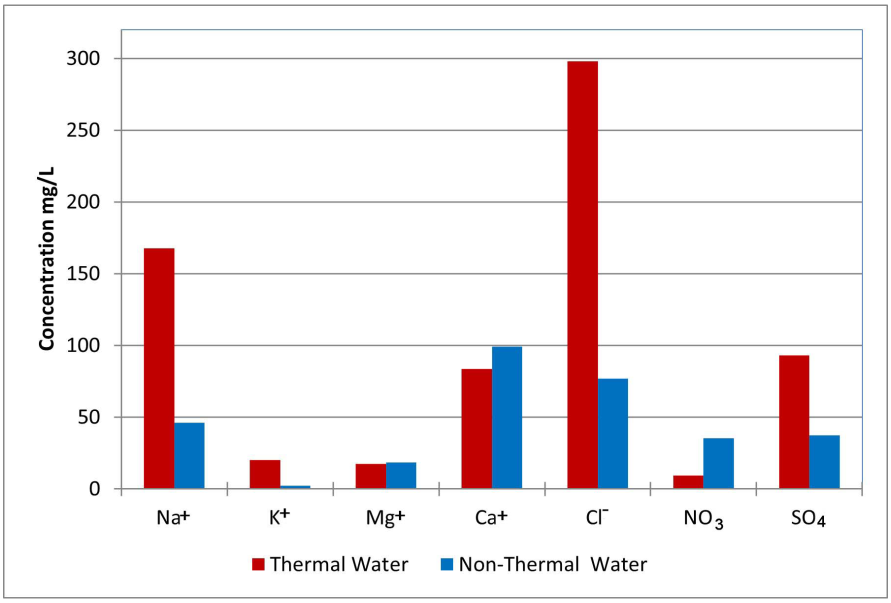

Figure 2. Major cations and anions in thermal and non-thermal water.

Some of heavy metals analysis were found in thermal water such as Fe, Li, Mn, Sr, Ag and Ba with concentrations 0.37, 0.132, 0.539, 2.66, 0.001, 0.075 mg·L^{-1}, respectively. Few elements of Heavy metals also were detected in non-thermal such as Fe, Mn, Sr, Zn, Ba and Al with concentration of 0.288, 0.237, 0.333, 0.134, 0.061 and 0.176 mg·L^{-1}, respectively. Strontium is dominant in thermal water followed by manganese and iron. Maximum activity of gross alpha and beta were 4.3 and 5.9 Bq·L^{-1} respectively in thermal water, these results are guaranteed during first few hours of reservoir filling, and then decrease in the first week to almost reach steady activity with little fluctuation.

Gamma spectrometer and ICP-MS were used to identify radionuclide that exists in thermal water. Results showed that average concentrations were 0.50 Bq·L^{-1} ± 0.05 Bq·L^{-1}, 0.65 Bq·L^{-1} ± 0.04 Bq·L^{-1}, 0.70 Bq·L^{-1} ± 0.12 Bq·L^{-1} for ^{226}R, ^{228}Ra and ^{40}K, respectively. Concentrations of above isotopes in non-thermal water were below detection limit. Detection limits were 0.045 Bq, 0.06 Bq and 0.1 Bq for ^{226}R, ^{228}Ra and ^{40}K, respectively. Concentration of ^{238}U was 9.8 ppt (part per trillion) and Sr isotopes ^{86}Sr, ^{87}Sr and ^{88}Sr were 207.6, 147.5 and 2056.3 ppb, respectively. Radon, concentration was 31 Bq·L^{-1} as measured in January in the year 2016.

3.2. Soil Characterization

Soil extract for all soil types was analyzed for major cations, and anions average concentration for all soil types was represented in **Table 1**. The highest concentrations for all cations and anions were measured in SZ1 followed by SZ2; moderate concentrations were measured in SW and SSa. Sodium ions are the dominant cations in SZ1 while chloride ions are the dominant anions.

Table 1. Major soluble cations and anions in soil extracts.

Soil Name	Na^+ (ppm)	K^+ (ppm)	Mg^{2+} (ppm)	Ca^{2+} (ppm)	Cl^- (ppm)	NO_3^- (ppm)	SO_4^{2-} (ppm)
SZ1	2661.3 ± 145.3	354.5 ± 40.3	219.1 ± 15.5	1114.5 ± 123.9	4225.7 ± 118.7	5460.6 ± 143.4	1019.8 ± 100.1
SZ2	178.4 ± 9.4	123.5 ± 5.1	35.4 ± 5.2	191.1 ± 30.2	281.4 ± 26.2	247.8 ± 13.6	179.2 ± 0.3
SW	23.5 ± 1.2	25.1 ± 1.2	9.4 ± 1.2	64.7 ± 6.3	46.7 ± 2.1	1.38 ± 0.2	31.2 ± 1.2
SSa	40.8 ± 3.4	3.8 ± 0.5	7.4 ± 0.91	25.4 ± 4.4	69.8 ± 3.4	1.39 ± 0.3	27.5 ± 0.9

Clay minerals are layer silicates that are formed usually as products of chemical weathering of other silicate minerals at the earth's surface, and the most common types are kaolinite, illite, chlorite vermiculite and smectite. Clay minerals in soil play an important role in exchange process and dissolved nutrients (Wu et al., 2012). **Table 2** shows that the dominant oxide in SZ1 is CaO; which will increase radium adsorption by this soil type which decreases radium availability for plants. The highest of Potassium oxide was found in SZ2.

Soil analysis by XRF showed that Calcite is dominant in SZ1 followed by quartz and kaolinite. Kaolinite CEC increases with pH > 6 soil such as that of SZ1 soil, but decreases when increasing dissolved Calcium (IAEA, 2014). Soil SZ1 analysis indicated high percent of quartz, calcite and Illite. Calcite and quartz also clear in SW in addition to Montmorollite which has high CEC value. Quartz is the dominant in SSa with very little contributions from other minerals. Illite CEC is about 10 - 40 meq per 100 g soil which is almost three times CEC of kaolinite (Borchardt 1977).

Table 2. Concentration of various oxides present in each of the four soil types used in this study.

Oxide	Concentration (%)			
	SZ1	SZ2	SW	SSa
CaO	42.47	25.72	12.19	3.09
SiO_2	30.45	50.8	55.59	76.32
Al_2O_3	9.034	12.62	18.34	13.89
Fe_2O_3	5.42	4.33	7.56	4.26
MgO	4.26	4.72	2.56	0.07
MnO	4.00	0.56	------	0.001
K_2O	2.07	2.68	1.73	0.067
Na_2O	1.02	0.28	0.41	0.0530
TiO_2	0.54	0.76	1.4	0.02
P_2O_5	0.53	0.77	0.41	0.005
BaO	0.19	0.063	0.608	-------
Cr_2O_3	--------	--------	-------	0.0003

Three samples from each soil type were analyzed by HPGe detector. Table 3 shows maximum (Max), minimum (Min) and average (Avg) activity for ^{226}Ra, ^{228}Ra and ^{40}K followed by uncertainty (Unc) column for each soil type. Activity expressed in Becquerel per kilogram (Bq·kg^{-1}). Soil activity varied in different soil categories activity of SZ1 >> SZ2 >> SW > SSa. Radium-226 is dominant in SZ1 and SZ2, types that are used to grow vegetables in Zara area. Lead-210 was detected in soils in high activity proportional to ^{226}Ra activity and its activity was 5180, 470.2, 51.8 and 10.7 Bq·kg^{-1} in SZ1, SZ2, SW and SSa, respectively. Cadmium-109 also was detected in high activity; 6229.6, 440.5, 71.9 and 14 Bq·kg^{-1} in SZ1, SZ2, SW and SSa respectively.

Table 3. Activity of ^{226}Ra, ^{228}Ra and ^{40}K in soil before planting.

Soil Type		^{40}K (Bq·kg^{-1})	Unc (Bq·kg^{-1})	^{226}Ra (Bq·kg^{-1})	Unc (Bq·kg^{-1})	^{228}Ra 228 (Bq·kg^{-1})	Unc (Bq·kg^{-1})
SZ1	Max	127.4	51.6	5475.1	120.5	ND	ND
	Min	110.3	60.2	5219.1	111.6	ND	ND
	Avg	119.9	51.3	5349.9	117.6	ND	ND
SZ2	Max	197.9	31.4	403.3	19.5	34.3	5.55
	Min	183.5	49.8	380.8	11.3	20.7	5.45
	Avg	190.7	40.6	392.1	23.0	26.7	5.73
SW	Max	149.3	13.1	20.3	1.9	19.1	2.19
	Min	130.2	15.4	19.6	2.1	9.1	2.72
	Avg	139.8	14.3	19.9	1.9	14.8	2.36

Continued

SSa	Max	9.9	0.85	9.0	0.56	10.1	0.53
	Min	9.6	1.02	7.8	0.33	8.1	0.15
	Avg	9.8	0.90	8.3	0.41	8.1	0.14

High content of silicate found in SZ2 (**Table 2**) may contributed to the decrease accumulation of ^{226}Ra, while high content of calcium oxide in SZ1 may contribute to increased ^{226}Ra adsorption and accumulation. Activity of ^{226}Ra is much higher than that reported by Al-Hamarneh and Awadallh (2009) and by Malkawi et al. (2013) with average reported values of 40.5 and 20.84 Bq·kg^{-1}, respectively. Activity of ^{226}Ra in SZ1 and SZ2 is also higher than that reported by Al-Zubaidi et al., (2016) for agricultural soils in Malaysia with an average reported value of 102 Bq·kg^{-1}.

3.3. Radium and Potassium-40 in Tomato Fruit, Leaves and Stems

The results of this study support the hypothesis that irrigation with thermal water influences the uptake and transfer of radionuclides, particularly Radium-226 (^{226}Ra), in tomato plants. The source of irrigation water had a statistically significant effect on ^{226}Ra activity in various plant tissues ($p < 0.05$), especially in roots and leaves, with thermal water generally leading to higher TF values compared to non-thermal water in several treatments.

The strong accumulation of ^{226}Ra in roots compared to aerial parts of the plant aligns with previous reports (IAEA, 2014), highlighting that radium tends to remain in the root zone due to its limited mobility. This is consistent with the low translocation of ^{226}Ra to fruits, where TF values remained below 0.01 in most cases. In contrast, ^{40}K, a plant-essential nutrient, showed higher mobility with TF values exceeding 100 in some sandy soil treatments, particularly for fruits, indicating its physiological preference and active translocation.

The soil characteristics played a crucial role in mediating radionuclide uptake. Sandy soil (SSa), with its low cation exchange capacity (CEC) and minimal clay content, exhibited the highest TF values for both ^{226}Ra and ^{40}K. Conversely, soils rich in clay minerals and oxides, such as SZ1 and SW, showed lower TF values, likely due to higher adsorption and binding of radionuclides to soil particles. These findings are consistent with literature reports (EPA, 2004; Wu et al., 2012), where radium affinity for mineral oxides and clays was found to decrease its bioavailability.

However, the current discussion underutilizes the extensive soil chemistry data presented. A more detailed linkage between oxide composition (e.g., CaO, Fe_2O_3, and K_2O content), mineralogy, and TF values is warranted. For instance, the high CaO concentration in SZ1 likely promoted radium adsorption via ion exchange and co-precipitation, thereby reducing bioavailability. Similarly, the high SiO_2 content in SZ2 may have reduced radium mobility due to physical entrapment or competition with other ions.

The exclusive detection of ^{228}Ra in tomato leaves grown in SSa soils suggests that soil type not only affects total uptake but also the distribution of specific isotopes. This may relate to the chemical similarity of ^{228}Ra with calcium and strontium, both of which are also present in high concentrations in thermal water, and may compete for plant uptake sites depending on ion availability and pH.

Mechanistically, radium uptake is not metabolically driven but occurs via passive processes similar to other alkaline earth elements (e.g., Ba^{2+}, Sr^{2+}). The ionic radius and charge density of radium allow it to mimic calcium and magnesium during uptake but not necessarily translocate efficiently beyond root tissues.

The experimental design revealed significant soil–water interaction effects for ^{226}Ra TF in fruits, leaves, and stems ($p < 0.05$). Yet, it is important to note that only selected root samples (from SZ1 and SZ2 under thermal irrigation) were analyzed, which limits the generalizability of root uptake patterns. A more robust sampling approach would strengthen conclusions regarding radium partitioning across all treatment groups.

Activity of ^{40}K and ^{226}Ra in tomato fruits are illustrated in Table 4. Radium-228 was not detected in tomato fruit. The highest ^{40}K was obtained in tomatoes that were grown in soil SW under irrigation of thermal water. Potassium-40 activity in tomato fruits that were irrigated with thermal water higher than that of tomatoes under irrigation by non-thermal. Maximum activity was 0.93 Bq·kg^{-1} (fresh weight) for plants grown in SZ1 and irrigated with thermal water. Analysis of variance indicated that soil type has significant effect on ^{40}K activity in tomato fruit, while irrigation water and soil*water interaction did not have any significant effect.

Table 4. Activity of ^{226}Ra, ^{228}Ra and ^{40}K in tomato fruit (Bq·kg^{-1} Fresh Weight).

Soil Name	Water Source		Fruits ^{40}K Bq·kg^{-1}	Leaves ^{40}K Bq·kg^{-1}	Stem ^{40}K Bq·kg^{-1}	Fruits ^{226}Ra Bq·kg^{-1}	Leaves ^{226}Ra Bq·kg^{-1}	Stems ^{226}Ra Bq·kg^{-1}
SZ1	**Thermal**	Max	134.44	29.68	43.48	1.00	13.24	2.82
		Min	131.40	24.52	35.57	0.86	11.72	2.08
		Avg	133.28	26.72	39.78	0.93	12.34	2.45
	Non-Thermal	Max	92.43	85.91	93.99	0.49	17.37	2.99
		Min	85.90	75.28	70.20	0.48	15.70	2.34
		Avg	90.02	81.80	80.33	0.48	16.33	2.71
SZ2	**Thermal**	Max	162.50	62.57	86.88	0.80	3.81	2.75
		Min	126.47	51.15	69.03	0.68	2.38	2.17
		Avg	140.12	55.37	78.21	0.75	2.91	2.52
	Non-Thermal	Max	108.00	86.00	48.32	0.68	5.63	1.69
		Min	97.40	78.55	35.02	0.49	5.14	1.53
		Avg	103.67	81.58	40.29	0.58	5.34	1.62

Continued

SW	**Thermal**	Max	167.57	35.15	79.80	0.74	6.22	3.00
		Min	139.24	30.44	74.86	0.55	6.07	2.40
		Avg	158.00	32.64	77.50	0.66	6.14	2.71
	Non-Thermal	Max	95.18	29.14	114.02	0.79	3.89	1.50
		Min	87.86	29.14	95.32	0.35	3.38	1.27
		Avg	92.15	29.14	104.99	0.60	3.60	1.42
SSa	**Thermal**	Max	126.34	30.53	54.69	0.75	7.71	0.54
		Min	107.57	23.80	54.69	0.63	5.64	0.40
		Avg	117.53	26.23	54.69	0.67	6.96	0.45
	Non-Thermal	Max	67.26	25.05	47.81	0.59	3.42	0.21
		Min	66.08	15.95	47.81	0.23	3.16	0.19
		Avg	66.86	19.79	47.81	0.38	3.29	0.20

Maximum activity was 0.93 Bq·kg^{-1} (fresh weight) for plants grown in SZ1 and irrigated with thermal water. Analysis of variance indicated that soil type has significant effect on ^{40}K activity in tomato fruit, while irrigation water and soil*water interaction did not have any significant effect. Accordingly, these results indicated that tomato uptake of ^{40}K was not influenced by changing the source of irrigation on same soil type or other soil types. All results obtained for ^{226}Ra activity in tomato fruits are in agreement with that found by Al-Absi et al. (2015) for tomato collected from Jordanian markets and to that obtained by Saleh et al., (2007) for tomato fruits in Egypt.

The highest ^{226}R in tomato leaves were in those grown in SZ1 and irrigated with non-thermal water followed by that grown in SSa and irrigated with thermal water. Low salinity of non-thermal water caused dissolution of radium salts to be more available for plants which caused raised ^{226}Ra activity in those irrigated with non-thermal to be more than those irrigated with thermal water in both SZ1 and SZ2 soils. Trend of radioactivity in leaves for cauliflower and tomato is the same except in SZ2 soil.

Radium-226 activity in tomato leaves is higher than cauliflower; tomato received more water from irrigation (145 L) compared to cauliflower (98 L). In addition, tomato growth stage lasted more than cauliflower.

Radium-228 in tomato leaves also was only detected in sandy soil (SSa) that was irrigated from thermal and non-thermal water. Tomato stems were collected and used for radioactivity measurements. According to statistical analysis, type of soil had significant effect on ^{40}K and ^{226}Ra activity in tomato stems. Irrigation source had significant effect on ^{226}Ra only, while soil * water interaction had no significant effect on both ^{40}K and ^{226}Ra in tomato stems.

3.4. Activity in Tomato Root

Only roots from SZ1 and SZ2 under thermal irrigation were analyzed due to instrument availability and sample throughput constraints. These treatments were prioritized based on their higher soil radioactivity levels. Future work should include a complete root analysis across all treatments to enhance statistical power and minimize selection bias.

Roots of tomatoes that were grown in SZ1 and SZ2 and irrigated with thermal water were analyzed while other treatment roots were not analyzed for technical reasons regarding instrument. Average activity of ^{226}Ra, ^{228}Ra and ^{40}K in Bq·kg^{-1} as fresh weight are shown in **Figure 3**.

Activity of ^{226}Ra in tomato root grown in SZ1 is 84.1 Bq·kg^{-1} which is eight folds higher than activity of that gown in SZ2 (11.5 Bq·kg^{-1}), while ^{228}Ra activity of root in SZ1 and SZ2 were almost similar with values of 8.7 and 7.8 Bq·kg^{-1} respectively.

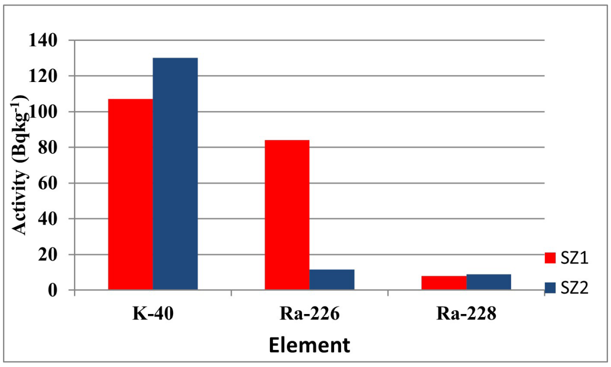

Figure 3. Activity of ^{226}Ra, ^{228}Ra and ^{40}K in Tomato Root.

These results are much higher than fruit and leaves which mean that plants uptake higher concentrations of radioactive elements but restricted amounts are being translocate to upper parts (IAEA, 2014). Results assured selectivity of radium isotopes during distribution in different plant tissues. Since ^{226}Ra is lighter than ^{228}Ra, it has more priority to move and distribute in plants.

The highest TF in tomato fruits was in sandy soil (SSa) followed by SZ2 under irrigation of thermal water, while the least was in SZ2 that was irrigated with non-thermal water. Average TF in tomato for ^{40}K in fruit > TF stem > TF leaves in SZ1 and SW while in SZ2 and SSa the trend was TF for ^{40}K in fruit > TF leaves > TF stems (**Table 5**).

Table 5. TF of ^{226}Ra, ^{228}Ra and ^{40}K in tomato fruits, leaves and stems.

Soil	Irrigation Source		TF ^{40}K			TF ^{226}Ra			TF ^{228}Ra		
			Fruit	Leave	Stem	Fruit	Leaves	Stem	Fruit	Leaves	Stem
SZ1	Thermal	Max	11.73	1.37	2.07	0.002	0.015	0.003	ND	ND	ND
		Min	11.46	1.13	1.69	0.002	0.013	0.002	ND	ND	ND
		Avg	11.63	1.23	1.89	0.002	0.014	0.003	ND	ND	ND
	Non-Thermal	Max	8.06	3.97	4.47	0.001	0.019	0.003	ND	ND	ND

Continued

		Min	7.49	3.48	3.65	0.001	0.017	0.003	ND	ND	ND
		Avg	7.85	3.78	4.07	0.001	0.018	0.003	ND	ND	ND
SZ2	Thermal	Max	9.47	1.93	2.76	0.022	0.056	0.042	ND	ND	ND
		Min	7.37	1.58	2.19	0.019	0.035	0.033	ND	ND	ND
		Avg	8.16	1.71	2.49	0.021	0.043	0.038	ND	ND	ND
	Non-Thermal	Max	6.29	2.65	1.54	0.019	0.083	0.026	ND	ND	ND
		Min	5.68	2.42	1.11	0.014	0.076	0.023	ND	ND	ND
		Avg	6.04	2.52	1.28	0.016	0.079	0.025	ND	ND	ND
SW	Thermal	Max	13.99	1.55	3.63	0.409	1.833	0.910	ND	ND	ND
		Min	11.63	1.35	3.41	0.304	1.790	0.729	ND	ND	ND
		Avg	13.19	1.43	3.53	0.365	1.811	0.822	ND	ND	ND
	Non-Thermal	Max	7.95	1.29	5.19	0.440	1.146	0.456	ND	ND	ND
		Min	7.34	1.13	4.34	0.192	0.995	0.384	ND	ND	ND
		Avg	7.69	1.22	4.78	0.331	1.060	0.432	ND	ND	ND
SSa	Thermal	Max	143.73	18.39	33.94	1.009	5.493	2.690	ND	0.815	ND
		Min	122.38	14.33	0.00	0.841	4.015	2.342	ND	0.634	ND
		Avg	133.71	16.04	11.31	0.906	4.956	2.543	ND	0.700	ND
	Non-Thermal	Max	76.52	15.09	29.67	0.787	2.437	1.101	ND	0.510	ND
		Min	75.18	9.61	0.00	0.303	2.251	0.951	ND	0.258	ND
		Avg	76.06	11.92	9.89	0.505	2.344	1.023	ND	0.343	ND

Transfer factor for ^{226}Ra in fruit < TF stems < TF leaves. The highest TF in tomato leaves was found in those grown in SSa soils and irrigated with thermal water. On the other hand, TF of tomato leaves grown in SZ1 and SZ2 soils was lower for those irrigated with thermal water than those irrigated with non-thermal water. This could be attributed to the higher salinity of soil that causes dissolution of radium salts.

Radium-228 was not detected in most of treatments except in sandy soil (SSa) and under the two sources of irrigation water in leaves only. TF for ^{228}Ra under thermal water irrigation was 0.7 while under non-thermal Irrigation was 0.34. Compared to that in cauliflower leaves, TF in tomato leaves is higher.

The analysis of variance shows that transfer factor was significantly affected by all sources of variation (soil type, source of irrigation and their interactions) in tomato fruits, leaves and stems for ^{226}Ra and only in fruits for ^{40}K. On the other hand, TF for ^{40}K in stems was not affected by any source of variation.

The results of this study approved the initial research hypothesis that radioactive elements will interact with soil and plants as a result of irrigation with thermal water. Transfer factor in fruits significantly affected by source of variation in this study (soil, water and soil*water interaction).

In summary, radioactivity transfer to plants is a function of multi variables including soil texture, soil chemical properties, water characteristics and plant metabolism. Transfer of ^{226}Ra activity in cauliflower and tomato was different in different soil types. High CEC values for SZ1, SZ2 and SW decrees TF compared to soil with low CEC value (SSa).

Supporting to the above results, studies reported by the EPA (2004) show that radium is readily adsorbed to clays and mineral oxides present in soils, especially at pH above 7 and the relative affinity of radium with other elements for ion exchange on clay minerals has been described as follows: Ra > Ba > Sr > Ca > Mg.

Radium can be dissolved in solutions having a varied pH value from Ph = 3 to pH = 10 (Encian, 2014). Dissolved radium is a double ionized state, Ra^{2+} (Smith & Amonette, 2006). Radium compounds can be soluble such as radium chloride, the radium bromide, the radium hydroxide, and the radium nitrate with solubility slightly lower than the chloride and barium bromide, and greater than the barium nitrate.

The insoluble radium compounds include the radium sulfate, the radium chromate, the radium iodate, the radium carbonate, and the radium tetrafluoroberyllate. The radium sulfate is the most insoluble known sulfate (Kirby et al., 1964). High concentration of sulfate in SZ1 caused high percent of total radium to precipitate compared to behavior of calcium sulfate percent as analyzed by Visual Minteq speciation in **Table 1** and **Table 2** compared to that of radium chloride.

Water characteristics also affect mobility of radioactive elements to plants. As found in ANOVA tables in Appendix A, irrigation water significantly affects radium transfer to plant tissues. Low salinity may cause some dissolution for radium salts in case of saline soil.

Mobility of elements affected ^{40}K activity in plants. No specific trend was found for TF in plant tissues. Since potassium is mobile element and ^{40}K is a part of total potassium, ^{40}K TF behavior related to movement of potassium in plants to compensate deficiency and as priorities in plants which is firstly given to fruits

Nutrient concentration in plants affected ^{226}Ra activity in cauliflower head. Vas et al. (1987) as cited by IAEA (2014) found that species with the highest concentration of Ra were associated with elevated Calcium concentration such as that present in cauliflower. Low tomato content of Calcium (5 mg per 100 g of fresh tomato) (USDA, 2018) decreases the opportunity for transfer of radium to tomato.

Radium concentration fractionates in different plant tissue; in roots higher than leaves which in turn higher than fruit. According to Simon and Ibrahim (1990), literature data suggest that Radium is not metabolically active and is not secondarily distributed among plant tissues and suggests that it might behave similarly to the other alkaline earth elements.

4. Conclusion and Recommendations

The outputs of this study confirm that irrigation with thermal water significantly influences the uptake and translocation of ^{226}Ra in tomato plants, with observable differences across soil types. In contrast, ^{40}K uptake is predominantly governed by soil potassium content, reflecting its role as an essential nutrient.

Transfer factor analysis showed that roots are the primary accumulation site for ^{226}Ra, accounting for over 85% of total radium content in tested treatments. However, accumulation in edible tissues such as fruits remained relatively low, mitigating potential health risks under current exposure scenarios. These findings suggest that thermal water or other water sources containing elevated levels of natural radionuclides could be considered as alternative irrigation sources, provided that appropriate management practices are applied, particularly with regard to soil type and crop selection.

Soil characteristics, particularly mineral composition and CEC, played a pivotal role in controlling radionuclide bioavailability. Soils with high clay and oxide content demonstrated lower TF values, likely due to stronger radium adsorption, while sandy soils with lower adsorption capacity allowed greater mobility and uptake.

These findings highlight the importance of considering both soil properties and irrigation water quality when assessing the radiological safety of agricultural practices in arid regions. Further research under field conditions is recommended to validate pot experiment findings and to explore mitigation strategies, such as soil amendments or crop selection that can reduce radionuclide uptake.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Acknowledgements

The authors would like to thank the Ministry of Water and Irrigation in Jordan for their kind permission to conduct the agricultural research experiment at the experimental station affiliated with their laboratory, and for their support in carrying out the required analyses. The authors also extend their gratitude to the Energy and Minerals Regulatory Commission (EMRC) for their technical assistance, and to the University of Jordan for providing laboratory resources and academic support throughout the research.

Conflicts of Interest

The authors also declare that they have no competing interests, financial or otherwise, that could have appeared to influence the work reported in this paper.

References

Ababneh, A. M., Masa'deh, M. S., Ababneh, Z. Q., Awawdeh, M. A., & Alyassin, A. M. (2009). Radioactivity Concentrations in Soil and Vegetables from the Northern Jordan Rift Valley and the Corresponding Dose Estimates. *Radiation Protection Dosimetry, 134,* 30-37. https://doi.org/10.1093/rpd/ncp064

Abu Hamad, N. (2017). Uncontrolled Urban Expansion of Amman City and the Disintegration of the Rainfed Lands. *Architecture Research, 7,* 24-28.

Al-Absi, E., Al-Abdullah, T., Shehadeh, H., & Al-Jundi, J. (2015). ^{226}Ra, ^{228}Ra, and ^{40}K Activity Concentration in Some Vegetables Consumed in Jordan, and Resultant Annual Ingestion Effective Dose. *Radiation Protection and Environment, 38,* 29-34. https://doi.org/10.4103/0972-0464.162819

Al-Hamarneh, I. F., & Awadallah, M. I. (2009). Soil Radioactivity Levels and Radiation Hazard Assessment in the Highlands of Northern Jordan. *Radiation Measurements, 44,* 102-110. https://doi.org/10.1016/j.radmeas.2008.11.005

Al-Okour, A., Ajlouni, A., Ajlouni, A., & Shakhatreh, S. (2013). Radiation Doses Due to Natural Radioactivity in Al Hammah Hot Springs, Jordan. *Contemporary Engineering Sciences, 6,* 127-134. https://doi.org/10.12988/ces.2013.13012

Al-Zubaidi, G., Hamid, F. B. S., & Abdul Rahman, I. (2016). Assessment of Natural Radioactivity Levels and Radiation Hazards in Agricultural and Virgin Soil in the State of Kedah, North of Malaysia. *The Scientific World Journal, 2016,* Article ID: 6178103. https://doi.org/10.1155/2016/6178103

Borchardt, G. (1977). Montmorillonite and Other Smectite Minerals. In J. B. Dixon, & S. B. Weed (Eds.), *Minerals in Soil Environments* (pp. 293-330). Soil Science Society of America.

El-Taher, A., & Al-Turki, A. (2014). Soil-to-Plant Transfer Factors of Naturally Occurring Radionuclides for Selected Plants Growing in Qassim, Saudi Arabia. *Life Science Journal, 11,* 965-972.

Encian, I. (2014). *Studies and Research on Radium in Groundwater.* Ph.D. Thesis, Faculty of Environmental Science and Engineering.

EPA (2004). *Understanding Variation in Partition Coefficient Kd Values Volume III: Review of Geochemistry and Available Kd Values for Americium, Arsenic, Curium, Iodine, Neptunium, Radium, and Technetium.* US Environmental Protection Agency Report US EPA 402-R-04-002C.

IAEA (2014). *Technical Report Series No 476. Environmental Behavior of Radium.*

Kirby, H. W., Salutsky, M. L., & Grace, W. R. (1964). *The Radiochemistry of Radium.* National Academy Sciences, National Research Council, NUCLEAR SCIENCE SERIES.

Malkawi, S. R., El-Gohary, M., Omari, M., Danah, A., Al-Mistarihi, Q., & Al-Malahim, E. (2013). Investigation of Radioactivity Levels in Soil at JUST Campus Prior to the Construction of JRTR. *Jordan Journal of Civil Engineering, 7,* 371-376.

Pallavicini, N. (2011). *Activity Concentration and Transfer Factors of Natural and Artificial Radionuclides in the Swedish Counties of Uppsala and Jutland.* Master's Thesis, Swedish University of Agricultural Sciences.

Saleh, H. I., Abdelfatah, H. F., Nadia, E. H., Hussein, M. A., & Mohammed, N. A. (2007). Radiological Study on Soils, Foodstuff and Fertilizers in the Alexandria Region, Egypt. *Turkish Journal of Engineering and Environmental Sciences, 31,* 9-17.

Schaffer, R., & Sass, I. (2012). The Thermal Springs of Jordan. *Environmental Earth Sciences, 72,* 171-187. https://doi.org/10.1007/s12665-013-2944-4

Simon, S. L., & Ibrahim, S. A. (1990). Biological Uptake of Radium by Terrestrial Plants. *The Environmental Behaviour of Radium, 1,* 545-599.

Smith, B., & Amonette, A. (2006). *The Environmental Transport of Radium and Plutonium: A Review* (p. 8). Institute for Energy and Environmental Research.

Szabo, Z., dePaul, V. T., Fischer, J. M., Kraemer, T. F., & Jacobsen, E. (2012). Occurrence and Geochemistry of Radium in Water from Principal Drinking-Water Aquifer Systems of the United States. *Applied Geochemistry, 27,* 729-752. https://doi.org/10.1016/j.apgeochem.2011.11.002

USDA (2018). *National Nutrient Database for Standard Reference.* https://www.nal.usda.gov/human-nutrition-and-food-safety/nutrient-lists-standard-reference-legacy-2018

Usikalu, M. R., Anoka, O. C., & Balogun, F. A. (2011). Radioactivity Measurements of the Jos Tin Mine Tailing in Northern Nigeria. *Archives of Physics Research, 2,* 80-86. http://scholarsresearchlibrary.com/archive.html

Vas Concellos, L. M. H., Amaral, E. C. S., Vianna, M. E., & Franca, P. (1987). Uptake of ^{226}Ra and ^{210}Pb by Food Crops Cultivated in a Region of High Natural Radioactivity in Brazil. *Journal of Environmental Radioactivity*, **5**, 287-302. https://doi.org/10.1016/0265-931X(87)90004-X

Vengosh, A., Hirschfeld, D., Vinson, D., Dwyer, G., Raanan, H., Rimawi, O. et al. (2009). High Naturally Occurring Radioactivity in Fossil Groundwater from the Middle East. *Environmental Science & Technology, 43,* 1769-1775. https://doi.org/10.1021/es802969r

Wu, L. M., Zhou, C. H., Keeling, J., Tong, D. S., & Yu, W. H. (2012). Towards an Understanding of the Role of Clay Minerals in Crude Oil Formation, Migration and Accumulation. *Earth-Science Reviews, 115,* 373-386. https://doi.org/10.1016/j.earscirev.2012.10.001