RADIOMETRIC EVALUATION AND ANALYSIS OF COMMONLY CONSUMED VEGETABLES IN SELANGOR, MALAYSIA.

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RADIOMETRIC EVALUATION AND ANALYSIS OF COMMONLY CONSUMED VEGETABLES IN SELANGOR, MALAYSIA.

ABSTRACT

The activity concentration of naturally occurring radionuclides in vegetables and peat soil was measured in this research to determine the transfer factors (TFs) of radionuclides from soil to vegetables collected from farms located in Klang, Selangor using a High Purity Germanium Detector. The results showed that the activity concentration ranges for ^{137}Cs (Caesium-137), ^{226}Ra (Radium-226), ^{232}Th (Thorium-232) and ^{40}K (Potassium-40) in the soil of the vegetable were (0.34 – 3.21) Bqkg^{-1}, (2.72 – 46.54) Bqkg^{-1}, (9.01 - 54.84) Bqkg^{-1}and (19.22 – 477.76) Bqkg^{-1}, respectively. The activity concentration ranges for ^{226}Ra, ^{232}Th and ^{40}K in various vegetable samples were (0.41 – 3.41) Bqkg^{-1}, (0.02 - 3.56) Bqkg^{-1}and (16.22 - 317.49) Bqkg^{-1}, respectively. The activity concentration for ^{137}Cs in the vegetable samples were below the detection limit (BDL). The TF from soil-to-plant for ^{226}Ra, ^{232}Th and ^{40}K was in the range of (0.01 - 0.67), (0.00 - 0.17) and (0.26 – 2.52), respectively. The values obtained, including the radium equivalent, $Ra_{eq,}$ were compared to the internationally recommended values. Ra_{eq} calculated in the soil samples from the vegetable farm are in the range of (17.09 – 161.75) Bqkg^{-1}, which is lower than the suggested value of 370 Bq/kg by United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

Radiological hazards from the soil and consumer exposure were evaluated using soil and vegetable activity concentrations. It is found that the External Hazard Index, H_{ex} and Internal Hazard Index, H_{in} are ranged from 0.05 to 0.44 and from 0.05 to 0.56, respectively, which are lower than the limit established by the European Commission of Radiation Protection(ECRP). The Radiological Level Index, I_{γ} for the soil ranges between 0.12 to 1.18.

However, one of the soils surrounding four angles bean has a Radiological Level Index, I_γ of 1.18 higher than the recommended value of 1. For the vegetable sample, it is found that the absorbed dose rate, D_N is ranged between 1.75 to 16.94 nGy h^{-1}. The value of Annual Ingestion Dose (A_{eff}) ranges from 2.54 µSv y^{-1} to 22.89 µSv y^{-1}. The range of Annual Effective Dose Equivalent (AEDE) is between 2.15 µSv y^{-1} to 20.78 µSv y^{-1}. The value of Excess Life-time Cancer Risk (ELCR) ranges between 0.80×10^{-5} to 7.79×10^{-5}. The Annual Ingestion Dose, Annual Effective Dose Equivalent and ELCR are found to be lower than the value recommended by UNSCEAR.

Results showed that the activity concentration of ^{137}Cs in the soil samples ranged between 0.34 ± 0.09 to 3.21 ± 0.17 Bqkg^{-1}. Dose rate computed from the corresponding value of activity concentration ranged from 0.01 to 0.10 nGyh^{-1}. The annual effective dose rate ranged between 1.25 to 11.8 µSv y^{-1}. The values of ELCR ranged between 0.47×10^{-5} to 4.45×10^{-5} which is lower than the safety limit of 0.29×10^{-3}. The results of this investigation show that the assessed values are below the UNCSEAR and ICRP recommended values and do not present radiological hazards to the general population.

Keywords: Activity concentration, natural radionuclide, transfer factor, radiological index, absorbed dose index

PENILAIAN DAN ANALISIS RADIOMETRI SAYUR-SAYURAN YANG BIASA DIMAKAN DI SELANGOR, MALAYSIA

ABSTRAK

Kajian penyelidikan ini mengukur kepekatan aktiviti radionuklid semula jadi di dalam sampel tanah dan sayur-sayuran yang di tanam di sebuah kebun tanah gambut yang terletak di daerah Klang, Selangor. Pengesan sinar gamma, HPGe digunakan untuk mengesan kepekatan aktiviti 3 unsur sinar radioaktif yang utama iaitu ^{137}Cs (Cesium-137), ^{226}Ra (Radium-226), ^{232}Th (Thorium-232) dan ^{40}K (Potassium-40)di dalam sampel tanah dan sampel sayur-sayuran. Kepekatan aktiviti radionuklid, ^{226}Ra, ^{232}Th dan ^{40}K di dalam sampel tanah mempunyai julat nilai masing-masing (0.34 – 3.21) Bqkg^{-1}, (2.72 – 46.54) Bqkg^{-1}, (9.01 - 54.84) Bqkg^{-1} dan (19.22 – 477.76) Bqkg^{-1}. Untuk sampel sayuran pula, julat pengukuran kepekatan aktiviti radionuklid ^{226}Ra, ^{232}Th dan ^{40}K masing-masing adalah (0.41 – 3.41) Bqkg^{-1}, (0.02 - 3.56) Bqkg^{-1} dan (16.22 - 317.49) Bqkg^{-1}. Pengukuran kepekatan akiviti radionuklid ^{137}Cs di dalam sampel sayuran didapati di bawah had pegesanan detektor (BDL). Faktor pemindahan (TF) unsur radioaktif dari tanah ke tumbuhan, untuk ^{226}Ra, ^{232}Th and ^{40}K mempunyai julat nilai masing-masing (0.01 - 0.67), (0.00 - 0.17) dan (0.26 – 2.52). Kesetaraan Radium, Ra_{eq} di dalam sampel tanah diukur dan didapati mempunyai julat nilai diantara 17.09 – 161.75 Bqkg^{-1} dimana nilai ini kurang dari nilai keselamatan iaitu 370 Bqkg^{-1} seperti yang dicadangkan oleh Jawatankuasa Saintifik Radiasi Atom, Pertubuhan Bangsa – Bangsa Bersatu (UNSCEAR).

Hasil kajian pengukuran kepekatan aktiviti radionuklid di dalam sampel tanah dan sayuran digunakan untuk menilai parameter bahaya radiologi terhadap pengguna dan penduduk tempatan. Indeks Radiasi Luaran H_{ex} dan Indeks Radiasi Dalaman, H_{in} dari sampel tanah

mempunyai julat nilai masing-masing (0.05-0.44) dan (0.05-0.56)m di bawah nilai-nilai yang disyorkarkan oleh Suruhanjay Perlindungan Sinaran Eropah (ECRP). Manakala paras Indeks Radiologi Gamma, I_γ mempunyai julat nilai (0.12- 1.18). I_γ untuk sampel tanah di mana Kacang Botol ditanam mempunyai nilai 1.18, melebihi paras yang dicadangkan iaitu 1. Keputusan kajian juga digunakan untuk menilai Kadar Penyerapan Dos Sinaran, D_N dari sayuran yang mempunyai julat nilai (1.75 – 16.94) nGy h^{-1}. Kadar Pendedahan Tahunan, A_{eff} mempunyai julat nilai (2.54 - 22.89) µSv y^{-1}. Kelebihan Risiko Kanser Seumur Hidup, ELCR mempunyai julat nilai 0.80×10^{-5} -7.79×10^{-5}. Kesemua parameter radiologi didapati kurang dari nilai-nilai yang disyorkan oleh UNSCEAR.

Hasil kajian pengukuran kepekatan aktiviti radionuklid ^{137}Cs di dalam sampel tanah mempunyai julat nilai 0.34 ± 0.09 - 3.21 ± 0.17 $Bqkg^{-1}$. Kadar penyerapan dos sinaran, D_N mempunyai julat nilai 0.01 - 0.10 $nGyh^{-1}$. Kadar pendedahan tahunan, A_{eff} mempunyai julat nilai 1.25 to 11.8 µSv y^{-1} . ELCR mempunyai julat nilai 0.47×10^{-5} to 4.45×10^{-5}. Kesemua parameter radiologi didapati kurang dari nilai-nilai yang disyorkan oleh UNSCEAR dan Suruhanjaya Antarabangsa Perlindungan Radologi (ICRP).

Kata kunci: Kepekatan activiti, radionuklid semula jadi, faktor pemindahan, indeks radiologi, indeks penyerapan dos

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D_N	:	Absorbed dose rate
AC	:	Activity concentration
AEDE	:	Annual effective dose equivalent
BDL	:	Below detection limit
ECRP	:	European Commission for Radiation Protection
ELCR	:	Excess life-time cancer risk
H_{ex}	:	External hazard index
HPGe	:	High purity germanium detector
H_{in}	:	Internal hazard index
IAEA	:	International atomic energy agency
ICRP	:	International commission on radiological protection
NORM	:	Naturally occurring radioactive material
I_γ	:	Radiological level index
Ra_{eq}	:	Radium equivalent
A_{eff}	:	The annual ingestion dose
TF	:	Transfer factor
UNSCEAR	:	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	:	World Health Organization

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CHAPTER 1: INTRODUCTION

1.1 General Background

In our planet, there are more than 60 radionuclides (radioactive elements) that were formed and may be found in the environment, which makes it a radioactive world. Radionuclides are radioactive elements that exist naturally in the environment and may be found in the atmosphere, water, and soil. Nature's radioactivity may be found in the rocks and soil of our planet, but it can also be found in the seas and oceans, as well as in construction and other materials(Kim et al., 2012).

It has been demonstrated that naturally occurring radionuclides from soil can be metabolically coupled with plants. In a similar way, radionuclides produced by people and released into the environment react similarly. As an alternative to root absorption, direct deposition on leaf surfaces may also occur, and when this occurs, radionuclides are taken up by plants through the leaves through the plant's metabolic processes. If long-lived radionuclides remain within reach of the roots of plants and if they are chemically accessible to the roots of plants, the capacity of the plants to absorb long-lived radionuclides is greatly impacted. The rates at which some radionuclides travel through different soils under varied pH and humidity conditions remain unknown. Animals absorb it through the consumption of roots or leaves of these plants, and it is then transferred to people by the consumption of meat or other animal products such as dairy, animal oil, or fat, as well as a direct transmission from plant to human.(Golmakani et al., 2008).

The radioisotopes U-238 and U-235 are the most abundant radioisotopes of natural uranium in the Earth's crust, with 99.28 percent and 0.72 percent abundances, respectively, in the planet's crust. Th-232 is the sole naturally occurring isotope of thorium, and it is found in abundant quantities on Earth. It is possible to find non-series radionuclides such as K-40 almost anywhere, including human and animal tissues, soils, and even the waters, in differing amounts. Overall, the average effective dosage for an person arising from natural background radiation is roughly 2.40 mSv on a yearly basis, according to current estimates. (UNSCEAR, 2000).

Phosphates can be absorbed by plants through their roots and leaves, while animals can do so through the plants they eat, as well as through phosphate-based mineral dietary supplements and the soil (among other sources). These radionuclides are eventually ingested by people when they consume animal products such as meat or milk, or when they come into direct contact with plants that directly consume them for sustenance.

The radionuclides that are ingested through the consumption of food and, to a lesser extent, water are the source of a sizeable portion of the standard radiation doses that are delivered to the different organs of the human body, most notably the skeleton. This is because radionuclides are absorbed into the body through the digestive tract. This is particularly accurate with regard to the skeleton. Investigations into the possible presence of these radionuclides in the food supply should unquestionably be incorporated into the environmental monitoring programme that the government is currently carrying out.(Korkmaz et al., 2011)

These radioactive sources occur naturally and are among the most significant contributors to the radiation doses that humans are exposed to on a daily basis. They are also among the most difficult to detect. It is Potassium-40, a member of the U-238 and Th-232 decay family,

which is the most significant since it occurs naturally in natural settings. The naturally occurring element potassium-40, which is a key component of cell material, may be found in virtually all foods as a naturally occurring component. The general public receives around 180 Sv/year from K-40, which is a cellular component that is needed for life. Considering that an average human individual has a total potassium content of around 0.14 kg of natural potassium, K-40 is the most prevalent naturally radioactive chemical in our own bodies. (Sanders, 2009).

Calculating the transfer factor (TF) allows one to make this comparison amongst the concentration of radioactivity per unit mass in a sample of vegetable or plant matter and the concentration of radioactivity per unit mass in the soil. The TFs are frequently used to assess the radiation dose to humans received through the ingestion route. It is widely considered as one of the most significant factors in studies to evaluate the impact of radionuclide emissions on the environment, and it is frequently employed in such research. (Asaduzzaman et al., 2015; IAEA, 2009)

The TF of different radionuclides is affected by a variety of reasons, including soil type, the physicochemical properties of the radionuclides, the soil environment, soil pH, texture, and exchangeable K, as well as the quantity of bicarbonate, clay, and organic matter present in the soil. Furthermore, plant species and varieties, as well as agricultural techniques such as irrigation, plowing, and the application of fertilisers, have an impact on the TF value. (Duong et al., 2021; Thabayneh, 2014)

In order to calculate the radiation doses that are given to humans, it is essential to detect and quantify the activity of several different radionuclides that are appear in the soil. Additionally, it is necessary to measure their TF to a number of different plant samples. All of these steps must be completed before the radiation doses can be determined.

A large amount of natural radiation is emitted by the terrestrial radionuclides (^{238}U, ^{226}Ra, ^{232}Th) and their decay products, as well as ^{40}K. Humans are subjected to a large quantity of natural radiation as a result of the presence of these radionuclides, which are present in adequate amounts and occur naturally. It is generally accepted that they are the single most significant factor contributing to both the internal and exterior exposure to terrestrial radiation in the United States. The biological effects of radiation are determined in part by the amount of radiation that is absorbed by a person, the types of radionuclides that are consumed, and the quantity of food that is eaten during the period that the person is exposed to radiation. It is possible to have two different kinds of effects on living things: deterministic effects and stochastic effects (or both)(Grosch, 2012).

Radiation can have an immediate effect as well as a long-term effect, which may manifest itself years or many generations after the first exposure. Radiation has a biological effect as a result of both direct and indirect effects on the body, according to the WHO. When radiation particles directly interact with complex bodily molecules, this is referred to as direct action. It is more complicated to deal with indirect radiation since it is significantly influenced by the energy loss impact of radiation on the body and tissue, as well as the chemistry that results.(Edwards and Lloyd, 1998)

There are two sorts of biological effects: Deterministic Effects and Stochastic Effects. Deterministic Effects are the more common. The non-stochastic effect is a phrase used to describe deterministic effects. These side effects are dependent on the length of time spent exposed, the amount of radiation received, and the kind of radiation. It has a threshold of dosages below which the effect does not manifest itself; the threshold might differ from person to person depending on the individual. When it comes to deterministic effects, they are those that get more severe as the dose is raised. Assume that the dose is increased, and

that the intensity of the effect rises as well. Erythema (reddening) of the skin and the development of radiation-induced cataracts are examples of deterministic effects (formerly called a non-stochastic effect) (Fry, 2001).

The stochastic effect refers to the effects of high radiation dose on a person. It occurs when the dose is increasing rapidly and has a high probability of causing an impact.

The absence of a threshold dosage beyond which one can be creatively certain that a stochastic impact would not occur is a limitation. The seriousness of the effects differs on the amount of radiation exposure absorbed. They can also be triggered by chance or by a small number of cells. A stochastic effect is a type of calculation that shows the likelihood that a given disease will have a high chance of occurrence (Choudhary, 2018).

According to a Ministry of Health (MOH) findings, bananas, apples, oranges, green leafy vegetables, bean type vegetables, and cabbages are the most commonly consumed fruits and vegetables in Malaysia, with bananas being the most popular. Green leafy vegetables are consumed on a daily basis by over 40 % of the adult population. The Ministry of Health recommends that people consume at least five portions of fruits and vegetables per day (about 400 g/day) since vegetables and fruits are classified as the second most significant food after rice and cereals(Ministry of Health Malaysia, 2010).

1.2 Objectives of this research

This study is to determine the radiological hazards of gamma emitting natural radionuclides in a peat soil farm and the vegetables grown in this farm. Vegetable samples are taken from three main groups, mainly, leafy type vegetables, beans/leguminous type vegetables and fruit type vegetables. The soil is obtained from Green Revolution Project, Klang, Selangor. The radionuclides which are to be determined ^{137}Cs, ^{226}Ra, ^{232}Th and ^{40}K using High Purity Germanium (HPGe).

The specific objectives:

- To analyse the activity concentration ($Bqkg^{-1}$) of the radionuclides ^{137}Cs, ^{226}Ra, ^{232}Th and ^{40}K in both soil and vegetable samples using the HPGe Gamma Detector
- To determine the transferred radionuclide from the soil in the vegetables which is known as the transfer factor.
- To calculate the radiological hazards such as radium equivalent, Ra_{eq}, External Hazard Index, H_{ex}, Internal Hazard Index, $H_{in,}$ and Gamma radioactivity Level Index, I_{γ} for the soil samples and to compare with the recommended values by UNCSEAR.
- To evaluate annual effective ingestion dose, A_{eff}, absorbed dose rate, D_N and annual effective dose equivalent, AEDE for the vegetable samples, and to analyse their impact on human consuming these vegetables
- To understand the Excess Lifetime Cancer Risk to determine likelihood of developing life-long cancer at some exposure due to consumption of the vegetables.

1.3 Scope of the study and thesis

This thesis involves 5 chapters. Chapter one represents the research background, goal and objectives of the work. Chapter two presents the literature reviews on the Naturally Occurring Radioactive Material (NORM), High Purity Germanium Gamma detector, radionuclide in the soil, nuclear fallout and anthropogenic Caesium -137 from the Fukushima Daiichi Nuclear Power Plant and the radiological hazards to human. Chapter three discusses the experimental procedures including the selection of the sampling area, sample collection, radioactivity measurement of the activity concentration of ^{137}Cs, ^{226}Ra, ^{232}Th and ^{40}K in both soil and vegetable samples using the HPGe Gamma Detector.

In Chapter four, the transfer factor (TF), the Radium Equivalent, $Ra_{eq,}$ the External hazard index, H_{ex}, Internal Hazard Index, $H_{in,}$ and the Radiological Level Index, I_{γ} have been determined for the soil surrounding and selected vegetables. For the vegetables grown in this farm, the Annual Effective Ingestion Dose, A_{eff}, Absorbed Dose Rate, D_N, and Annual Effective Dose Equivalent, AEDE, have also been calculated. Finally, these values are used to assess the ELCR to the human and compared with the average worldwide values. Lastly, Chapter five concludes the whole thesis and recommend future works.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In our environment, there are three types of naturally radioactive nuclei: uranium, strontium, and thorium. The first group of nuclei consists of uranium-238, uranium-235, thorium-232, potassium-40, rubidium-87, tin-124, lanthanum-138, samarium-147, lutecium-176, and a few additional nuclei that can be regarded to be extremely rare. The second group of nuclei consists of uranium-238, uranium-235, and thorium These nuclei are thought to have half-lives that are equivalent to the age of the earth, according to estimates.(Issa et al., 2013)

The second group of nuclei is a representation of the products of natural decay or fission that were produced by the first group of nuclei. The third type of nuclide is one that originates from the environment; it includes the results of radioactive nuclear particles' interactions with air, water, and rocks. Tritium, beryllium-7, beryllium-10, carbon-14, and chlorine-17 are examples of elements in this category, which are formed as a result of contact with high-energy cosmic rays. Several elements have been discovered as a consequence of neutron capture, while others are thought to be of extra-terrestrial origin.

The presence of air is one of the media that allows for the occurrence of the natural radioactivity process. The following are the causes of natural radioactivity in the atmosphere: a) Emissions of radioactive series and the decay products of radioactive series: In addition to cosmic dust and micrometeorites, cosmogenic substances can enter the atmosphere on their own. When nuclear active cosmic ray particles contact with air molecules, isotopes are produced that have a high concentration in the 15 km to 20 km

altitude zone, with low concentrations in the rest of the world's height zone. In the altitude range of 0 to 15 km, the primary sources of radioactivity are radon, thoron, and their decay products, which are principally the short-lived isotopes polonium-218, lead-214, and bismuth-214. Lead-210, bismuth-210, and polonium-210 are examples of long-lived products that have made significant contributions. It is roughly 100 times more likely that emanations will be concentrated in the ground air layer over land than it will be over water.(Weerakkody et al., 2017)

2.2 Radioactive decay

Radioactive nuclides, often known as radionuclides, are radioactive nuclides that are unstable. They decay, or disintegrate, and lose a significant amount of mass-energy as a result of the emission of particles and photons. There are two sorts of radionuclides. The first is the natural radionuclide. Primarily, there are natural radionuclides, which are radioactive elements that occur naturally and may be produced by chemical or isotope separation processes. They mostly radiate alpha particles, beta particles, and gamma radiation, but a few disintegrate spontaneously by fission into smaller particles. Second, there are the artificial radionuclides, which are created by nuclear processes and are typically less stable, as well as emitting a larger spectrum of different forms of radiation than natural radionuclides.(Ojovan et al., 2019)

Considering that our planet's age is around 10^{10} years old, it is only possible that radioactive nuclides produced during the creation of this planet will still be in existence if their half-lives are just a few orders of magnitude longer than this length of time. There are around 20 such nuclides, some of which have extremely long half-lives and have such low activity that they are essentially stable, while others which have shorter half-lives and are present only in trace amounts. Other radionuclides found in the environment have

developed more recently than the earth and have a high specific activity, indicating that they have originated lately. In general, the radionuclides generated by the decay of long-lived parent nuclides are the most valuable natural radionuclides available.(Lugaro et al., 2018)

Radioactive decay is a statistical process. Given a single unstable nucleus, it cannot be predicted when it will disintegrate. It is only possible to define a probability, λ, which it will decay in the next second. λ is called the decay constant, or the disintegration constant. It is constant property of a particular nuclide and is totally independent of the physical environment of the nuclei or of their age. Thus, if a nucleus does not happen to decay in, say, a period of one year, the probability that it will do so in the next second is the same as it was in the first second of the year. The unit of λ is s^{-1}.

On the other hand, with a radioactive source comprising a statistically large number of nuclei, it can be predicted, with a certainty defined by statistical error, that in one second a fraction λ of these nuclei will decay. Thus, with N_o nuclei, the number decaying in one second is $N_o\lambda$, leaving N_o-$N_o\lambda$ nuclei so that, in the next second, (N_o-$N_o\lambda$) λ nuclei decay, and so on. (L'Annunziata, 2012)

Clearly, the number of nuclei present at any time is a variable, N, which decreases with time. In fact, if there are N_o nuclei present when the timing measurement commences, i.e., at time t = 0, then the number N remaining at any time t later is given by an exponential formula of the form $N = N_o e^{-\lambda t}$. When N is plotted against time, a curved graph is produced as a result. A straight line can also be obtained by plotting the natural logarithm of N against time, t, since doing so will result in a straight line.

$$lnN = \ln (N_o e^{-\lambda t}) \tag{2.1}$$

$$lnN = \ln\ N_o + \ln\ (e^{-\lambda t}) \quad (2.2)$$

$$lnN = \ln\ N_o - \lambda t \quad (2.3)$$

The activity, A, of a radioactive source material is the number of nuclei in the specimen that decay in unit time; that is, the average number of disintegrations per second. It is given by A = Nλ and like N, decreases exponentially with time. The specific activity is the activity per gram or kilogram of material. The most widely used unit of activity is the curie (C or Ci), although the SI unit is the Becquerel (Bq). These are defined as

$$1\ \text{Ci} = 3.7 \times 10^{10}\ \text{disintegrations per second}$$

$$1\ \text{Bq} = 1\ \text{disintegration per second}$$

A curie is an extremely large activity. For most purposes, activities, or source strengths, ranging from a millicurie (1 mCi) to a microcurie (1 μCi) are used. It is important to note that one disintegration does not necessarily yield one particle or photon. The average number of radiations emitted by a source material, in each disintegration, depends on the decay mechanism. The activity must be multiplied by this number in order to estimate the number of emissions per second from a radioactive source.(Glascock, 2014)

2.3 Gamma radiation

A nucleus can be left in an excited energy state by any nuclear process, including alpha decay, beta decay, and every other nuclear process. The nucleus then de-excites, in the same way as does an excited atom, by an isometric transition to its ground state, emitting one (or more) gamma ray photons whose energy, hv, is given by a Bohr-type formula

$$E_\gamma = hv = E_2 - E_1 \quad (2.4)$$

Where E_2 and E_1 are the nucleon energy values singly, if a Shell Model is appropriate, collectively, if a Collective Model applies to the nucleus involved.

A nucleus in an excited state is called a nuclear isomer of the nuclide. If the excited state is long-lived, then it may be referred to as a metastable state. Such nuclides are usually designated with an 'm'. For example, technetium-99m is a metastable state of Tc-99, with a half-life of 6.02h. (Wallbrink et al., 2002)

Apart from the decay of metastable states, gamma decay is virtually immediately following some other process and its half-life is that of the other process which produces the isometric condition. Two of the most widely used gamma ray sources are Cs-137 (0.662 MeV) and Co-60 (1.172 MeV & 1.333 MeV).

Alpha and beta spectrometry are both frequently employed, but gamma ray spectrometry is by far the more common method. The primary reason for this is the fact that a far larger spectrum of nuclides can be produced to emit gamma radiation; nevertheless, it is also true that photons can be recovered from the source material much more easily than they can from other sources.

The gamma energy spectrum is as distinctive of the nucleus as the X-ray spectrum is of the atom, and it may be used to identify or locate the position of radionuclides in their natural environment. Unlike its X-ray counterpart, gamma ray spectrometry is capable of distinguishing between various isotopes of the same element with remarkable ease.(L'Annunziata, 2012; Wallbrink et al., 2002)

2.4 Naturally Occurring Radioactive Substances

The naturally occurring radionuclides can be separated into those that occur individually and those that are components of three different chains of radioactive elements (1) the

uranium series which originates with U-238 (Table 2.1); (2) the thorium series which originates with Th-232 (Table 2.3); and (3) the actinium series which originates with U-235 (Table 2.3).

When the earth was first formed, each of the three categories of elements that decay radioactively could be found in the crust of the earth. The isotopes of uranium that are most frequently discovered in natural settings have mass numbers of 234, 235, and 238 respectively.

The element U-238, which is the parent of the uranium series, is found in quantities of 99.28% and is in equilibrium with its great granddaughter U-234, which is found in quantities of 0.0058%. U-235, which is present in an amount of 0.71%, is the parent isotope of the actinium series. Additionally, it is the primary nuclide that is utilised in the fission process. (Bajoga et al., 2015; Emara, 1996)

Uranium may be discovered in nearly all rocks and soils. Uranium isotopes themselves do not contribute to the gamma-ray background because they are gamma emitters, and they are present in too low of a strength to give considerably to the internal gamma dose given to human. However, it is possible to determine the incidence of uranium in food and human tissues, which is something that would be expected given that uranium is present in soils and fertilisers. This is because uranium is a naturally occurring.(Kathren, 1984).

Table 2.1: Nuclides of the Uranium Series with their γ emissions.

Isotope	Relative Isotope Abundance (%)	Half-life	Energy (keV)	Percent Yield %
U-238	99.28	4.5×10^9 years	48	23
Th-234	-	24.1 days	92	4.0
Pa-234M	-	1.17 min	390 (IT) 817	0.13 4
U-234	0.0057	2.4×10^5 years	93	5
Th-230	-	7.7×10^4 years	68 253	0.6 0.02
Ra-226	-	1600 years	186 260	4 0.007
Rn-222	-	3.82 days	510	0.007
Pb-214	-	26.8 min	53 242 295 352	1.6 4 19 36
Po-214	-	1.64×10^{-4} sec	799	0.014
Tl-210	-	1.3 min	296 795 1310	80 100 21
Pb-210	-	22.3 years	46.5	4
Po-210	-	138.4 days	800	0.0011
Pb-206	25.2	Stable	-	-

Table 2.2: Nuclides of the Thorium Series with their γ emissions.

Isotope	Relative Isotopic Abundance (%)	Half-life	Energy (keV)	Percent Yield %
Th-232	100	1.41 x 10^{10} years	55	24
Ac-228	-	6.15 hr	58 129 184	53 5.2 <1
Th-228	-	1.91 years	83	1.6
Ra-224	-	3.66 days	241	3.7
Rn-220	-	55.6 sec	500	0.07
Pb-212	-	10.6 hr	176 238 300	<1 47 3.2
Tl--208	-	3.06 min	2610 860 580 510	100 12 86 23
Pb-208	52.3	Stable	-	-

Table 2.3: Nuclides of the Actinium Series with their γ emissions.

Isotope	Relative Isotopic Abundance (%)	Half-life	Energy (keV)	Percent yield %
U-235	0.72	7.04 x 10^8 years	110 143 163 185 205	2.5 11.0 5.0 54.0 5.0
Th-231	-	25.64 hr	26 85	2 10
Pa-231	-	3.28 x 10^4 years	27 290	6 6
Ac-227	-	21.77 years	70	0.08
Th-227	-	18.72 days	50 237 310	8 15 8
Fr-223	-	21.8 min	50 80 234	40 13 4
Ra-223	-	11.44 days	149 270 330	10 10 6
Rn-219	-	3.96 sec	272 401	9 5

Table 2.3, continued

Pb-211	-	36.1 min	405 427 832	3.4 1.8 3.4
Bi-211	-	2.15 min	350	14
Po-211	-	0.516 sec	570 900	0.5 0.5
Tl-207	-	4.77 min	870	0.16
Pb-207	21.7	Stable	-	-

2.5 Gamma Spectroscopy

Gamma ray spectrum analysis and research are two terms that have been used to describe what is known as spectroscopy for scientific and technical reasons, respectively. Gamma ray spectrometers are the equipment used to view and gather such data for scientific and technical purposes. Gamma ray spectrometers are extremely complex instruments that are utilised for the purpose of determining the manner in which gamma radiation's energy is distributed. Inorganic scintillators like NaI(Tl) and semiconductor detectors are two types of detectors that are particularly valuable for the detection of gamma rays with energies larger than several hundred keV. Both of these types of detectors are known as inorganic scintillators. When carrying out gamma spectroscopy, scintillation detectors are the instruments of choice.(Perez & Pibida, 2004)

A scintillation detector is made up of a number of different parts, the most important of which are a scintillator crystal that is tailored to the requirements of the application, a photomultiplier tube, and a circuit for detecting the height of the pulses produced by the photomultiplier tube. The effectiveness that a scintillation counter boasts (due to its vast size

and great density), along with the high precision and count speeds that it is feasible to attain, are the primary benefits that it offers. Iodine has a high atomic number, which means that a considerable proportion of all connections will end up in the full absorption of gamma-ray energy. As a direct result of the high photo fraction, the photo fraction will be quite high.(Crouthamel et al., 2013).

2.5.1 HPGe Detector - Germanium

To achieve the high level of precision in energy resolution that this study requires, a detector based on germanium, such as the HPGe detector, is being utilised. In situations where a high level of energy resolution is required, such as in gamma spectroscopy and x-ray spectroscopy, as well as in other applications, the semiconductor detectors that are based on germanium are the ones that are used the most frequently. Because germanium's atomic number is noticeably higher than that of silicon, which significantly increases the likelihood of gamma ray contact, germanium is favoured over silicon for the purpose of gamma spectroscopy. This is due to the fact that germanium's atomic number is significantly higher than that of silicon.(Hung et al., 2016)

In addition, the standard amount of energy that is required to form an electron-hole pair in germanium is far smaller than the amount of energy that is required in silicon. The average amount of energy that is needed in germanium is 2.9 eV, while the average amount of energy that is needed in silicon is 3.6 eV. This also supplies the latter with a higher level of energy resolution. It is a function of energy if a germanium detector has a wide full width at half maximum (FWHM). The FWHM for a 1.3 MeV photon is 2.1 keV, which is extremely low.(Knoll, 2010)

2.6 High-purity germanium detectors

According to Knoll (2010), When it comes to gamma spectroscopy applications in the laboratory, high-purity germanium detectors, also known as HPGe detectors, are the most detailed and accurate alternative available. Germanium detectors are a considerable step forward in terms of efficiency when it comes to radiation detection when compared to silicon detectors. This is because germanium has an atomic number that is far greater than that of silicon, and also because the average amount of energy that is required to generate an electron-hole pair in germanium is significantly lower than what is needed in silicon (3.6 eV for silicon versus 2.9 eV for germanium).

As a consequence of Ge's attribute of having a substantially greater linear attenuation coefficient when compared to the attenuation coefficients of other elements, Ge has a shorter mean free path than the other elements. In comparison to detectors made of silicon, germanium detectors provide a number of benefits. One of these benefits is that germanium detectors may be made sensitive down to thicknesses of only one centimetre while still being depleted. This enables detectors made of germanium to function as full absorption detectors for gamma rays with energy of up to several MeV.(Hung et al., 2016a)

It was not possible to manufacture germanium crystals with a purity high enough to allow them to be used as spectroscopic detectors prior to the development of modern purifying technologies. A detector's material's purity is critical in terms of detection performance. The compilation of electron-hole pairs within the detector must be completed in a sufficiently quick period of time. Furthermore, there must be no traps that might avoid them from reaching the contacts for gathering information. The reasons for trapping might be:

- Impurities contained inside the atomic arrangements of the semiconductor

- Due to the presence of physical imperfections, the lattice may contain interstitial atoms and vacancies.
- Damage done by radiation that results in interstitial atoms

Impurities in the crystals cause electrons and holes to become trapped, which in turn results in the detectors not functioning very well. The end result was the doping of germanium crystals with lithium ions, which made it possible for electrons and holes to move to the contacts and construct a signal. As a direct result of this, germanium crystals were doped with lithium ions (Ge(Li)), which allowed for the creation of an intrinsic region in which electrons and holes could go to the contacts and combine to generate a signal. The Ge(Li) formula was utilised in order to successfully complete this task. To attain optimum effectiveness, the HPGe detectors should work using liquid nitrogen temperatures at -196 °C, which are extremely low since the noise generated by thermal excitation is quite high at ambient temperature (Conti et al., 2013).

High-performance germanium detectors, also known as HPGe, are utilised in a diverse selection of contexts for the purpose of measuring radiation thanks to the high resolution they offer. Some of these applications include monitoring personnel and the environment for radiation contamination, radiometric assay, medical applications, nuclear security, and the safety of nuclear power plants. Other applications include monitoring personnel for radiation exposure and monitoring the environment.

2.6.1 Parts of HPGe Detectors

The requirement that germanium detectors be refrigerated to the temperature of liquid nitrogen in order for them to function correctly is the most significant disadvantage associated with these devices. Because germanium has a very small energy gap in

comparison to other semiconductors, these detectors need to be cooled so that the thermal production of charge carriers can be maintained at a level that is satisfactory. If this is not done, the detector's energy resolution will suffer as a result of the noise caused by leakage current. The energy gap for germanium is extremely small (E_{gap}= 0.67 eV). As a consequence of cooling to the temperature of liquid nitrogen (-196 degrees Celsius), thermal excitations of valence electrons are diminished. As a consequence of this, only gamma ray interactions are capable of supplying an electron with the energy needed to overcome the band gap and enter the conduction band (Joel et al., 2017).

Because of this, high-performance germanium (HPGe) detectors and cryostats are widely used in conjunction with one another in scientific research. A metal container that has been emptied is used to store the germanium crystals that are housed in the detector holder. This is done to protect the crystals from being damaged during the production process. In order to lessen the number of photons with low energy that are taken in, the "end-cap" and the holder of the detector are both made out of materials that are very thin. Inside, the holder is typically composed of metal and has a thickness of around one millimetre all the way around.

In addition, aluminium is frequently utilised in the manufacturing process during the construction of the endcap and the flange. The HPGe crystal is brought into direct thermal connection with a metal rod while it is contained within the holder, which causes the temperature of the HPGe crystal to rise. It is the job of the cold finger to transport heat from the detector to the storage tank for liquid nitrogen, and then from storage tank for liquid nitrogen back to the detector assembly (Knoll, 2010).

The cryostat is a device that consists of a vacuum metal container, a cold finger, and a Dewar flask for holding liquid nitrogen cryogen in liquid nitrogen. All of these components are taped together to ensure that they remain hermetically sealed. When designing cryostat

packages, it is usual to include a germanium detector preamplifier as an integral component of the overall system design.

The preamp and the amplifier are combined into one component because the preamp and the amplifier should be located within a close proximity to one another, and the goal is to lower the capacitance of the system as a whole. Additionally, the input stages of the preamp have cooling implemented for them. In order to complete the experiment, the cold finger is extended beyond the vacuum border of the cryostat and to a Dewar flask with liquid nitrogen. This is done so that the experiment can be carried out. (Lutz et al., 2007)

The temperature of the HPGe crystal is kept at a constant low level by repeatedly dipping a cold finger into liquid nitrogen. This helps to maintain the crystal in its low-temperature state. The gradual boiling of the liquid is what keeps the temperature of liquid nitrogen at -196 degrees Celsius. This process also produces nitrogen gas as a by-product of the boiling of the liquid, so the two processes work together to achieve this temperature.

It is a cumbersome process to lower the temperature by using liquid nitrogen because the detector needs to be allowed to cool to its working temperature gradually over the course of several hours before it can be used, and it cannot be allowed to warm up while it is being used. It is possible to let HPGe detectors warm up to room temperature before using them if they have been put away for an extended period of time. It should be emphasised that Ge(Li) crystals should not heat up because doing so may cause the lithium to escape from the crystal, which would result in the detector not functioning properly.

There are now commercially available systems that make use of innovative cooling techniques (like a pulse tube cooler, for instance) to reduce or remove the requirement for

liquid nitrogen chilling entirely. This refrigeration system is completely devoid of liquid nitrogen due to the fact that it is powered solely by electricity (Stabin, 2007).

2.6.2 HPGe Detector – Principle of Operation

The following are the main aspects to remember about the operation of semiconductor detectors:

- After entering the sensitive volume (germanium crystal) and interacting with the semiconductor material, ionising radiation is emitted from the detector.
- An electron-hole pair is produced when a high-energy photon ionises the atoms of a semiconductor after it has travelled through the detector and caused those atoms to become ionised. The quantity of energy that is radiated away from a semiconductor is proportional to the number of electron-hole pairs that are produced within the semiconductor. Some electrons migrate from the valence band to the conduction band, and this movement creates holes in the valence band.
- Because germanium may have a reduced, delicate width of centimetres, it is could completely attract high-energy photons; this ability allows it to be used in a variety of applications (up to few MeV).
- As a result of the action of an electric field, electrons and holes are driven to the electrodes, where they generate a pulse that is picked up by a circuit that is situated outside the device.
- This pulse contains information on the total amount of energy that was first emitted by the radiation that was coming into contact with the object. The number of pulses of this kind that are delivered in a specific amount of time provides data on the intensity of the radiation.

A photon releases some of its energy during its journey and has the potential to be absorbed completely. The production of approximately 3 x 10^5 electron-hole pairs is the outcome of the entire absorption of a photon with an energy of 1 MeV. When we put this value next to the total amount of free carriers that are present in a 1 cm^3 intrinsic semiconductor, we see that it is completely inconsequential. (Hung et al., 2016; Lutz et al., 2007)

Because of the passage of a particle over the detector, ionisation of the atoms in the semiconductor takes place, which ultimately results in the production of electron-hole pairs. In contrast, thermal excitation predominates in germanium-based detectors that are active when the temperature is at room temperature. A variety of factors, including dopants, impurities, and irregularities in the structural lattice, can all play a role in causing it.

It is significantly influenced by the E_{gap} (the space between the valence and conduction bands), is extremely small for germanium (E_{gap}= 0.67 eV) and hence very stable. Some types of semiconductors require active cooling because thermal excitation causes detector noise, which is a result of thermal excitation (e.g. germanium)(Hasegawa et al., 1991; Pehl, et al., 1972).

2.7 Gamma Spectrometry Using Sodium Iodide Detector

This is the scintillator material that is most often used. It is reasonably priced and widely available. It has been possible to create detectors with diameters of up to 0.75 metres. The cylindrical sodium iodide detector, which had an outer diameter of 76 millimetres and an internal height of 76 millimetres, for several years the industry normal gamma ray spectrometer detector. In more conventional words, this detector had an outside diameter of 76 millimetres. 3 by 3 detector (3"x3") is another name for this detector.

The iodide atom in the NaI(Tl) contributes to the high gamma – ray absorption coefficient and, as a result, the high intrinsic efficiency of the compound. When the energy is low, there is a considerable likelihood of total absorption occurring. The fact that NaI(Tl) has the top yield of all the inorganic scintillators when used with conventional photomultipliers (Figure 1) means that it also has the highest energy resolution of them all. (Owens and Peacock, 2004)

Although its performance is superior to that of other materials, NaI(Tl) does have a number of drawbacks that should be taken into consideration. This material is brittle, and it is easily distorted when subjected to thermal shock. It is also temperature gradient sensitive. Because it attracts and retains moisture, it is essential that it be stored in an airtight container at all times. In addition to that, it demonstrates the prolonged afterglow that was discussed earlier. At low count rates, this is not certainly an issue because the phosphorescence pulse can be reduced electrically; however, at high count rates, they have a tendency to accumulate and restrict high count rate performance because they be inclined to pile up. This is because at low count rates, the phosphorescence pulse can be eliminated electrically (Crouthamel et al., 2013).

Potassium has a chemical composition that is very similar to that of sodium, and as a result of this similarity in chemical composition, potassium is a very likely contaminant in sodium salts. Because only a slight percentage of the potassium that occurs naturally is radioactive ^{40}K, it is essential that the sodium iodide that is utilised in the production of detectors be of a high quality. In that case, the background of the detector would be significantly higher than it should be. In most cases, a manufacturer will require that the purity of the sodium iodide they sell have less than 0.5 parts per million (ppm) of potassium in it.

The scintillator NaI(Tl) gamma spectrometry is a good choice for detecting gamma photons in a laboratory setting. Figure 2.1 depicts a schematic representation of a typical gamma spectrometry system that makes use of a NaI(Tl) crystal. The emission of visible light from a thallium-activated NaI crystal occurs when gamma photons come into contact with the crystal. The amount of energy that is deposited in the crystal by the photon is directly proportional to the amount of visible light that is produced by the gamma photon. Because it is an impurity, the thallium in the crystal is only present in very small amounts. Despite this, it is a crucial part in the scintillation process and performs an important part as a guiding element (Knoll, 2010).

NaI(Tl) crystal and the photomultiplier tube are connected through optical coupling (Figure 2.1). It is a phototube that detects visible light and creates an electrical pulsation with an amplitude that is proportionate to the intensity of the light it detects. When the phototube produces an electrical pulse, it is routed to a linear amplifier, where its amplitude is boosted so that the pulse may be used more easily in the succeeding electronic circuit board. When the pulse has been amplified, it is transmitted to a multichannel analyser (MCA), which is capable of measuring the amplitude of the pulse using electronics.

Using a measurement of the voltage interval within which they fall, the MCA classifies pulses into groups. Aspects of the recorded spectrum such as the number of gamma counts that fall inside each period of photon energy may be understood in terms of the pulse height, which is related to how much energy is lost by the incident gamma photon in the crystal.(Hossain et al., 2012; Wallbrink et al., 2002).

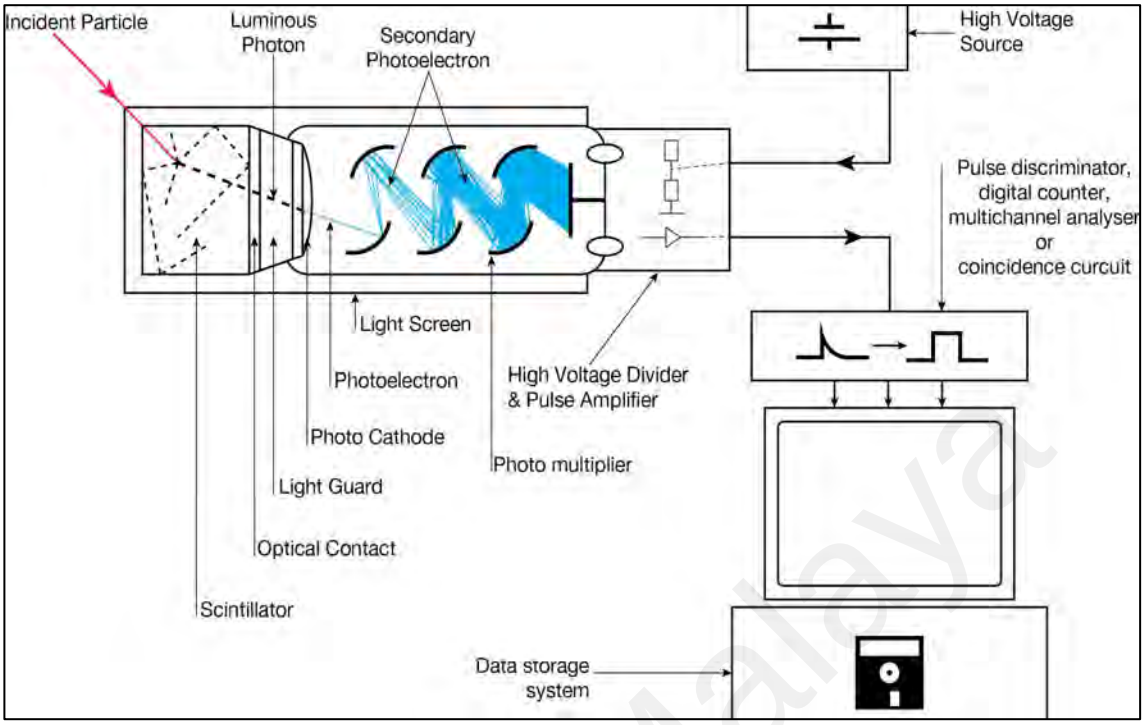

Figure 2.1: The photomultiplier tube is coupled to the NaI(Tl) crystal. (Knoll, 2010)

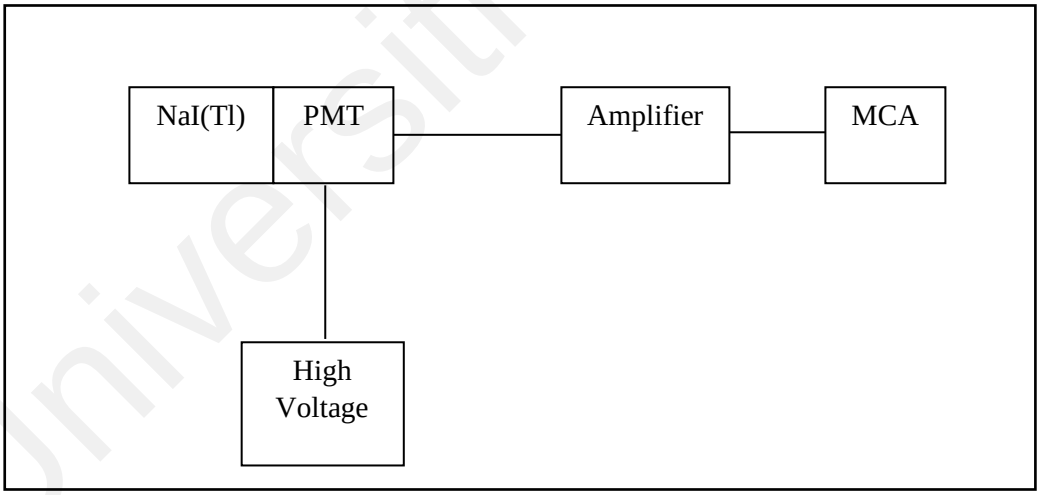

Figure 2.2: Gamma scintillation spectrometer system. (Knoll, 2010)

2.8 Comparison of Sodium Iodide and Germanium Detector

The distinctions between the NaI(Tl) and the HPGe detectors, as well as the benefits and drawbacks associated with each one, are compared and contrasted in Table 2.4. When spectrometry is the primary concern, as it is in the vast majority of situations, the detector of choice is the high-purity germanium, or HPGe, detector. Scintillation detectors systems offer a reliable and cost-effective alternative to conventional methods in situations where the detection of only one or two nuclides is required and where energy resolution is not a primary concern.

When high-resolution germanium detectors were first introduced in the 1980s, there was some debate as to which type of detector was preferable for low-count-rate measurements: low-resolution sodium iodide detectors or high-resolution germanium detectors. This was due to the fact that sodium iodide detectors have a lower resolution than germanium detectors. Those who argued in favour of the former position stated that the quality of the statistical findings would improve if there was a greater number of counts contained within a peak that had been produced by a specific amount of radioactivity (Glascock, 2014).

To be more specific, as soon as they were available for commercial use, high-resolution germanium detectors produced consistently more accurate peak regions and a lower threshold of detection than sodium iodide detectors did. This was the case as soon as the germanium detectors became commercially available. Because germanium detectors have a better resolution than sodium iodide detectors, this was the result that was seen.

As a result, even though there are fewer counts in a germanium spectrum, they are concentrated in a few channels, as opposed to the counts in a sodium iodide spectrum, which

are scattered across multiple channels. As a result, peaks in the germanium spectra are easier to detect, and as a result, the limit of measurement for this element is lower than that of other elements (Qadr, 2020).

The resolution of the two detectors is very different from one another, and the increase in count rate that is provided by the sodium iodide detector is not sufficient to make up for the resolution gap. Because there is not a significant need for high resolution spectrometry and there is no requirement for the additional cost that a semiconductor detector provides, the utilisation of a semiconductor detector is not recommended under circumstances with a low count rate. This is because there is not a significant need for high resolution spectrometry.

In addition, there are scenarios in which the detector environment is not suited for germanium detectors that may be imagined. If the spectroscopic requirements are not very complicated, the comparatively small size of the entire scintillation system will suffice(Joel et al., 2017; Perez & Peacock, 2004).

Table 2.4 NaI(Tl) and HPGe detectors are evaluated in comparison.

Sodium Iodide	**HPGe**
Inexpensive (×10)	
More effective (×10)	
Higher numbers obtainable	
Functional at room temperature	Operates at very low temperature, -196 °C
Sensitive to temperature	Insensitive to temperature
Sensitive to anode voltage (V^7)	Insensitive to bias voltage
Poor energy resolution (6.01%, 81 keV for 3 × 3 in at 1332 keV)	Good energy resolution (0.16%, 2.0 keV typical at 1332 keV)

2.9 Radionuclides in soil

The ability of plants to absorb a long-lived radionuclide is highly dependent on whether the radionuclide remains within reach of the roots of the plants and the amount to which it is chemically accessible. When a radionuclide is introduced in a soluble form, it can adsorb on clays, precipitate as an oxide or hydroxide, chelate with soil organics, or, in the most unlikely of cases, remain in solution in the soil solution.

Because of this, the extent to which the radionuclide is evenly dispersed among these various fractions will determine not only how long it will remain at the site of the deposition, but also how much of it will be available to be absorbed by plants. Natural radioactivity in soil can be calculated using the total soil volume of 7.894×10^5 m^3 as shown in Table 2.5 and that activity levels vary considerably dependent on soil variety, mineral compositions, and density(Alharbi et al., 2013; Miah et al., 1998).

Table 2.5: Natural Radioactivity per Square Mile at 1 Inch Depth

Nuclide	Activity	Mass of Nuclide	Activity found in the volume of soil
Uranium	0.7 pCi (25 $Bqkg^{-1}$)	2200 kg	0.8 curies (31 GBq)
Thorium	1.1 pCi/g (40 $Bqkg^{-1}$)	12000 kg	1.4 curies (52 GBq)
Potassium 40	11 pCi/g (400 $Bqkg^{-1}$)	2000 kg	13 curies (500GBq)
Radium	1.3 pCi/g (48 $Bqkg^{-1}$)	1.7 g	1.7 curies (63 GBq)
Radon	0.17 pCi/g (10 $Bqkg^{-1}$)	1.1 g	0.2 curies (7.4 GBq)
		Total	> 17 curies (>653 GBq)

2.9.1 Measurement of natural radioactivity and radiological hazards of ^{226}Ra, ^{232}Th and ^{40}K in selected Asian Countries

This section provides a summary of studies that were carried out by a variety of researchers in a number of Asian nations. Near the Roopur Nuclear Power Plant in Bangladesh, fifteen soil samples were taken from Natore, Kushtia, and Prabhna, located approximately 30 kilometres apart (Md. Samiul Ehsan et al., 2019). Using the HPGe gamma detector, the AC of ^{226}Ra, ^{232}Th, and ^{40}K were found to be 12.42 $Bqkg^{-1}$, 12.6 $Bqkg^{-1}$ and 198.9 $Bqkg^{-1,}$ respectively. These figures are within UNSCEAR's proposed global average. The D_N was found to have a mean value of 21.3 nGy y^{-1}, and the A_{eff} is 0.033 mSv y^{-1}. Notably, no unnatural radioactivity discovered in the analysed soil samples.

In a habitat of mangroves, seagrasses, and coral reefs along the coast of Guanxi Province in China, the natural radioactivity in beach sand and soil was measured.(Liu and Lin, 2018). Sand and soil samples were analysed using HPGe spectroscopy. The AC of ^{226}Ra, ^{232}Th, and ^{40}K was found to have an average value of 6.9, 9.6 and 39.6 $Bqkg^{-1}$, respectively. Radiological hazards including, Ra_{eq}, H_{ex} and the H_{in}, I_{γ}, D_N and A_{eff} were calculated in this study. All the radiological hazard values are within the suggested values.

Soil samples were collected from six sites in Egypt's Southern Mines and analysed using an HPGe detector. AC of ^{226}Ra, ^{232}Th and ^{40}K reported has a range of 5.00 – 23.68 $Bqkg^{-1}$, 1.86 – 10.09 $Bqkg^{-1}$ and 292.81 – 659.57 $Bqkg^{-1}$, respectively. The Ra_{eq} in the soil, ranges between 22.098 to 81.8028 $Bqkg^{-1,}$ which is lesser compared to the maximum value of 370 $Bqkg^{-1}$. The I_{γ} was found to be less than 1 (Sroor et al., 2001).

Studies conducted on the natural radioactivity level in the soil samples from Botteng Utara Village, Mamuja Regency, Indonesia was found to have a higher value than the world's

suggested value for ^{226}Ra & ^{232}Th. The AC of these two radionuclides is 1042.29±98.16 Bqkg^{-1} and 1756.12±165.21 Bqkg^{-1} which is 29 and 58 times more compared to the world's concentration value (UNSCEAR). However, the average AC of ^{40}K was 232.63±22.66 Bqkg^{-1} which is smaller than 400 Bqkg^{-1}, the recommended value. The Ra_{eq} in the soil samples has an average value of 3773.42 Bqkg$^{-1,}$ which is found to be more than the recommended value. The H_{ex} and the H_{in} values are 9.65 and 14.21, respectively, which are greater than the recommended safety limits. This study also found that the A_{eff} by the general public living in Botteng Utara is 10.40 mSv y^{-1} which is 21.67 times higher than the global effective dose (Nurokhim et al., 2020).

In Ramsar and Mahallat, Iran, research was conducted to detect natural radioactivity and analyse community's exposure to natural radiation in High-Level Natural Radiation Areas (HLBRA). 979 soil samples were accumulated from this zone, and samples were evaluated using the HPGe gamma detector. The AC of ^{40}K, ^{226}Ra and ^{232}Th, were observed to have an average value of 457.7 Bqkg^{-1}, 24.3 Bqkg^{-1}and 25.8 Bqkg^{-1}, respectively. The average calculated D_N was 46.7 nGy h^{-1} which is lesser than the world standard outdoor exposure due to gamma radiation 58 nGy h^{-1} (UNSCEAR, 2000). The mean outdoor and indoor annual effective dose due to external exposure is 0.06 mSv y^{-1}and 0.55 mSv y^{-1}, respectively. (Kardan et al., 2017).

19 soil samples were gathered from Nineveh Province, Iraq, to determine the AC utilizing NaI(Tl) detector. AC of ^{226}Ra, ^{232}Th and ^{40}K ranges between 21.25 to 58.73 Bqkg^{-1}, 11.22 to 31.63 Bqkg^{-1} and 17.02 to 40.98 Bqkg$^{-1,}$ respectively. It was found that the average AC of ^{226}Ra is greater than the recommended value, while the activity of ^{232}Th and ^{40}K was observed to be smaller. However, the Ra_{eq}, A_{eff} I_{γ}, H_{in} and H_{ex} values were found to have an average value of 89.41 Bqkg^{-1} , 59.99 µSv y^{-1}, 0.648, 0.236 and 0.329, respectively, which were lower

than their corresponding allowed limit given by the world average values (Najam et al., 2015).

A research group from Jordan collected soil samples from Ma'an and used HPGe spectroscopy to analyse the AC of ^{226}Ra, ^{232}Th and ^{40}K. It was observed that the mean AC of ^{226}Ra, ^{232}Th and ^{40}K is 57.7 Bqkg^{-1}, 18.1 Bqkg^{-1} and 138.1 Bqkg$^{-1,}$ respectively. The mean value of Ra_{eq}, D_N, A_{eff}, H_{ex}, and, H_{in}, in the Ma'an soil were 94.21 Bqkg^{-1}, 37.15 nGyh^{-1}, 45.59 µSv y^{-1}, 0.25 and 0.41". As a result, Ma'an soil has minimal natural radioactivity and is safe for the general people, according to the research team, and the soil in that area is acceptable for building materials and safe for other human activities without posing a radioactive concern (Saleh & Shayeb, 2014).

Soil samples were collected from 160 elementary schools from the South Korean peninsula to analyse radioactivity and assess environmental radiation. The soil AC in the investigated area was measured using HPGe gamma detector. It was found that ^{40}K has the highest concentration of 871.70±167.33 Bqkg^{-1}. Both ^{226}Ra and ^{232}Th have an AC of 59.20±17.11 Bqkg^{-1} and 25.27 ±7.94 Bqkg^{-1}. However, no radiological hazard was analysed in these studies, but it is noticeable that an AC of ^{40}K in this report is twice higher than the recommended value. The AC of ^{232}Th is also greater than the suggested value (Kim et al., 2012).

90 soils and samples of sand were analysed from various parts in southern part of Kuwait. HPGe spectroscopy was used to analyse the AC of ^{226}Ra, ^{232}Th and ^{40}K. It was found that the AC for ^{226}Ra, ^{232}Th and ^{40}K ranges from 9.02 to 17.48 Bqkg^{-1}, 7.90 to 14.29 Bqkg^{-1} and 259.6 to 347.3 Bqkg$^{-1,}$ respectively. It was also reported that the mean value of D_N, Ra_{eq}, H_{ex}, and H_{in} and A_{eff} are 24.65±0.26 nGyh^{-1}, 50.72±0.50 Bqkg^{-1}, 0.17, 0.14 and 30.0±0.3 µSv y$^{-1,}$

respectively. These obtained measurements were found within the recommended values (A. D. Bajoga et al., 2015).

In Laos, soil samples were gathered at numerous places of Thoulakhom district of Vientiane and analysed using HPGe detector. The mean value of ^{226}Ra, ^{232}Th and ^{40}K was found to be at 28.2 $Bqkg^{-1}$, 31.8 $Bqkg^{-1}$ and 840 $Bqkg^{-1,}$ respectively. Ra_{eq}, H_{ex}, $H_{in,}$ and I_{γ} were found to have an average value of 66.05±0.72 $Bqkg^{-1}$, 0.20±0.12, 0.26±0.13 and 0.52±0.32, respectively. The obtained D_N, ranged from 60 to 119.4 $nGyh^{-1}$is greater than the recommended value of 50 $nGyh^{-1}$(Xayheungsy & Khiem, 2018).

The AC of naturally occurring radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in 30 agricultural and uncultivated soil samples gathered from the state of Kedah, Malaysia, was investigated using an HPGe gamma-ray detector. The mean radioactivity concentration was found to be 102.08±3.96, 133.96± 2.92, and 325.87 ±9.83 $Bqkg^{-1}$, respectively, in the agricultural soil. In the uncultivated soil, it was found that the AC was 65.24± 2.00, 83.39± 2.27 and 136.98± 9.76 $Bqkg^{-1}$, respectively. The radioactivity concentrations in agricultural soils were higher than those in uncultivated soils, which is notable. The average AC of ^{226}Ra and ^{232}Th were more significant than the world suggested values. However, the average AC of ^{40}K is below the recommended value. The research group also found that the average values of the D_N in the air are 141.62 nGy h^{-1} for the agricultural soul and 87.47 nGy h^{-1} in the uncultivated soil, where the two values are greater than the global average value of 50 nGy h^{-1} in both soil types(Alzubaidi et al., 2016).

Soil, coal, and construction materials samples were gathered from several cities and provinces in Mongolia to study the AC of ^{226}Ra, ^{232}Th and ^{40}K using HPGe detector. The mean value of ^{226}Ra, ^{232}Th and ^{40}K was at 28.2 $Bqkg^{-1}$, 31.8 $Bqkg^{-1}$ and 840 $Bqkg^{-1}$,

respectively. The average value of the dose rate in air is 86.9 $nGyh^{-1}$, where the value obtained is greater than the recommended value of 50 nGy h^{-1} (Shagjjamba &Zuzaan, 2006).

A total of 125 saline soil samples were collected near Lahore, Pakistan, in Rakh Dera Chal. The AC of ^{226}Ra, ^{232}Th and ^{40}K were detected using an HPGe gamma-ray detector. The range of AC of these radionuclides ranges from 24.75 – 28.17 $Bqkg^{-1}$, 45.46 – 52.61 $Bqkg^{-1}$ and 524.84 – 601.62 $Bqkg^{-1,}$ respectively. The values of D_N was observed to be 65 $nGyh^{-1}$ which is greater than the recommended value (Akhtar et al., 2005).

A research group from Qatar collected 129 soil samples from the Qatarian Peninsula and HPGe was used to analyse the AC of ^{226}Ra, ^{232}Th and ^{40}K. The mean value of the AC of these radionuclides is 17.2±1.6 $Bqkg^{-1}$, 6.38± 0.26 $Bqkg^{-1}$ and 169± 5 $Bqkg^{-1}$, respectively. In the soil samples, the value was determined to be within the predicted range when compared to the world average value of 30, 35, and 400 $Bqkg^{-1}$, respectively. In this investigation, no radiation dangers were calculated or reported. There were no radiological hazards calculated or reported in this study (Al-Sulaiti et al., 2017).

In Saudi Arabia, the research group used NaI(Tl) gamma-ray spectrometry to analyse soil samples from the Asir province. The results showed that the average value of AC of ^{226}Ra, ^{232}Th and ^{40}K" are in the range of 38.2 – 44.1, 23.49 – 41.9 and 182.5 – 251.5 $Bqkg^{-1}$ respectively. It is also found that the Ra_{eq} ranges from 21.2 to 326.5 $Bqkg^{-1}$. The values of the D_N and A_{eff} ranged from 9.7 to 144.6 $nGyh^{-1}$ and 11.9 to 177.5 μSvy^{-1}, respectively. Other radiological hazards, H_{ex}, H_{in}, and I_γ were found to be in the range of 0.1 to 0.9 and 0.2 to 2.3. The ELCR was found to be in the range of 4.167×10^{-05} to 6.211×10^{-04}. The mean value of radiological hazards of all samples was observed to be lesser than the recommended value. Hence, the research group found that the soil in this area is safe for the general public (Ibraheem et al., 2018).

Soil samples were taken at 23 places along Sri Lanka's northern west coast to analyse the AC of ^{226}Ra, ^{232}Th and ^{40}K activity using HPGe detector. The AC of these radionuclides is ranged from 0.7 to 83, 16 – 256 and 62.4 – 295 $Bqkg^{-1,}$ respectively. The D_N was found to be with an average value of 61.0 $nGyh^{-1}$ which is higher than the recommended value. Meanwhile, the A_{eff} was 74.9 μSvy^{-1} which is lower than the suggested value of 480 $\mu Sv\ y^{-1}$ (Weerakkody et al., 2017).

Studies conducted in Taiwan reported that the AC of ^{238}U (^{226}Ra), ^{232}Th and ^{40}K has an average value of 22.53, 33.43 and 406.62 $Bqkg^{-1}$, respectively, and are within the recommended value. The soil was collected from 16 different locations, including an area nearby a nuclear power plant, Lan-Tu. The soil samples were analysed using the HPGe gamma detector. The average D_N, and A_{eff} were 49.32 $nGyh^{-1}$ and 60.48 $\mu Sv\ y^{-1}$, respectively, while the average value of Ra_{eq}, H_{ex} and H_{in} are 101.72 $Bqkg^{-1}$, 0.27 and 0.34, respectively. These values were determined to be far closer to the suggested minimums than the recommended maximums. (Tsai et al., 2011).

In South India, soil samples were taken from Yelagiri Hills, and the AC of ^{226}Ra, ^{232}Th and ^{40}K were investigated using NaI(Tl) detector. The AC of the radionuclides ranged from 2.17 to 53.23, 13.54 to 89.89 and 625.09 to 2207.3 $Bqkg^{-1}$, respectively. The average value of Ra_{eq}, D_N and H_{ex} were 168.58 $Bqkg^{-1}$, 88.62 $nGyh^{-1}$, 0.106 $mSvy^{-1}$and 0.478, respectively. The radiation hazard values obtained in this study do not exceed the recommended value (Ravisankar et al., 2012).

Soil samples by the Chao Phyraya River in Thailand were collected, and the AC of ^{238}U and ^{232}Th decay chain and from ^{40}K were analysed using the HPGe detector. AC of ^{238}U(^{226}Ra), ^{232}Th and ^{40}K was found to be 55.3 – 65.2, 60.7 – 69.1 and 393 - 478 $Bqkg^{-1}$, respectively. It was discovered that these values were more than the suggested value. The

radiological hazards, which is the D_N in the air from the soils are ranged from 81.6 to 90.4 $nGyh^{-1}$, while the outdoor A_{eff} ranged from 100.1 to 110.8 μSv y^{-1} (Santawamaitre et al., 2011). The radiological hazard values are higher than the world average value reported by UNSCEAR (UNSCEAR, 2000), although it remains within the dose criterion of 1 mSv y^{-1} recommended by ICRP (Cousins et al.,, 2011).

In Yemen, soil samples were collected around Juban Town, and the AC of ^{226}Ra, ^{232}Th and ^{40}K were determined using the HPGe detector. The average value of AC of these radionuclides was 44.4±4.5 $Bqkg^{-1}$, 58.2±5.1 $Bqkg^{-1}$ and 822.7±31.0 $Bqkg^{-1}$, respectively. The levels that were discovered to be higher in this study were found to be higher than the values that were suggested by UNSCEAR. As for the radiological hazard, which is Ra_{eq}, I_{γ}, H_{ex}, it is found that the average values are 191 $Bqkg^{-1}$, 0.71 and 0.52, respectively. The D_N is found to be 89.45 $nGyh^{-1}$ which is within the average radiation between 24 – 160 nGy h^{-1} reported by UNSCEAR(Abd El-mageed et al., 2011).

2.9.2 Activity measurement techniques

Table 2.6: Measurement of AC of radionuclides and other radiological hazards using different techniques in selected Asian countries.

Findings	Detector	Materials Studies	Area of Study	References
AC, D_N, Ra_{eq}, H_{ex}	NaI(Tl)	Soil	Yelagiri Hills, India	(Ravisankar et al., 2012)
AC, D_N, A_{eff}	HPGe	Soil	Northern West Coast, Sri Lanka	(Weerakkody et al., 2017)

Table 2.6, continued

Findings	Detector	Materials Studies	Area of Study	References
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ ,A_{eff}	HPGe	Saline soil	Rakh Deha Chal, Pakistan	(Akhtar et al., 2005)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ ,A_{eff}	HPGe	Soil near Nuclear Plant	Natore, Kushtia and Pabna district, Bangladesh	(Md. Samiul Ehsan et al., 2019)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, ,A_{eff}	HPGe	Soil	Ma'an, Jordon	(Saleh & Shayeb, 2014)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ ,A_{eff}	NaI(Tl)	Soil	Ninevah Province, Iraq	(Najam & Younis, 2015)
AC, D_N, A_{eff}	HPGe	Soil from places with a lot of natural radiation	Ramsar and Mahallat, Iran	(Kardan et al., 2017)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ ,A_{eff}	HPGe	Soil and Sand	Southern Kuwait, Kuwait	(Bajoga et al., 2015)
AC	HPGe	Soil	Qatar Peninsula, Qatar	(Al-Sulaiti et al., 2017)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ ,$A_{eff,}$ ELCR	NaI(Tl)	Soil	Asir region, Saudi Arabia	(Ibraheem et al., 2018)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ	HPGe	Soil	Juban, Yemen	(Abd El-mageed et al., 2011)
AC, Ra_{eq}, I_γ	HPGe	Mining Soil	Southern Mines, Egypt	(Sroor et al., 2001)
AC, Ra_{eq}, H_{ex}, H_{in}, A_{eff}	HPGe	Soil	Botteng Utara Village, Mamuju Regency, Indonesia	(Nurokhim et al., 2020)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ ,A_{eff}	HPGe	Soil	Thoulakhom District, Laos	(Xayheungsy & Khiem, 2018)

Table 2.6, continued

AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ ,A_{eff}	HPGe	Agricultural and uncultivated soil	Kedah, Malaysia	(Alzubaidi et al., 2016)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ ,A_{eff}	HPGe	Soil	Chao Phyraya, Thailand	(Santawamaitre et al., 2011)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, I_γ ,A_{eff}	HPGe	Beach along coastline	Guanxi, China	(Liu & Lin, 2018)
AC	HPGe	Soil samples from elementary schools	S. Korea Peninsula	(Kim et al., 2012)
AC, D_N, Ra_{eq}, H_{ex}, H_{in}, A_{eff}	HPGe	Soil near Nuclear Plant	Taiwan	(Tsai et al., 2011)
AC, D_N	HPGe	Soil, coal and building materials	Mongolia	(Shagjjamba & Zuzaan, 2006)

Table 2.6 shows the different measurement techniques used by research groups from the 20 countries in Asia. It can be noticed that these research groups widely used the HPGe gamma detector compared to NaI(Tl) detector. Soil is the main sample used to analyse the AC of ^{226}Ra, ^{232}Th and ^{40}K, while in some studies, soil, coal and building material are analysed. However, it is noticeable that soil samples near a nuclear plant were analysed, which is in Taiwan and Bangladesh. It was found that the AC in the soil near a nuclear plant in Taiwan and Bangladesh have lower AC than the world standard values. Other radiological hazards include Ra_{eq}, H_{ex}, H_{in}, D_N and A_{eff} of the soil near the nuclear plants is within the recommended values.

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

According to Table 2.6, Most Asian countries were found to have AC of ^{226}Ra, ^{232}Th, and ^{40}K within the recommended values of 35, 30, and 400 Bqkg^{-1}. However, the AC of ^{226}Ra and ^{232}Th are 1042.29±98.16 Bqkg$^{-1,}$ and 1756.12±165.21 Bqkg^{-1}, respectively, which are greater than the world standard value and the highest compared to other countries presented here. Another country that has a greater value of ^{226}Ra and ^{232}Th compared to the world average value is Malaysia, where its AC is 65.24±2.00 Bqkg^{-1} and 83.39±2.00 Bqkg^{-1}, respectively in the uncultivated soil and 102.08±2.00 Bqkg^{-1} and 133.96 ±2.00 Bqkg^{-1} in the agricultural soil. According to the research group, it was suggested that phosphate fertilizers could contribute to the greater AC of ^{226}Ra, especially in agricultural soil.

The geographical and geological characteristics, as well as the usage of fertilisers in the soil, influence the active concentration of these radionuclides in different parts of Asia. (Alharbi & Taher, 2013).

As for the AC of ^{40}K, countries such as South Korea, Pakistan, Yemen, and Laos are found to have higher AC value compared to the world average value of 400 Bqkg^{-1}. South Korea has the highest ^{40}K AC of 871.70 Bqkg^{-1}. This is of significant concern as soil samples were collected from elementary schools on the South Korean Peninsula. The high concentration of ^{40}K in this study location, according to the researchers, could be related to the fact that it is a granite region with multiple basalt zones (Kim et al., 2012).

The D_N gamma dose rate absorbed in the air is determined 1 m above the soil surface to ensure uniform radionuclide distribution. The population-weighted values give a mean absorbed dose rate to air by terrestrial gamma radiation of 60 nGyh^{-1}, which is according to the report that was published by UNSCEAR (UNSCEAR, 2000). According to the findings

of this study, the countries of Laos, Malaysia, Mongolia, Sri Lanka, and Thailand have among the highest rates of doses absorbed. Agricultural soils in Kedah, North of Malaysia have the highest absorbed dose rate of 141.62 $nGyh^{-1}$ compared to the other Asian countries. The use of artificial fertilisers might be the main reason for the high gamma absorbed dose rate in the studied soil, as reported in other literature (Durusoy & Yildirim, 2017; Yaprak & Aslani, 2010). Phosphate fertilisers essential for plant nutrition are also reported as the main contributor to the high concentration of ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K radionuclides, which accumulate in the agricultural soil in time and might possess a serious environmental hazard (Becegato et al., 2008; Reta et al., 2018).

Most of the soil study found that the average annual effective dose is lower compared to the recommended value by UNSCEAR, which is 0.5 $mSvy^{-1}$. On the other hand, the effective yearly dosage that is stated as being typical in Indonesia is 10.40 $mSvy^{-1}$, which is 21 times higher than the figure that is advised. Hence, Bottteng Utara, the study area in Indonesia, has higher radiological hazards due to the presence of very high AC due to ^{226}Ra, ^{232}Th and ^{40}K.

Samples collected from Asian countries are divided into four major regions, South Asia, Middle East Asia, Southeast Asia, and East Asia. Countries according to the respective regions are shown in Table 2.7.

Table 2.7: **Radioactivity Concentration ($Bqkg^{-1}$) of soil samples according to Asia countries**

Region	Countries	Radioactivity Concentration ($Bqkg^{-1}$)			
		^{226}Ra	^{232}Th	^{40}K	Ra_{eq}
South Asia	India	27.70	51.72	1416.19	210.71
	Sri Lanka	41.85	136.00	178.70	250.09
	Pakistan	26.46	49.03	565.23	140.10
	Bangladesh	12.42	12.60	198.90	45.75
	Average	27.11	62.34	589.76	161.66
Middle East Asia	Jordan	57.70	18.10	138.10	94.22
	Iraq	39.99	21.42	29.00	72.85
	Iran	24.30	25.80	457.70	96.44
	Kuwait	13.25	11.09	303.45	52.47
	Qatar	17.20	6.38	169.00	39.34
	Saudi Arabia	41.15	32.69	217.00	104.61
	Yemen	44.40	58.20	822.70	190.97
	Egypt	14.32	5.98	476.19	59.54
	Average	31.54	22.46	326.64	88.80
Southeast Asia	Indonesia	1042.29	1756.12	232.63	3571.45
	Laos	28.20	31.80	840.00	138.35
	Malaysia	102.08	133.96	325.87	318.73
	Thailand	60.25	64.90	435.50	186.59
	Average	308.21	496.70	458.50	1053.78
East Asia	China	6.90	9.60	39.60	23.68
	Mongolia	28.20	31.80	840.00	138.35
	Taiwan	22.53	33.43	406.62	101.64
	South Korea	59.20	25.27	871.70	162.46
	Average	29.21	25.03	539.48	106.53

2.10 Nuclear Fallout and Anthropogenic Cesium-137

The term "fallout" refers to the radioactive particles that are dispersed throughout the atmosphere as a result of an explosion caused by nuclear fission or fusion. In the event that a ground burst took place, it is composed of shards of weapons, products of fission, and radiated soil. Particles of fallout can range in dimension from a few thousandths of a millimetre up to various millimetres.

Within a few minutes of the explosion, the vast majority of this substance drops directly back down near to ground zero, but some of it goes high into the atmosphere and is dispersed throughout the atmosphere. Over the course of the next few hours, days, and months, this material is going to be dispersed across the entire planet. The term "early fallout" refers to events that take place within the first twenty-four hours after an explosion, while the term "delayed fallout" refers to events that take place days or even years later. One of two categories can be used to describe fallout.

The large number of the radiation hazard that comes from nuclear explosions is caused by short-lived radionuclides that are found outside of the body; these are typically restricted to the area that is windward of the point where the weapon was detonated. The radioactive fission fragments that cause this radiation hazard have half-lives ranging from a few seconds to a few months. Additionally, the intense neutron flux in the area around the burst causes the soil and other materials in the area to become radioactive(Prăvălie, 2014).

A relatively short amount of time is sufficient to cause the destruction of the vast majority of the particles. Even so, even further than the blast radius of the exploding weapons, there would be areas (hot spots) that the survivors would not be able to enter because of the radioactive pollution caused by long-lived radioactive isotopes such as strontium 90 or caesium 137. These long-lived radioactive isotopes would render the area unsafe for human

habitation. These long-lived radioactive isotopes would render these areas uninhabitable. For a period of time ranging from one to five years after the initial nuclear attack, this persistent radiation hazard may pose a significant danger to those who have survived a nuclear conflict. There is no known cure for radiation poisoning.

Because of a number of different factors, it is difficult to make accurate predictions regarding the amount and levels of radioactive fallout. The yield and design of the weapon, the height of the explosion, the nature of the surface underneath the point of burst, and the climatic circumstances, such as the direction and speed of the wind, are all aspects that need to be taken into consideration in this situation.(Chandrashekara & Somashekarappa, 2016).

If the fireball doesn't hit the ground during an air burst, then the amount of fallout might be very low. Instead, radioactive fallout from an underground or subsurface nuclear explosion can have a similar impact on the environment. That's because radioactive dust can spread over large areas.

2.10.1 Reactor Accidents and The Release of Radioactive Materials

The fission process in a nuclear power plant uses fuel, which can be uranium or plutonium, to produce the energy that is then used to heat water and turn turbine generators that are driven by steam. In addition to the release of energy, fuel fission results in the production of radioactive by-products of fission. It is of the highest significance that, in the case of an accident, the support structure (core) that carries the fuel and fission products does not incur any damage. This is because the fuel and fission products are extremely dangerous.

It is due to the possibility that radioactive materials may leak out into the environment if the facility were to sustain such damage. The consequences would be quite severe in the event that something of this nature actually took place. The inability of the core cooling

system to function properly is one of the potential reasons why something like this may take place(Ginzburg et al 1991).

The reactor's core and the fuel itself are at risk of melting if these conditions persist. The release of radioactive material into the environment can be caused by explosions in the reactor caused by high temperatures and pressures. In most reactors, a steel-walled vessel around the reactor core reduces the risk of a cooling system failure. A steel-reinforced concrete containment structure surrounds the vessel, keeping the radioactive material safe for as long as possible. A cooling system failure will have less of an impact with this design.

To be clear, nuclear weapon detonation explosions differ from nuclear reactor accidents. This is due to the fact that nuclear weapons require isotopes of uranium or plutonium that are highly enriched, and these aren't typically found in power plants. Consequently, when a nuclear weapon is detonated, the explosions are not the same as those that have been observed in reactor accidents(Saenko et al., 2011).

2.10.2: Fallout from the Fukushima Daiichi Nuclear Power Plant (FDNPP) tragedy

An earthquake and tsunami devastated Japan on March 11, 2011, causing the Fukushima Daiichi Nuclear Power Plant (FDNPP) tragedy. Radionuclides, mainly ^{134}Cs and ^{137}Cs, were discharged into the natural ecosystem after the accident and deposited on soil as radioactive pollutants (Kanasashi et al., 2020).

As an anthropogenic radionuclide, ^{137}Cs does not occur in the natural environment where its half-life is around 30 years, which is extremely lengthy. This specific isotope of caesium is both a beta and gamma emitter. Its presence in the environment is mostly due to nuclear weapons testing that occurred between the 1950s and the 1970s, according to the Environmental Protection Agency. The Chernobyl nuclear reactor tragedy in 1986 resulted

in an increase in radioactive fallout entering the environment, with ^{137}Cs being one of the radionuclides found in the fallout. Testing of nuclear weapons, the nuclear fuel reprocessing plants, and the Chernobyl disaster, which resulted in the release of 15 and 30 $\times 10^{15}$ Bq of ^{137}Cs and ^{134}Cs, respectively, were the primary sources of radioactive contamination (Buesseler, 2014). It was discovered in the marine sand around Malaysian waters that this radioactive fallout had occurred (Abdul Adziz et al., 2010).

Heavy fission products containing ^{137}Cs are the most common. The fission of a variety of thorium, uranium, and plutonium isotopes produce a 6 percent ^{137}Cs production in all situations. ^{137}Cesium is abundant in the nuclear fuel, and in areas contaminated by a fission by-product following nuclear disasters, as a result of the high yield of fission. A continuing concern is posed by the high quantities of ^{137}Cs created during fission events. ^{137}Cs has a long half-life to ensure that objects and regions contaminated by the radioactive element continue to be hazardous to population for a generation or more. It is, however, quick enough to ensure that even little concentrations of ^{137}Cs emit harmful radiation doses (its specific radioactivity is 3.2×10^{12} Bqg^{-1})(Lammer & Scherer, 1991).

Large doses of ionising radiation can induce noticeable health impacts such as hair loss, skin burns, vomiting, gastrointestinal suffering and even loss of life when applied in high enough amounts (Acute Radiation Syndrome). A radioisotope's function, as well as the route, magnitude, and duration of exposure, determine the long-term health concerns associated with it, which may include an elevated risk of cancer.

Medullar dystrophy, problems of the procreative function, and impacts on the liver and kidney functions are all caused by high doses of ^{137}Cs. Individuals have also been found to have bone mineralization disorders and brain impairment, according to the research. Even at

the lowest dose, ^{137}Cs can cause disruptions in the sleep cycle, but they are not associated with psychological problems.

In addition, the cardiovascular system was affected. Despite the fact that ^{137}Cs has been demonstrated to have biological effects on vitamin D, cholesterol, and steroid hormone metabolism, these effects do not appear in clinical symptoms. ^{137}Cs causes immunological deficits, prenatal and foetal deformations, a rise in thyroid cancer, and neurological problems in humans, among other things. (Lestaevel et al., 2010).

2.10.3: Nuclear fallout in Malaysia

Because Malaysia is situated in the south of South China Sea, radio-caesium from FDNPP events is expected to be carried to the country at low activity concentrations or at a level that is only marginally significant, considering the country's geographic location (Wan Mahmood et al., 2018). A study on the activity concentration of ^{137}Cs in surface soil of Fraser's Hill, Malaysia, a popular hillside tourist destination, was found to be between 0.26 Bqkg^{-1} and 5.15 Bqkg^{-1}.(Bakar et al., 2017) A similar study was conducted at different slopes of a hill in Cameron Highlands, Malaysia.

The ^{137}Cs activity concentrations range detected at top locality was from 0.05 Bqkg^{-1} to 1.53 Bqkg^{-1}, the centre was 0.22 Bqkg^{-1} to 2.11 Bqkg^{-1}, bottom was from 0.00 Bqkg^{-1} to 2.03 Bqkg^{-1} and forestry was 0.00 Bqkg^{-1} to 0.96 Bqkg^{-1}. The researchers concluded that the activity concentration of ^{137}Cs at the top is lowest, while at the bottom is highest, showing that there is a downward transport of ^{137}Cs (Hamzah et al., 2012).Since there are few studies carried out on the agricultural soil in Malaysia, the significance of the ^{137}Cs study in this area could provide baseline data to assess the radiological risks to the overall population. The study of ^{137}Cs activity concentration in soil, namely in agricultural soil in the district of Klang, Selangor, is carried out to establish the fallout radioactivity. Outcomes will be

assessed with the recommended values by UNSCEAR and ICRP in order to assess the radiological risks to the general public living around the vegetable farm.

2.11 Radiological hazards of natural radioactivity

Since radionuclides are present in the environment, human beings are consistently subjected to the radiation that is released by the environment. This is because the ground contains naturally occurring radioactive elements that contribute to its radioactivity. If there are extremely high numbers of them present in the environment, then this poses a potentially catastrophic risk.

The people who live in the community where the radiation is present may suffer severe consequences as a result of this situation. There is some evidence to suggest that human activities can have an effect on the radionuclides that occur naturally in soil. These radionuclides can be found in the ground. It is possible for the concentration of radionuclides to rise as a result of certain industrial activities, such as the manufacture of fertiliser, the mining of coal, the exploration for oil and gas, and the creation of cement (phosphate)(Alharbi and A. El-Taher, 2013; Najam and Younis, 2015).

Even though there is no place on Earth that is totally free of radioactivity, soil that contains naturally occurring radionuclides in concentrations that are higher than the maximum allowable exposure limit can be extremely hazardous and have a significant detrimental effect on the health of people who live there. Despite the fact that there is nowhere on Earth devoid of radioactivity, soil with naturally occurring radionuclides in concentrations higher than the maximum allowable exposure limit can be extremely dangerous and even deadly. Despite the fact that there is nowhere on Earth completely devoid of radioactivity, this situation has arisen.

It is necessary to determine the amount of radiation that people are exposed to daily from natural sources in order to compute the risk to their health that is consequently posed by this exposure. As a direct result of this, it is necessary to determine the amount of radiation that people are exposed to. This risk may be estimated by estimating the quantity of radiation that individuals are exposed to daily from natural sources. This radiation exposure can be found in the environment.

Radioactivity is something that occurs in the natural world. It is something that we do on a regular basis. There are naturally occurring radioactive elements in the ecosystem around us, including the air we inhale and the food we consume. We, ourselves are made of radioactive elements. Radioactivity is also helpful in a wide variety of sectors, including agriculture, medicine, mining, geology, archaeology, biology, and many more.(Dauer et al., 2010; Real et al., 2004).

The level of radiation that is emitted is influenced both by the quantity of naturally occurring radioactive materials (NORM) in the ground and the amount of time a person is exposed to them. It is essential to have an accurate understanding of the radioactive content of the soil in order to correctly assess the level of radiological danger that it poses to the people who live in that area.

This can be accomplished by conducting an experiment in which the radioactive content of the soil is measured. It is possible for soil to be a significant source of radiation exposure if it possesses a high concentration of radionuclides, is located in an area that is radioactive on the inside as well as the outside and is exposed to both types of radiation. It is possible that the levels of radionuclides in the soil of locations where food crops are cultivated could cause a hazard to the health of humans.

The possibility that radioactively contaminated products are carcinogenic (that is, they have the ability to cause cancer) or mutagenic (that is, they have the ability to cause cell mutations) is a risk associated with these products; however, these negative health effects frequently take place over time and are therefore difficult to attribute to the consumption of a single food item. The same is true (perhaps even more so) for processors who may come into contact with radiologically contaminated food on a daily basis, as their level of exposure may be higher than that of those who consume the food in normal quantities as part of their daily diet.

This is because processors may come into contact with food that has been radioactively contaminated. There have been very few radioactive incidents that have resulted in the recall of food; the vast majority of these incidents are related to the nuclear accidents that were discussed before.(Siddhuraju et al., 2002)

2.11.1 Effects of radiation on human

When ionising radiation comes into contact with a cell, the energy of the radiation is taken in (absorbed) by the molecules that make up the cell. This energy can either cause ionisation, which is the process of removing electrons from molecules, or it can break the bonds that hold molecules together. The types of molecules that are produced as a result, known as radicals, have a high level of chemical reactivity and may or may not have an electrical charge.

These free radicals interact with other molecules found in the cell, which can either directly or indirectly result in damage to the cell. The majority of the time, water molecules are impacted. However, the involvement of other substances found within the cell, such as

DNA or proteins, cannot be ruled out (carrier molecules of genetic information)(Edwards & Lloyd, 1998).

In most cases, the cell is able to repair any damage caused by radiation, which means that there should be no discernible biological effects. In the event that the cell is unable to repair the damage, however, it is typically eliminated through a process known as targeted programmed cell death (apoptosis).

When a cell suffers substantial damage as a result of being subjected to radiation at very high doses, the cell loses the ability to regulate its own demise, and the cell eventually passes away (necrosis). In the case that a repair is insufficient or partial, there is a risk that cells will form that have undergone genetic modification (mutation) and are also able to multiply (Mettler, 2012).

2.11.2 Types of Health Effects

Ionizing radiation can be harmful to cells and the genetic substance they contain if it comes into contact with them and interacts with DNA. This damage, if not properly restored, can result in the death of the cell or potentially harmful alterations or mutations in the DNA.

The way radiation doses affect one's health can be broken down into two types: deterministic and stochastic. When a certain dose threshold is achieved, deterministic effects begin to take place, which means that an amount that is lower than the threshold is not likely to generate the specific effect. The dose has an increasing relationship to the intensity of the effect. Erythema, which is a reddening of the skin, is an illustration of a deterministic effect with a threshold dose of about 300 rad (3 Gy). The term "short-term" health consequences are commonly used to refer to deterministic health effects, despite the fact that it may not correctly characterise all of these effects.(Choudhary, 2018).

Chance has a role in the occurrence of stochastic effects. The population will have a greater chance of experiencing the effect if they take higher doses, but the intensity of the effect will remain the same regardless of how much medication they take. Cancer is the primary stochastic impact caused by radiation dose, and it typically manifests itself some years after initial exposure. It is generally accepted that stochastic health effects do not have a minimum required dose in order to manifest themselves. Because of this, no radiation dosage level is ever regarded to be "safe," and doses ought to constantly be maintained at the lowest level that is practicably possible (ALARA).

The term "long-term" health effects are commonly used to refer to stochastic health effects, despite the fact that this may not adequately represent all stochastic health effects.(Fry, 2001). The comparison of the deterministic and stochastic health effects is shown in the table 2.8.

Table 2.8: Comparison of Deterministic and Stochastic Health Effects

	Deterministic	**Stochastic**
Threshold dose	Typically, deterministic effects have a dose below which they do not present themselves in any noticeable way.	It is considered that stochastic effects have no threshold dose. One DNA mutation may be enough to have an effect.
Likelihood of experiencing adverse health impacts	If the dose is higher than the threshold, the impact happens.	The likelihood that an impact may occur increases with dose.
The severity of health effects	The severity of the impact increases in direct proportion to the dose administered.	The dose has no effect on the impact's strength. All-or-nothing reaction: a person either experiences the impact on their health or does not.

Table 2.8, continued

Effects	Hair loss, cataract, skin injury	Cancer, leukaemia, and heredity effects

CHAPTER 3: MATERIALS AND METHODS

3.1 Study area

Both soil and vegetables have been collected from three farms in Kampung Johan Setia, Selangor, an agricultural area located approximately 50 km southeast of Kuala Lumpur, Malaysia, which is known as the Green Revolution Land, the local state government's initiative to encourage agricultural activities in this area started in the early 1990s. The location of this farm at latitude 2°57’03.5’N and longitude 101°28’30.0’E and is shown in Figures 3.1 and 3.2. The soil type in this is analysed, and it is found as tropical peat soil where this soil type is considered extremely soft, wet, and unconsolidated deposits(Kazemian et al., 2009).

This particular research site has a peat soil that was created from the debris of the surrounding forest and is made up of a collection of partially decomposed organic matter. It has a predominantly organic composition and a dark brown coloration all throughout. In addition to this, it has a high capacity for holding water, which can be anywhere from 15 to 20 times the weight of the substance when dry. There is a possibility that peat soil is deficient in nutrient levels, and in general, peat soils have a pH value that falls somewhere in the range of 3.0 to 4.5. The properties of this peat soil collected from the farms are shown in Table 3.1. Figures 3.3 – 3.5 show the farm area and vegetables collected for this work.

Table 3.1: Basic properties of Peat Soil in these farms

Basic soil property	Value
Moisture Content (%)	668
Specific Gravity (%)	1.40
Fibre Composition (%)	90
Organic Content (%)	96
Ash Content (%)	4
pH	3.51
Peat Soil Classification	Fibrous

3.2 Sample Collection

A total of nine vegetables are collected from the three farms located in these areas. Five samples of each vegetable are collected from all three farms. These vegetables are grouped into three main types of vegetables. They are leaf-type vegetables such as Japanese Mustard (*Brassica juncea)*, Spinach (*Spinacia oleracea*), and Water Spinach (*Ipomoea aquatic).* The fruit type vegetables are Bitter Gourd (*Momordica charantia*), Cucumber (*Cucumis sativus*), and Round Brinjal *(Solanum melongena)*. Beans type of vegetables is Long Beans (*Vigna sesquipedolis)*, Lady's Finger or Okra (*Hibiscus esculentus)*, and Four Angled Bean or Winged Bean (*Psophocarpus tetragonolobus)*.

The vegetables are selected based on the frequency of fruits and vegetables consumed by adults in Selangor as shown in Table 3.2(Nurul Izzah et al., 2012). Vegetables samples are taken at 100 to 150 m from each sampling area. This is to ensure there is no duplication of sample especially on the soil samples taken. An area of 30 cm × 30 cm was identified where the respective vegetables are grown. The soil of 0-10 cm depth is cleared, and 10-30 cm depth is taken as a sample. Roughly 1 kg of soil was gathered. The samples of vegetables, fully

grown and ready for harvesting, were taken from the same type of soil or area. About 3-5 kg of edible parts of these vegetables were collected.

Table 3.2: Consumption rate of vegetables (fresh weight) in a year by adults in Selangor

Vegetable Type	Consumption Rate (kg per person y^{-1})
Leafy	12.41
Root	12.41
Brassica	16.42
Fruits	11.68
Leguminous	14.32
Other	4.74
Total	71.63

Map data ©2021 Google

Figure 3.1. Map showing sampling sites at Kampung Johan Setia

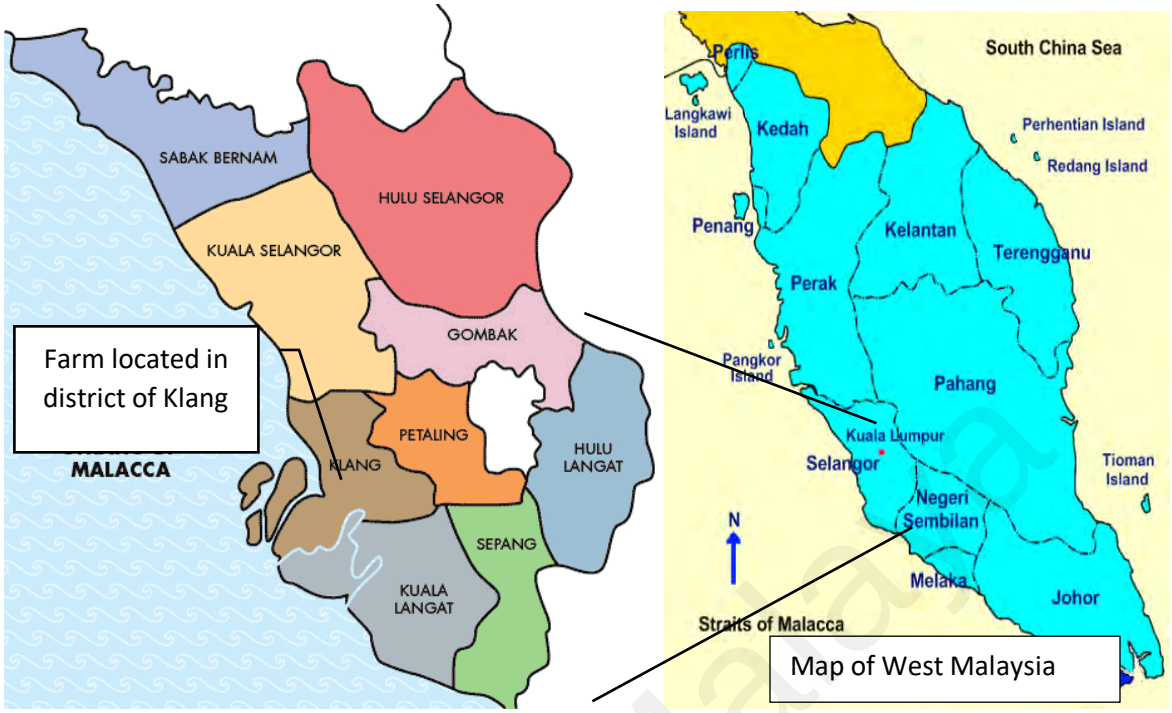

Figure 3.2. Location of the vegetable farm in the district of Klang, Selangor.

Figure 3.3. Peat Soil Farm where Leafy Vegetables were collected

Figure 3.4: Farm workers helped to collect the Japanese Mustard and soil samples

Figure 3.5: Bitter Gourd and Cucumber collected from sampling

3.3 Sampling Technique

Samples taken from the study site were brought to the laboratory in a plastic bag, with each plastic bag being labelled appropriately. All large stones were removed from the soil sample, and the whole sample was passed through a stainless-steel sieve. The soil sample was dried in the oven at a temperature of 105 °C for a period of 24 hours before being further ground into refined grains using a mortar and pestle. The vegetable samples have been cut into smaller pieces before drying them in the oven at a temperature of 70 °C. The dried sample was then ground into a fine grain and passed through a sieve. Both soil and vegetable sample are dehydrated to achieve dry weight sample according to procedure suggested by IAEA protocols. Due to the spontaneous properties of the radioactive elements in the samples, the dehydration process will not affect the quantification of the activity concentrations of the radioactive elements(IAEA, 2009). Both samples were weighted using an electronic balance that was held in a Marinelli beaker, sealed, and stored for a period of 4 -5 weeks at room temperature to allow secular equilibrium between ^{226}Ra and its daughter nuclide before taken for gamma spectrometric analysis. (Cruz da Silva et al., 2020; Naveed et al., 2005). Figures 3.6 – 3.9 illustrate the sample preparation of vegetables and soil samples.

(a) Long Bean

(b) Spinach

Figure 3.6: Vegetables are cut into small pieces before dried in the oven

Figure 3.7: Dried Vegetable samples are grinded

Figure 3.8: Soil samples are dried using oven

Figure 3.9: Dried, pulverized, and sieved soil and vegetable samples are sealed in the 500 ml Marinelli beakers for radioactivity measurements

3.4 Radioactivity Measurements

Figure 3.10: HPGe Gamma Detector on the right with the liquid nitrogen tank on the left

Figure 3.11: Standard radioactive source used to calibrate the detector

HPGe gamma detector and standard radioactive source have been used to measure and evaluate the important properties of all the samples as depicted in Figures 3.10 and 3.11. The standard source is used to calibrate the HPGe gamma detector and the details and results were mentioned in chapter 4. Each soil and vegetable samples and background data were counted for 86400s to diminish the counting error and background counts. With the reference to the Gamma ray energies shown in **Table 3.3**, gamma spectroscopy was used to verify the activities of ^{226}Ra, ^{232}Th, and ^{40}K. The specific activity of ^{226}Ra was assessed from gamma-ray lines of ^{214}Pb at 351 keV and ^{214}Bi at 609.3 and 1764.5 keV, while the specific activity of ^{232}Th had been valued from gamma-ray lines of ^{228}Ac at 338.4, 911.1, and 968.9 keV, ^{212}Pb at 238.63 keV, and ^{208}Tl at 583.19 keV. The specific activity of ^{40}K was directly established from its gamma-ray line at 1460.8 keV.

Table 3.3: Gamma-ray energy and emission rate for ^{238} U, ^{232}Th, and ^{40}K radionuclides.

Element	Nuclide	Half-Life	Energy of Gamma Ray (keV)	Emission Rate	Sources
^{238}U	^{214}Pb	26.8 min	351.00	35.8	^{238}U (^{226}Ra) series
	^{214}Pb	19.9 min	609.30 1764.50	45.4 15.3	
^{232}Th	^{228}Ac	6.15h	338.40 911.10 968.90	11.4 25.8 17.4	
	^{212}Pb		238.63	46.6	
	^{208}Tl		583.19	85.0	
^{40}K	^{40}K	1.28 x 10^9 years	1460.80	10.7	Primordial

3.5 The Activity Concentration

The ACs, A_{Ei} (Bqkg^{-1}) of these radionuclides were calculated using the following formula:

$$A_{Ei} = \frac{N_{Ei}}{C_{eff} \times t \times m \times \gamma} \quad (3.1)$$

where N_{Ei} is the total count of a peak at energy E, C_{eff} is the detection efficiency at energy E, γ is the percentage of gamma emission probability of the radionuclide i for a transition at energy E, m is the mass in kg of the measured sample and t is the counting time(Kumar and Sharma, 2021).

3.6 Transfer Factors

The soil-to-plant TF measures the transfer of radionuclides from soil to plant taken through the plant roots. TFs (transfer coefficients between soil and plants), TF, i.e., the ratio

$$TF = \frac{[R_i, Bq\ kg^{-1}]^{plant}}{[R_i, Bq\ kg^{-1}]^{soil}} \quad (3.2)$$

where R_i is the uptake of the i^{th} radionuclide by plants from the soil through the soil to plant pathway (Adjirackor et al. 2017).

3.7 Radium equivalent activity concentration

The ACs of ^{226}Ra, ^{232}Th, and ^{40}K in soils are non-uniform. The radium equivalent AC (Ra_{eq}) is often used to determine the total AC in a sample. Ra_{eq} is calculated based on the estimation that 10 Bq/kg of ^{226}Ra, 7 Bq/kg of ^{232}Th, and 130 Bqkg^{-1} of ^{40}K exhibit the same gamma dose rate. Therefore, the Ra_{eq} is calculated by the following equation: (Durusoy, 2017; Farai, 2005)

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K \quad (3.3)$$

Where C_{Ra}, C_{Th} and C_K are the ACs of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bqkg^{-1}.

3.8 External Hazard index (H_{ex})

H_{ex} is another index that has been broadly used to set a threshold of exposure to human. The limit of the external hazard index is 1.00. The H_{ex} can be determined with the equation(Ibraheem et al., 2018; S. A. M. Issa et al., 2014):

$$External\ Hazard\ Index, H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (3.4)$$

Where C_{Ra}, C_{Th} and C_K are the ACs of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bqkg^{-1}.

3.9 Internal Hazard Index (H_{in})

The H_{in} is the internal exposure to radon and its hazardous progenies via inhalation or food. The H_{in} is defined as

$$Internal\ Hazard\ Index, H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (3.5)$$

Where C_{Ra}, C_{Th} and C_K are the ACs of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bqkg^{-1}.(Kumar and Sharma, 2021)

3.10 Radioactivity Level Index, (I_γ)

The I_γ is used to monitor radiological dose within the human body and to quantify the risky threshold of radionuclides in the human body when subjected to the amount of indoor and outdoor annual effective doses of gamma radiation from the radioactive nuclides in the soils. In addition, the I_γ is used to monitor the radiological dose outside the human body in order to determine whether or not it is safe for humans to be exposed to it. In order to guarantee that the soil surrounding the veggies is free of any potential dangers, the values that are calculated for I_γ should be less than or equal to one. Calculations of the values of I_γ are performed in accordance with the equation.(S. Issa et al., 2013):

$$Radioactivity\ Index\ Level, I_\gamma = \frac{C_{Ra}}{150} + \frac{C_{Th}}{100} + \frac{C_K}{1500} \quad (3.6)$$

Where C_{Ra}, C_{Th} and C_K are the ACs of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bqkg^{-1}.

3.11 Annual effective ingestion dose, A_{eff}

The A_{eff} dose to human due to consumption of vegetables is calculated in the following equation(IAEA, 2009):

$$A_{eff}\ (\mu Sv\ y^{-1}) = Activity\ Concentration\ (Bqkg^{-1}) \times Annual\ intake\ (kg\ y^{-1}) \times DCF\ (\mu Sv\ Bq^{-1}) \quad (3.7)$$

Where DCF is the dose conversion factor for ingestion, 0.28 µSv Bq^{-1} for ^{226}Ra, 0.23 µSv Bq^{-1} for ^{232}Th and 0.0062 µSv Bq^{-1} for ^{40}K(Chandrashekara and Somashekarappa, 2016).

The annual intake of vegetable type is 12.4 kgy^{-1} for leaf, 14.04 kgy^{-1} for beans and 11.68 kgy^{-1} for fruit. The annual intake of vegetable is calculated based on the consumption of vegetables by adults from Selangor, Malaysia which is shown in Table 3.2. (Nurul Izzah et al., 2012)

The average worldwide annual effective ingestion dose A_{eff} of ^{226}Ra and ^{232}Th is 120 µSv y^{-1} and for ^{40}K is 170 µSv y^{-1}, with a total annual dose of 290 µSv y^{-1} (UNSCEAR, 2000)

3.12 Absorbed dose rate, D_N

The contribution of naturally occurring radionuclides in the D_N depends on the AC of ^{226}Ra, ^{232}Th, and ^{40}K. It is a total ionising dose, and it is divided by the time it takes to deliver the dose. Higher is the dose; the greater is the harm and damages to the human body. The international recommended values of the D_N recommended are 55 nGy hr^{-1} (UNSCEAR, 2000). Therefore, the D_N (nGy h^{-1}), is calculated with the following equation(Hamzah et al., 2011; Šoštarić et al., 2021):

$$Absorbed\ Dose\ Rate, D_N = 0.461C_{Ra} + 0.623C_{Th} + 0.0414C_K \quad (3.8)$$

For the anthropogenic nuclide ^{137}Cs, the dose rate, D_R ($nGyh^{-1}$) is calculated using the formula in equation 3.

$$D_R = 0.03 \times A_{cs} \quad (3.9)$$

Where A_{cs} is the activity concentration of ^{137}Cs and 0.03 $nGyh^{-1}$ per $Bqkg^{-1}$ is the dose conversions factor for the ^{137}Cs.

3.13 Annual effective dose equivalent, AEDE

The AEDE (μSvy^{-1}), due to natural radionuclides was quantified using the occupancy of 0.2 and the dose conversion coefficient (0.7 Sv Gy^{-1}) to convert the absorbed dose rate into the effective dose (UNSCEAR, 2000). The population's annual effective dose can be estimated by following the theoretical model (Ghias et al., 2021)

$$AEDE = D_N(nGy\ h^{-1}) \times 8760(h) \times 0.2 \times 0.7(\ SvGy^{-1}) \quad (3.10)$$

3.14 Excess life-time cancer risk (ELCR)

It's possible to suffer from a wide range of health problems after being exposed to radiation on different parts of your body for different lengths of time. The increased cancer risk per unit dose can be estimated by examining the number of cancer patients exposed to a particular amount of radiation with the number of cancer similar clinical characteristics who were not exposed to radiation. It is possible that there is a risk of harm if there is an elevated relative cancer risk per provided dosage. After being exposed to cancer-causing substances, an individual's lifetime chance of dying from cancer is proportionate to their lifetime risk of acquiring cancer. The following formula can be used to determine the ELCR(Ravisankar et al., 2016).

$$ELCR = AEDR \times DL \times RF \quad (3.11)$$

Whereas AEDR is the annual effective dose rate, DL is the length of life, 75 years, for Malaysian(DOSM, 2021), and RF is the risk factor that is 0.05 for the public according to International Commission on Radiological Protection ICRP(Clarke et al., 1993; Cousins et al., 2011). The worldwide documented ELCR value is 0.29×10^{-3} (UNSCEAR, 2000).

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Detector Efficiency Curve

The ACs of ^{226}Ra, ^{232}Th, and ^{40}K in the samples were determined using a Closed-end coaxial HPGe gamma-ray spectrometer (Canberra; Model GC3018, serial no. 04089401; 59 mm crystal diameter; 50 mm long; 2500V operational voltage) having a relative efficiency of 30 % and an energy resolution of 1.8 keV-FWHM at the 1332.5 keV peak of ^{60}Co. To reduce the external gamma-ray background in the measured spectrum, a cylindrical lead shield with a fixed bottom and a movable cover shielded the detector. The HPGe detector was connected to a 16 k MCA2 (Multi Channel Analyser 2)for data acquisition. The gamma rays radiated from the samples were evaluated by Genie 2000 Canberra software. The spectrum of the standard source is given in Figure 4.1 and energy calibration and channel number calibration of the spectrometer are shown in Figure 4.2 and Figure 4.3, respectively. This calibration of detector was achieved using Marinelli calibration sources encompassing the radionuclides shown in table 4.1. The calibration source with a preliminary activity of 5.076 μCi was acquired from Eckert & Ziegler, Isotope Products Laboratories (Valencia, CA 91355, USA).

Table 4.1: List of standard sources used to calibrate the HPGe detector

Nuclide	Activity (μCi)	Channel	Energy (keV)	Efficiency
Cd-109	1.558	464.00	88.00	0.18
Co-57	0.06224	652.00	122.00	0.05
Ce-139	0.07659	893.00	166.00	0.07
Hg-203	0.2287	1515.00	279.00	0.14
Sn-113	0.3030	2132.00	392.00	0.11
Sr-85	0.3719	2802.00	514.00	0.09
Cs-137	0.2650	3612.00	661.60	0.07
Y-88	0.6072	4907.00	898.00	0.05
Co-60	0.3235	6416.00	1173.20	0.03
Co-60	0.3235	7288.00	1332.50	0.03
Y-88	0.6072	10047.00	1836.00	0.02

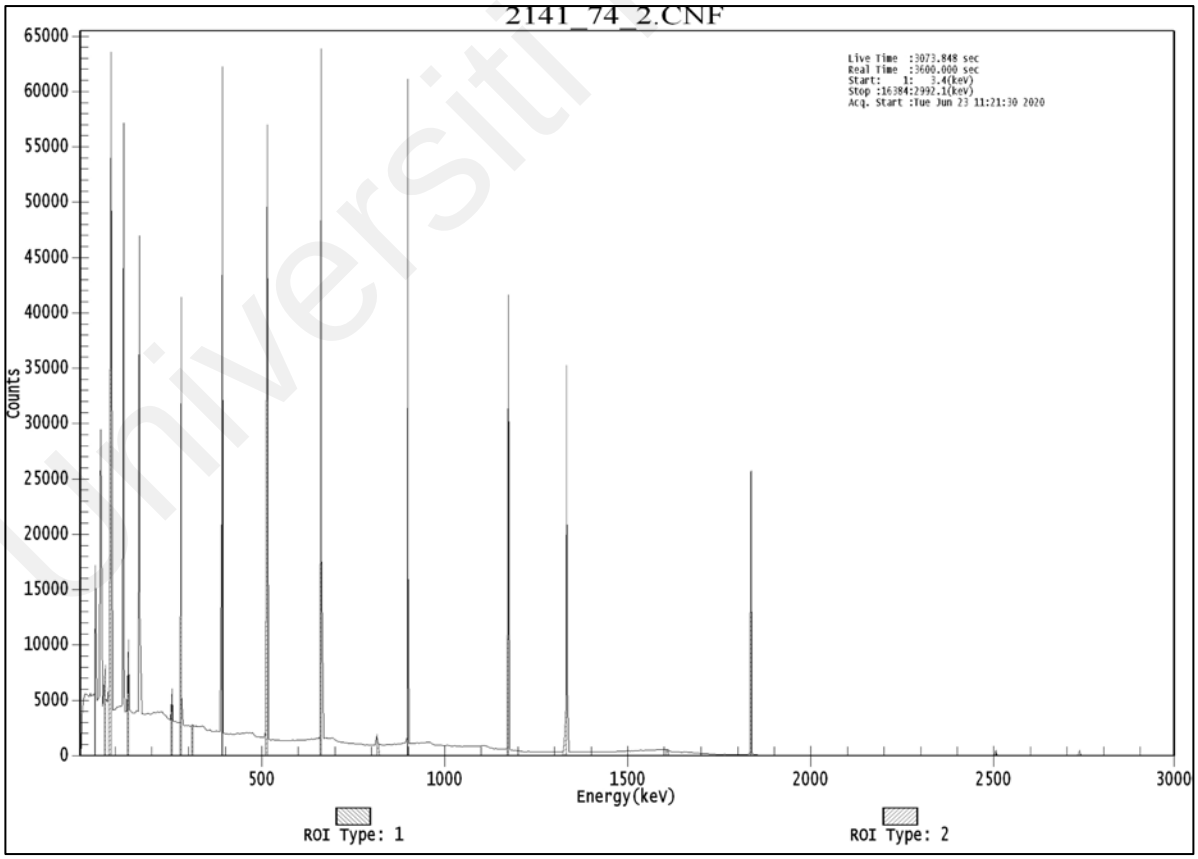

Figure 4.1: Spectrum of radionuclides obtained by HPGe detector

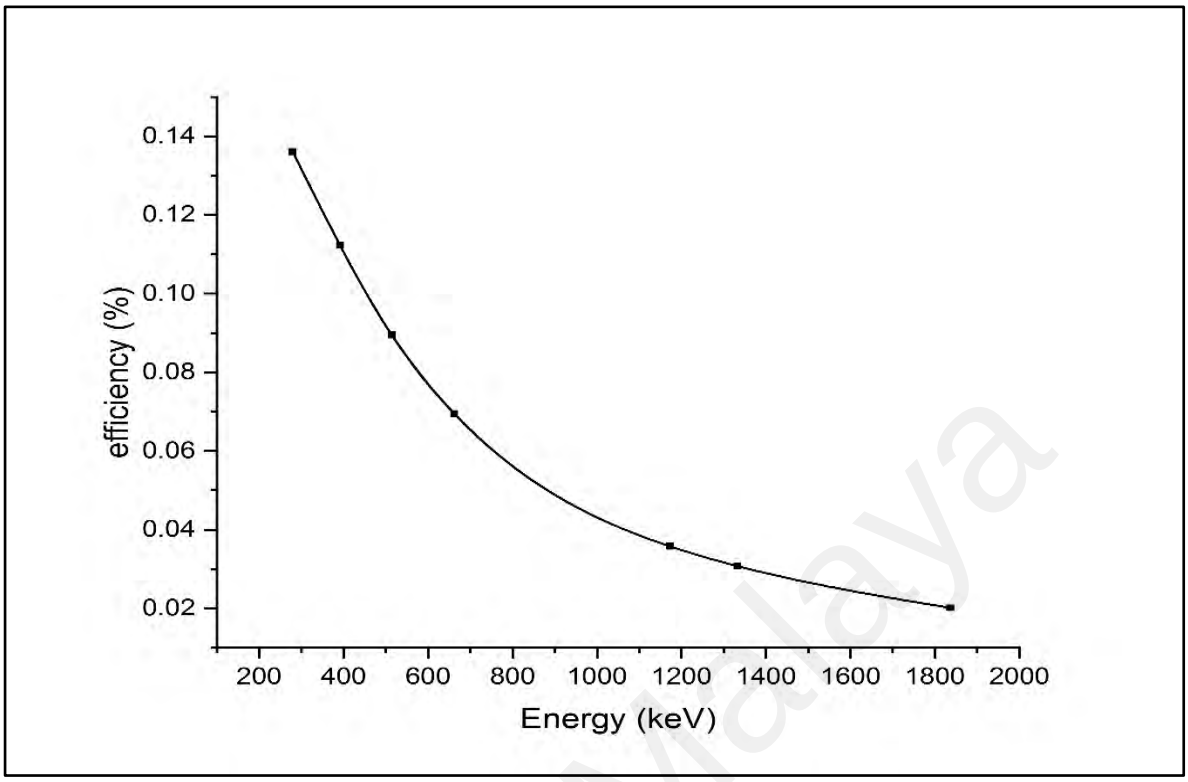

Figure 4.2: Detector's Energy Efficiency curve.

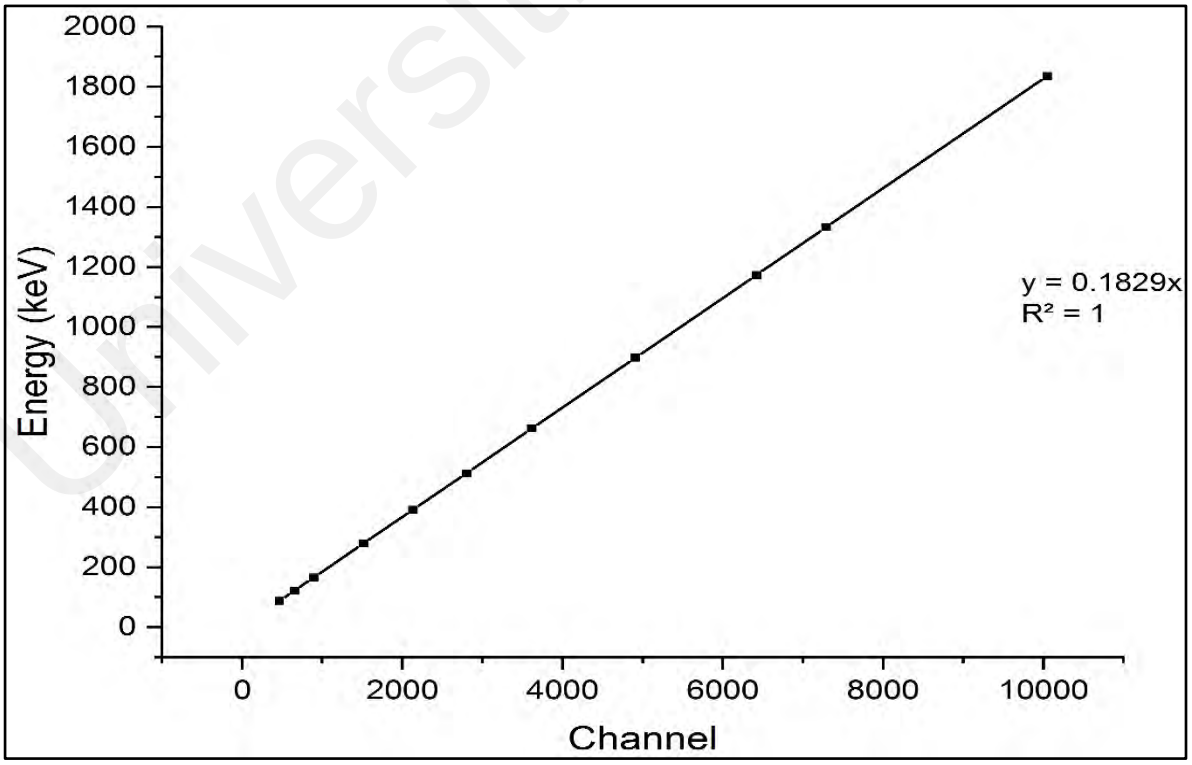

Figure 4.3: Energy versus Channel Number.

4.2 Activity concentration in soil samples surrounding the vegetables

Table 4.2: The AC of natural radionuclides in soil samples (dry weight) surrounding the respective vegetables

Vegetable Types	Vegetables	AC in soil ($Bqkg^{-1}$)		
		^{40}K	^{226}Ra	^{232}Th
Leaf	Spinach	65.1±0.3	10.3±0.5	24.0±0.7
	Japanese Mustard	19.2±0.2	2.7±0.6	9.0±0.3
	Water Spinach	126±6	8.5±0.6	23.3±0.6
Beans	Okra	34.5±0.2	2.9±0.6	16.0±0.5
	Long Beans	99.4±0.3	4.7±0.6	19.8±0.6
	Four Angled Bean	478±6	46.5±0.2	54.8±0.4
Fruit	Cucumber	83.9±0.5	6.3±0.8	23.5±0.7
	Round Brinjal	83.1±0.7	9.8±0.7	18.3±0.6
	Bitter Gourd	84.2±0.3	7.8±0.6	14.7±0.5
Arithmetical Mean		119.23	11.08	22.60
Max		477.76	46.54	54.84
Min		19.22	2.72	9.01
Standard Error (SE)		46.08	4.53	4.34
Standard Deviation (SD)		138.24	13.58	13.03
Geometrical Mean GM)		81.09	7.50	20.17
Geometrical Standard Deviation (GSD)		138.24	13.58	13.03
Kurtosis		7.67	7.97	5.83
Skewness		2.69	2.76	2.19

The ACs of natural radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in soil and vegetable samples collected from peat soil farm located in Kampung Johan Setia, Selangor, are shown in Table 4.2. Figure 4.4 shows the AC in soils taken around the respective vegetables. The worldwide average concentrations by UNSCEAR (2008) for ^{226}Ra, ^{232}Th, and ^{40}K in soil samples is 35 Bqkg^{-1}, 30 Bqkg^{-1}, and 400 Bqkg^{-1}, respectively. Soil samples taken from this farm have a lower average value of AC of ^{226}Ra, ^{232}Th, and ^{40}K, which are 11.08 Bqkg^{-1}, 22.60 Bqkg^{-1}, and 119.23 Bqkg^{-1}, respectively.

However, the AC of ^{226}Ra, ^{232}Th, and ^{40}K in the Four Angles Beans soil sample is 46.54 Bqkg^{-1}, 54.84 Bqkg^{-1}, and 477.76 Bqkg^{-1}, which are greater than the worldwide average value for the respective radionuclides. The lowest concentration of ^{226}Ra, ^{232}Th, and ^{40}K compared to the worldwide average concentrations is in the Japanese Mustard soil samples. The ACs are 2.72 Bqkg^{-1}, 9.01 Bqkg^{-1}, and 19.22 Bqkg^{-1} for the respective radionuclides.

The AC of the peat soil analysed in this research is compared with research conducted by Kh. Asaduzzaman et.al. The reseachers conducted similar analysis on mining soil located in Puchong, Selangor were the AC of ^{226}Ra, ^{232}Th and ^{40}K are found to be in the range of 99.6-128 Bqkg^{-1}, 7.2-11.1 Bqkg^{-1} and 657-903 Bqkg^{-1} respectively. Lateric soil sample from Lembah Beringin has AC of ^{226}Ra, ^{232}Th and ^{40}K are found to be in the range of 122-142 Bqkg^{-1}, 17.7-32.6 Bqkg^{-1} and 492-546 Bqkg^{-1} respectively. The researcher also conducted analysis on peat soil located in Chemor where the AC of ^{226}Ra, ^{232}Th and ^{40}K are found to be in the range of 72.7-112 Bqkg^{-1}, 33.6-71.6 Bqkg^{-1} and 385-441 Bqkg^{-1} respectively. (Asaduzzaman et al., 2014). In comparasion with AC of obtained in this research, it is found that AC of ^{40}K is almost the same as the AC of the Peat soil from Chemor and relatively lesser than other soil type. Wheras, the AC of ^{226}Ra and ^{232}Th is higher compared to other soil type.

4.3 Activity concentration in vegetable samples

Table 4.3: The AC of natural radionuclides in vegetable samples (dry weight)

Vegetable Types	Vegetables	AC in vegetables ($Bqkg^{-1}$)		
		^{40}K	^{226}Ra	^{232}Th
Leaf	Spinach	34.3±0.9	0.96±0.65	1.1±0.1
	Japanese Mustard	20.4±0.5	1.8±0.2	0.10±0.02
	Water Spinach	318±8	3.4±0.3	3.6±0.3
Beans	Okra	16.2±0.4	1.3±0.8	0.85±0.51
	Long Beans	129±6	1.6±0.2	3.3±0.2
	Four Angled Bean	122±5	0.41±0.26	0.83±0.05
Fruit	Cucumber	139±4	1.4±0.2	0.04±0.1
	Round Brinjal	130±1	2.7±0.1	2.95±0.58
	Bitter Gourd	194±5	0.71±0.05	0.02±0.01
Arithmetical Mean		122.70	1.58	1.41
Max		317.49	3.41	3.56
Min		16.22	0.41	0.02
Standard Error (SE)		31.85	0.32	0.48
Standard Deviation (SD)		95.55	0.94	1.45
Geometrical Mean (GM)		83.72	1.33	0.51
Geometrical Standard Deviation (GSD)		95.56	0.95	1.45
Kurtosis		1.10	0.41	-1.55
Skewness		0.88	0.89	0.64

Figure 4.5 shows the AC of ^{226}Ra, ^{232}Th, and ^{40}K in vegetable samples. The highest concentration of radionuclide ^{226}Ra, ^{232}Th, and ^{40}K, is found in Four Angles Bean with an

AC of 46.54 Bqkg^{-1}, 54.84 Bqkg^{-1}, and 477.76 Bqkg^{-1}, respectively. This beans type vegetable also has the highest Ra_{eq} value compared to other vegetables, which is 161.75 Bqkg^{-1}. Leaf-type vegetables generally have lower radionuclide concentration, especially Japanese Mustard. The AC of ^{226}Ra, ^{232}Th, and ^{40}K is Japanese Mustard is 2.72 Bqkg^{-1}, 9.01 Bqkg^{-1}, and 19.22 Bqkg^{-1}, respectively. ^{40}K is the highest radionuclide absorbed by these vegetables. This may be caused by the heavy use of NPK fertilisers in the soil by the planters to improve crop yield.

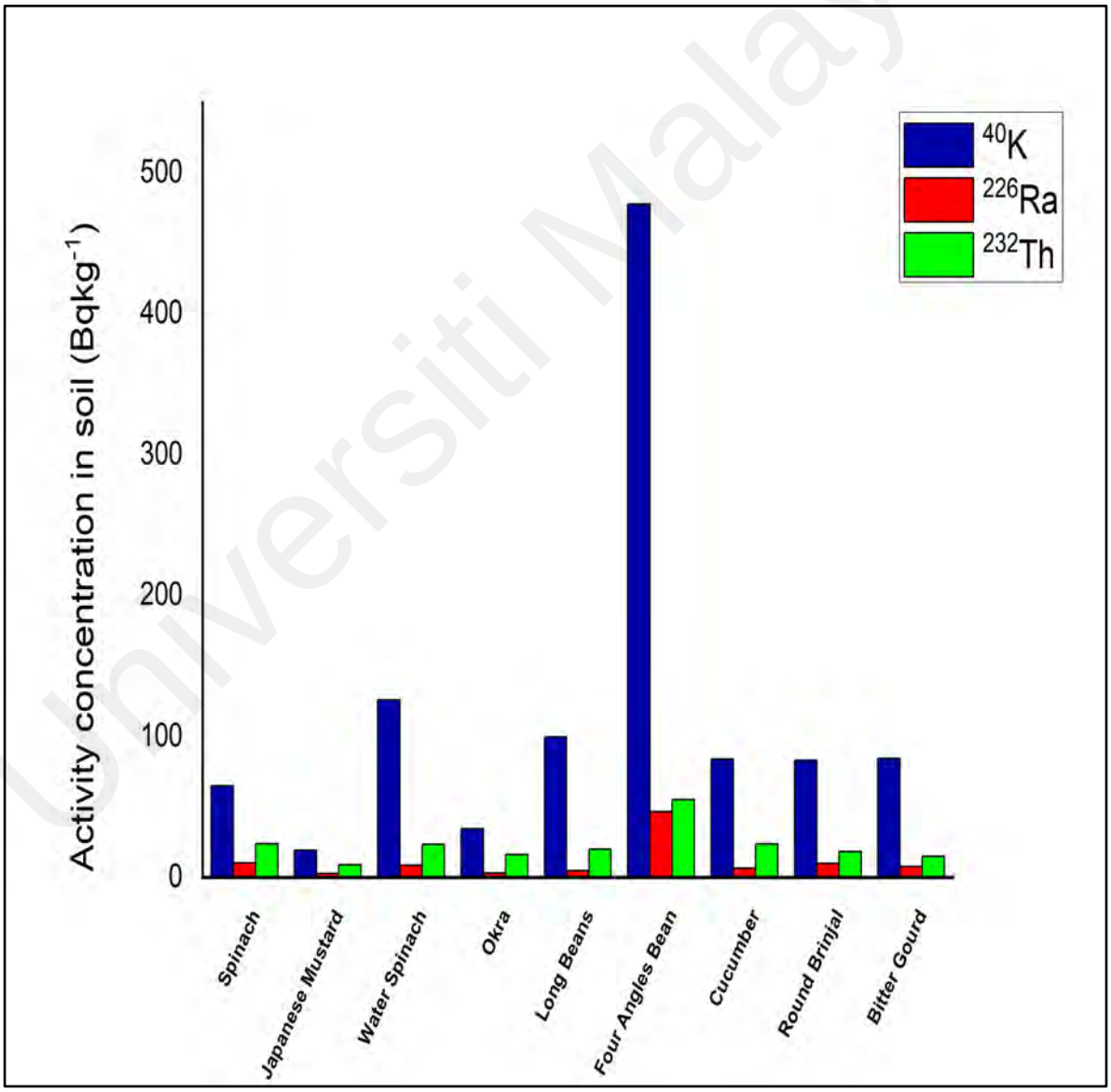

Figure 4.4: Radionuclide concentrations in soil

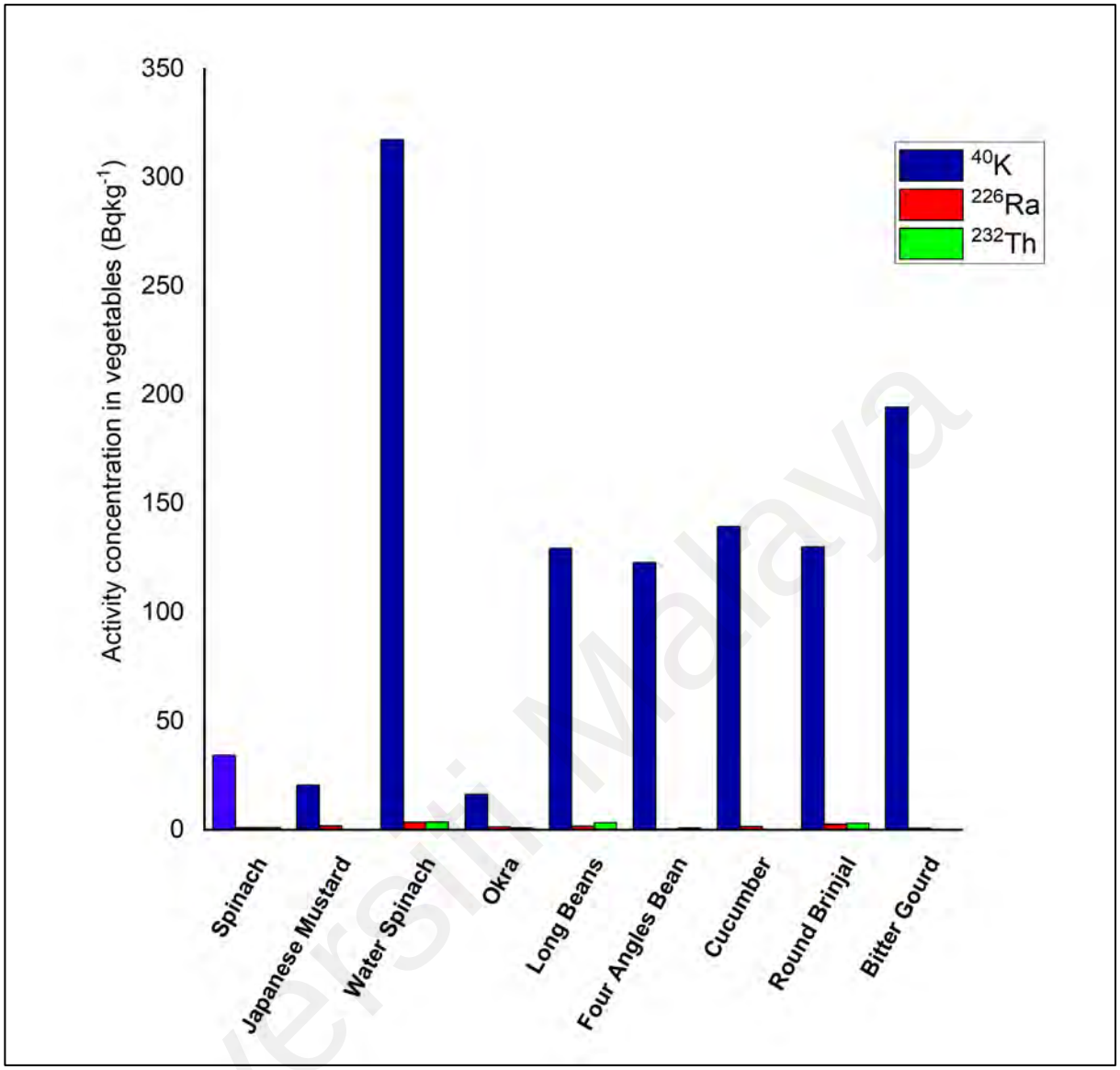

Figure 4.5: Radionuclide concentrations in vegetables

The AC of natural radionuclides in all the soil samples was $^{40}K>^{232}Th>^{226}Ra$. It is noticeable that ^{40}K has the highest absorption of radionuclides in the soil given that it is a minimal isotope of naturally occurring potassium which is the seventh most plentiful element on the Earth. ^{40}K makes up 2.6% of the weight of Earth's crust. The higher concentration of ^{232}Th related to ^{226}Ra may be due to the variation in chemical speciation and solubility of the parent nuclide, ^{232}Th and ^{238}U, respectively, in a natural environment. Because of their comparable ionic sizes and bonding capabilities, thorium and uranium are frequently found

together in the crust of the Earth. However, they are usually fractioned during the surficial process, such as weathering, transportation, and deposition (Kritsananuwat, 2017).

The AC of ^{226}Ra, ^{232}Th and ^{40}K in these studies is compared with the AC values reported on other countries as listed in Table 4.4. The comparison shows that the ^{226}Ra activity is lower than the reported value in Nigeria, Turkey, Jordon, and Vietnam. But the AC is higher than the reported value in Egypt, India, Iraq, and Saudi Arabia. Regarding the concentration of ^{232}Th, it is higher than the reported value in India, Iraq but lower than the reported value in Nigeria, Egypt, Pakistan, Turkey, Jordan, Saudi Arabia, and Vietnam. On the other hand, the concentration of ^{40}K is much lower compared to most countries except Saudi Arabia.

Table 4.4: A comparison between concentration (Bqkg^{-1}) for vegetable samples with values reported in other countries

Country	^{226}Ra	^{232}Th	^{40}K	References
Nigeria	BDL-32.1	BDL-9.6	80.6 – 213	Jibiri, 2007
Egypt	BDL-1.5	BDL-4.5	235-507	El-Reefy, 2006
India	0.01 -1.16	0.02-1.26	45.9-649	Ramachandran, 1989
Pakistan	BDL-2.41	2.37-7.20	189.9-412.3	Matiullah, 2008
Turkey	15.96 – 52.8	BDL-10.54	491.61-2324.5	Bolca,2007
Iraq	0.20-1.45	0.11-0.48	68.07-1355.36	Azeez, 2019
Jordan	57.7	18.1	138.1	Saleh, 2013
Saudi Arabia	1.02	2.53	1.05	Abu Shayeb, 2020
Vietnam	24.1	30.8	258	Duong, 2020
Malaysia	0.41-3.41	0.02-3.56	6.22-317.49	Present Study

BDL is below the detection limit

It might be presumed that the soil texture, clay content, pH value and the combination between the existing ions is more significant for the uptake than the content of available K only. The mutual correlation of different factors that influence the soil-to-plant transfer of radiocaesium and established two schemes for soil classification for the prediction of TFs for radiocaesium where either exchangeable K or pH plays a significant role(Sanzharova et al., 2020). Thus, the soils, investigated in the present study can be appropriately related to the first classification system defined by the soil group, mechanical composition, and pH value.

Ions containing nutrients are taken up by plants as needed. Depending on the element's role in plant metabolism, it is transported to different parts of the plant, where it can accumulate to a greater extent than in other regions.

In addition to that, radionuclides can be absorbed at the same time as nutrients. It's possible that their chemical behaviour is comparable to that of a necessary nutrient. The levels of these radionuclides were found to be rather high in the soil samples that were obtained from farms; the most plausible explanation for this is that decades of labour had been put in to recondition the soil. Large quantities of NPK fertilisers have been utilised in the past and are still being used now for the purpose of enhancing agricultural crop yield.

This is possibly another cause for the observed higher radioactive concentrations in the food crops linked to those that were stated in the literature. Virtually identical values of TFs for radionuclides are the result of the extremely complicated behaviour of elements in the soil, despite the fact that the radionuclides are present in soil at various concentration levels. Yunoki et al., has observed that the metal-selective function of plants during the intake of elements to support the mechanism of homeostasis in a normal environment might influence the degrees of accumulation of naturally occurring radioactive elements (Yunoki et al., 1993).

The quantity of radioactivity that is present in plants may also help us examine the effect that ionising radiation has on plants and determining that amount allows us to do both of these things. This might be due to the fact that the radioactive isotopes that are found in plants have the capacity to modify the cell kinds and models of plants, or it could be due to the fact that plants have evolved to be better able to cope with dangerous environmental contaminants.

Researching these alterations might also make it feasible for us to pick original or evolutionary plant species that have the ability to keep a high level of radioactivity throughout the course of time. Because the growth of the plant and its genetic makeup have no effect on the fertility of the plant. Because of this, the application of phytoremediation technologies might become more effective and useful in the future.(Thien et al., 2020).

Because the levels of activity and concentrations of natural radionuclides in the soils that were investigated fell within the range of what is considered to be the average for the entire world, it is possible that the population will not be exposed to any levels of radiation that are considered to be harmful as a direct result of this. On the other hand, individuals who take in consistent amounts of radionuclides through their diets over the course of a long period of time may experience negative effects on their health. It is essential to have a solid overview of the performance of radionuclides in relation to mitigation and changes in the speciation of elements within the soil. Additionally, it is essential to have a good understanding of the availability of these elements for uptake by plants over time, various agricultural practises, and the significance of recycling through animal manure. All of this information is essential.

It is undesirable to have a higher concentration of radioactive substances in the environment; as a result, research ought to be carried out to figure out the concentration of radionuclides in soil and the method by which they are transferred to plants. This is because

having a higher concentration of radioactive substances in the environment is undesirable. This is due to the fact that it is not ideal for there to be a greater concentration of radioactive chemicals in the environment. This is because it is not optimal for there to be a bigger concentration of radioactive compounds in the environment, and this is the primary reason why this is the case. Because of this, it will be possible to take the necessary steps in radiology and dosimetry with the aim of reducing the harmful effects of ionising radiation to the greatest extent that is practically possible. This will be an important step in the fight against cancer and other diseases caused by radiation.

4.4 Radium equivalent activity concentration

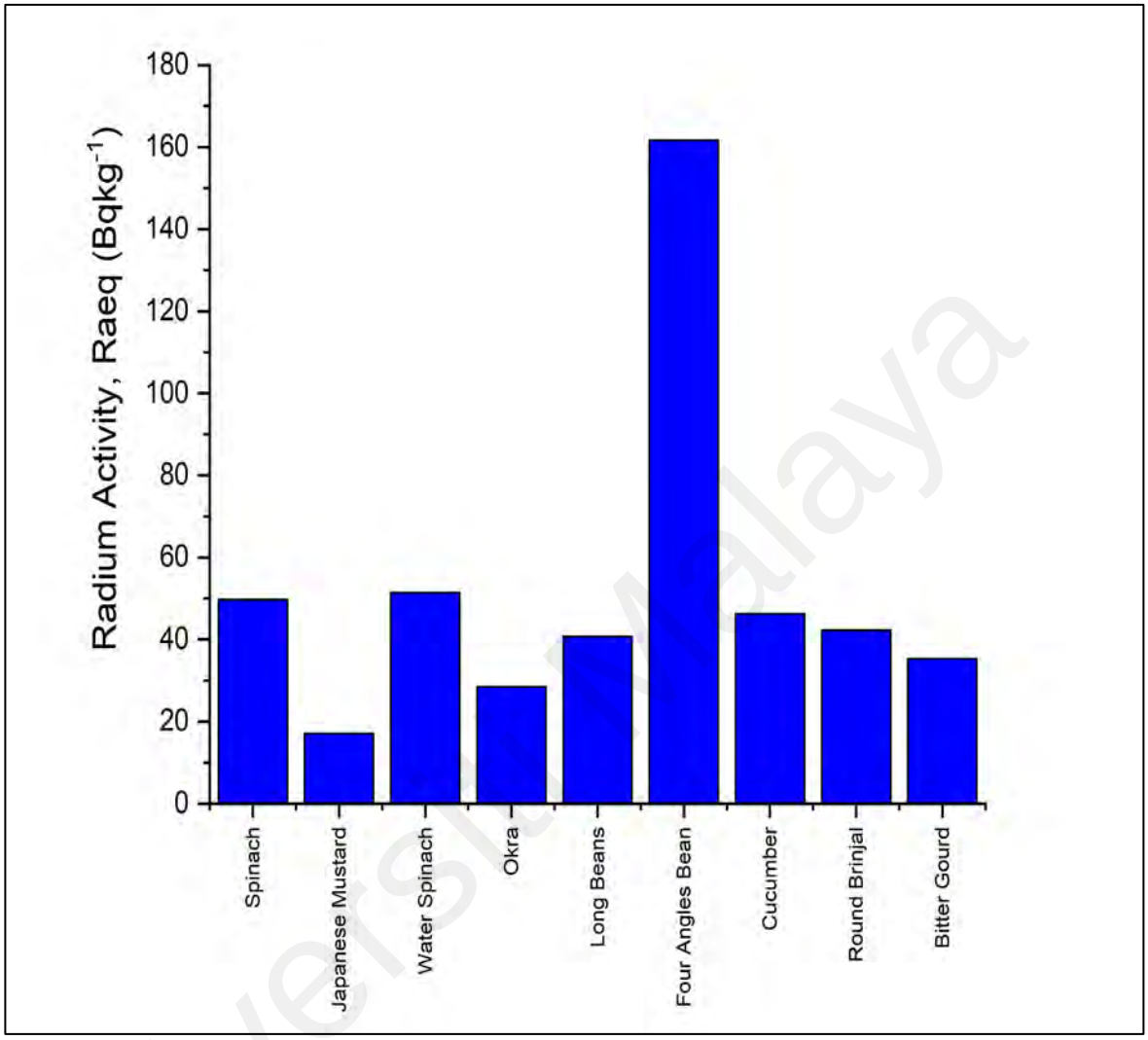

Figure 4.6: Radium equivalent Ra_{eq} in peat soil vegetable farm

Ra_{eq}, a decay result of uranium and thorium. It can be found in extremely trace amounts throughout the natural environment, including in rocks, soil, and water. Additionally, Ra exists in the natural environment at extremely low concentrations. Therefore, elevated levels of radium can be found in rocks or soil in locations where uranium and thorium are present at relatively high concentrations(Ahmed et al., 2018).

The maximum value of Ra_{eq} in soil should be less than 370 $Bqkg^{-1}$to ensure its external dose does not surpass 1.5 $mGyh^{-1}$ (UNSCEAR, 1988). Fig.4.6 presents Ra_{eq} calculated in

soil samples from the study area, and it ranges from 17.09 to 161.75 $Bqkg^{-1}$. The slight variation in Ra_{eq} in this study is due to differences in ACs of natural radionuclides within the studied vegetable farm. In general, it is considerably lower than the upper limit value of 370 $Bqkg^{-1}$. Subsequently, the other hazard indices will also be substantially lower than recommended limits.

4.5 Transfer factor from soil to vegetables

Table 4.5: Transfer factor from soil-to-vegetables based on the dry weight of samples

Vegetable Types	Vegetables	Sample	Transfer Factor (TF)		
			^{40}K	^{226}Ra	^{232}Th
Leaf	Spinach	V1	0.53	0.09	0.04
	Japanese Mustard	V2	1.06	0.67	0.01
	Water Spinach	V3	2.52	0.40	0.15
Beans	Okra	V4	0.47	0.43	0.05
	Long Beans	V5	1.30	0.34	0.17
	Four Angled Bean	V6	0.26	0.01	0.02
Fruit	Cucumber	V7	1.66	0.23	0.00
	Round Brinjal	V8	1.56	0.27	0.16
	Bitter Gourd	V9	2.31	0.09	0.00
Arithmetical Mean			1.30	0.28	0.07
Max			2.52	0.67	0.17
Min			0.26	0.01	0.00
Standard Error (SE)			0.27	0.07	0.02
Standard Deviation (SD)			0.80	0.21	0.07
Geometrical Mean GM)			1.03	0.18	0.03
Geometrical Standard Deviation (GSD)			0.80	0.21	0.07

The concentration of radionuclides in soils and plants can be used to determine soil to-plant TFs (transfer coefficients between soil and plants). In literature, this ratio is also known as the relative concentration factor, or plant -soil concentration ratio, CR (Kathren, 1984). It is important to keep in mind that if TF is greater than one, this will result in a transfer of radionuclides from plants to livestock and then to humans through the food chain. This may result in a significant increase in the number of radiation hazards faced by the human population(Thabayneh, 2014).

The TFs from soil to the respective vegetables are shown in table 4.5. The overall TF value varied from 0.001 to 2.52. TFs for ^{40}K are greater than those of other radionuclides in all the vegetable samples. Nearly all of it are greater than 1, suggesting a higher ^{40}K uptake from the soil. The highest TF for ^{40}K is in the Water Spinach, which is 2.52, and the lowest is in Four Angles Bean, which is 0.26. It is common knowledge that potassium is an indispensable nutrient for absorption. Plants draw potassium from the soil in varying amounts, depending on their metabolism, and this amount is determined by the potassium content of the soil.

It is interesting to note that nine different types of vegetables are grown in soil with the same physical-chemical properties and the same concentration of radionuclides. However, the TF value varies significantly depending on the variety of vegetable. The fruit type vegetable has the highest average TF value for ^{40}K, which is 1.84, and the lowest average TF value for ^{232}Th, which is 0.05 compared to other types of vegetables.

According to the report from IAEA (IAEA, 2009), the data compiled from the soil-to-plant transfer factor for ^{40}K in the plant was in the range of 0.49 – 5.60 with an average value of 1.4. In the present study, the average value of TF for ^{40}K in the vegetables was found higher than IAEA stated value, which is 1.30. For ^{226}Ra, the average value stated by IAEA

is 0.11 with a range of 0.01 – 1.0. In the present study, the average TF value for ^{226}Ra is 0.28 with a range of 0.01 - 0.67, which shows that the average value is higher than the reported value. However, the observed range values in this study are within the IAEA range reported value. For ^{232}Th, it is noticeable that the average value in this study is 0.07, which is higher than the IAEA average value of 0.058 and the range value in this study is 0.00 – 0.17, which is higher than the reported range value of 0.035 – 0.15.

The soil-to-plant transfer factors for ^{137}Cs is not significant because of its low concentration in environmental samples as was acquired in this study. The result of this study indicated that ^{137}Cs was not identified in the vegetables, and transfer factor is not relevant.

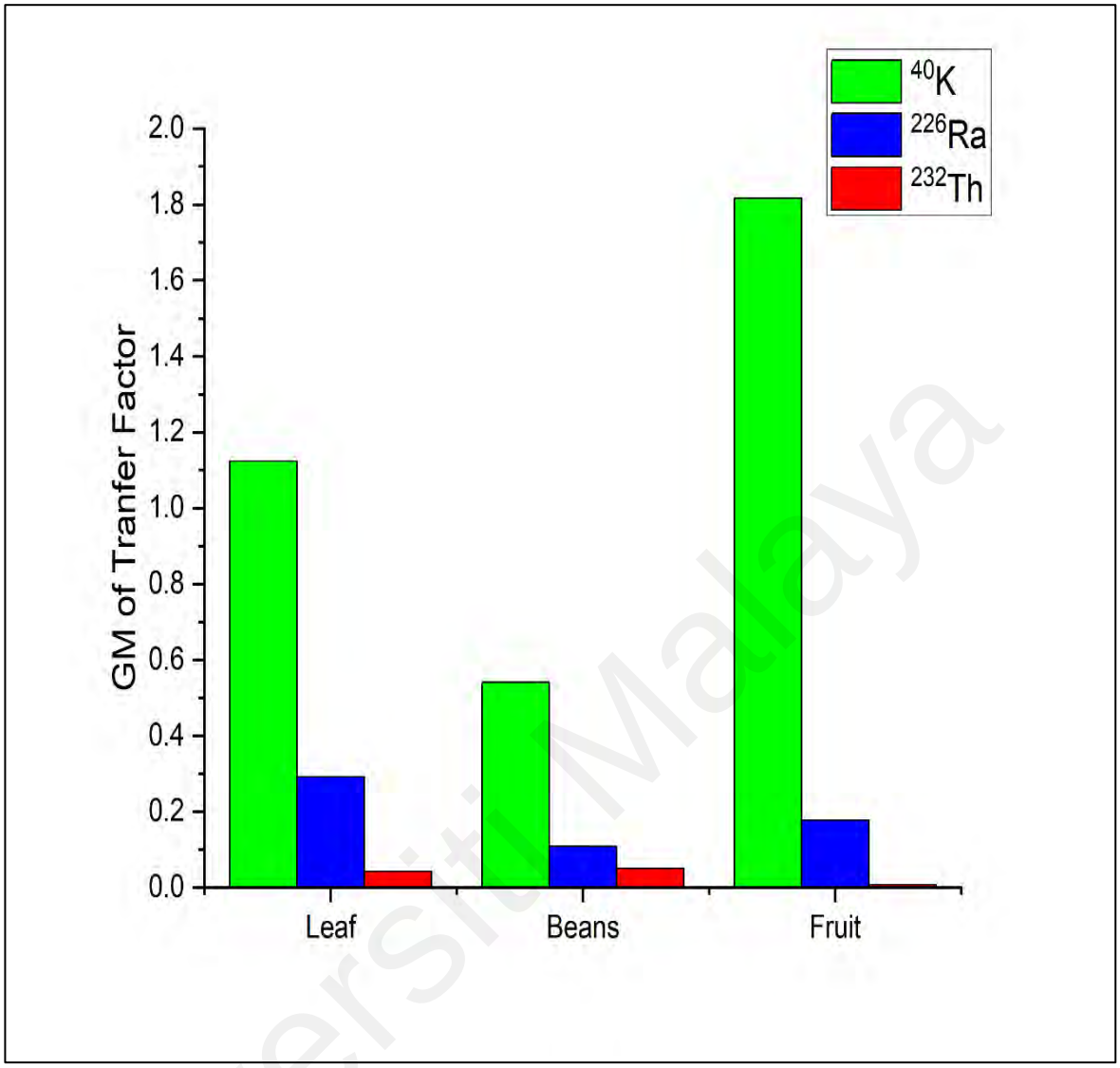

Figure 4.7: Geometrical Mean of TF for Leaf, Beans and Fruit type vegetables.

The soil-to-vegetables geometrical mean of TF of ^{226}Ra, ^{232}Th, and ^{40}K in a different group of vegetables are shown in Figure 4.7. Overall, the TFs of ^{40}K were considerably more significant than those of ^{226}Ra and ^{232}Th. The TF of ^{40}K in leaf and fruit type vegetables are greater than 1 compared to beans type vegetables. These results can be compared with a study conducted with tropical plants where the uptake of ^{40}K shows similar behaviour where the highest values of TF were observed in the growing parts of the plants, such as edible fleshy organs, new leaves, twigs, and twigs bark(Velasco and Anjos, 2021). Similarly, in

Vietnam, green vegetables have greater TFs in the ^{40}K range than tubers and legumes. The researchers believe that the greater biological potassium need and its availability to this type of vegetable than to other crops accounts for the higher TF value of ^{40}K in leafy vegetables. (Duong Van et al., 2020).

The TF values for ^{226}Ra is compared with the amended IAEA data collection for soil to plant transfer of radionuclides in the tropical environment. In this study, the GM of TF was 0.29 which is slightly higher than the reported value 0.22 for the leafy vegetables while the GM of TF for fruit type vegetables in this study was 0.18, which is 15 times greater than the amount described in the revised IAEA data. However, this study's soil group is peat soil which is more acidic and has higher organic matter, >90%, compared to the types of soil group in the revised tropical dataset (Doering et al., 2021).

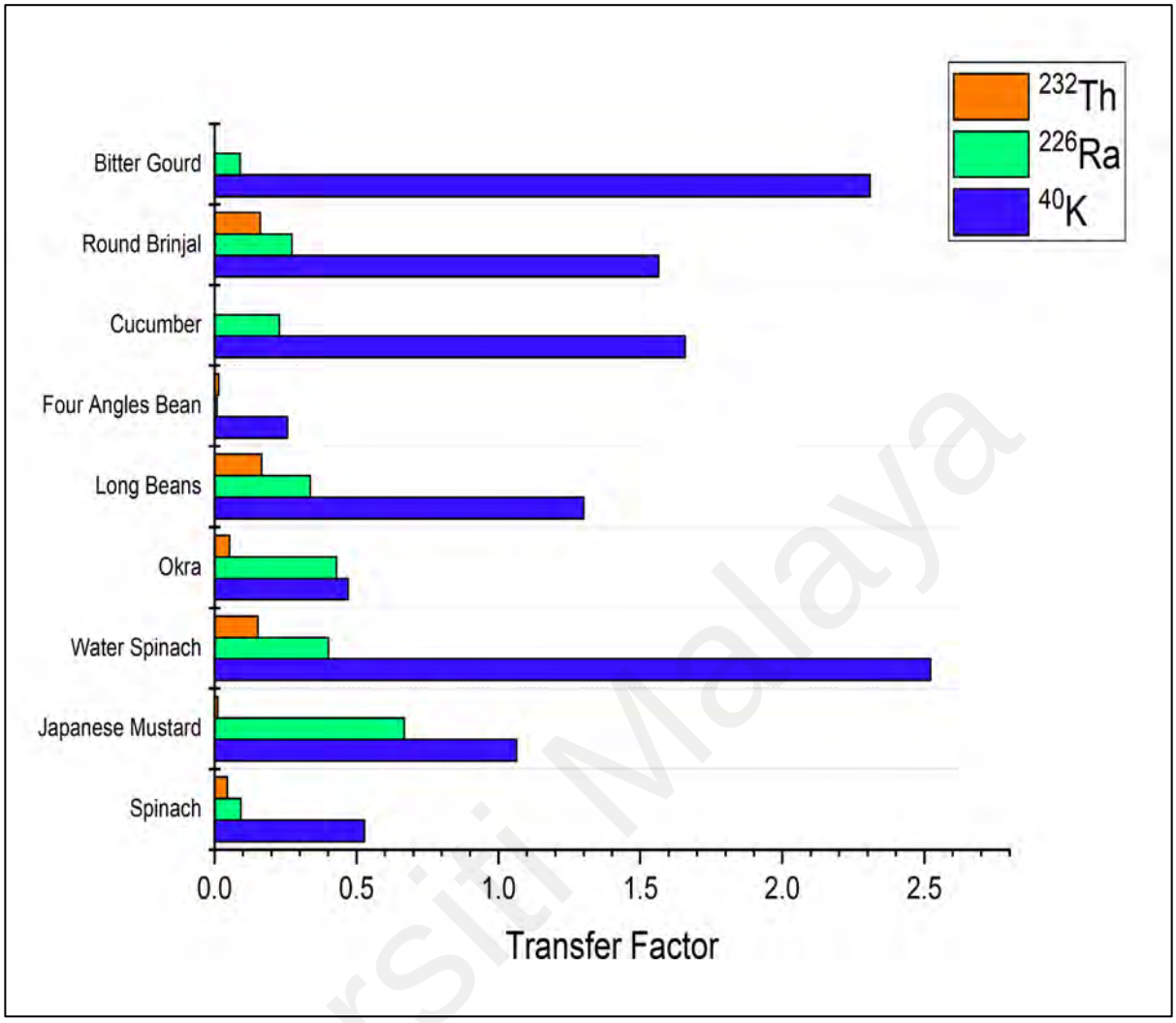

Figure 4.8: TF from the soil surrounding the vegetable root to the respective vegetables

4.6 External H_{ex}, internal, H_{in} hazard index and Radioactivity Level Index, I_γ, for soil surrounding the respective vegetable samples

Table 4.6: External Hazard Index, H_{ex}, Internal Hazard Index H_{in}, and Radioactivity Level Index, (I_γ) for soil surrounding the respective vegetable samples

Soil Samples Surrounding vegetables	H_{ex}	H_{in}	I_γ
Spinach	0.13	0.16	0.35
Japanese Mustard	0.05	0.05	0.12
Water Spinach	0.14	0.16	0.37
Okra	0.08	0.09	0.20
Long Beans	0.11	0.12	0.30
Four Angles Bean	0.44	0.56	1.18
Cucumber	0.13	0.14	0.33
Round Brinjal	0.11	0.14	0.30
Bitter Gourd	0.10	0.12	0.26
Average Value	0.14	0.17	0.38
Maximum	0.44	0.05	1.18
Minimum	0.05	0.56	0.12

As shown in table 4.6, Radioactivity Level Index, I_γ is ranging from 0.12 to 1.18 with an average value of 0.38 in this vegetable farm. The lowest value is in Japanese Mustard which is 0.12, and the highest I_γ value is found in the soil surrounding the Four Angles Bean, which is 1.18, higher than the suggested value, which is 1 (UNSCEAR, 2000). This implies that the soil surrounding the Four Angles Bean should be avoided and not used for further agricultural activities.

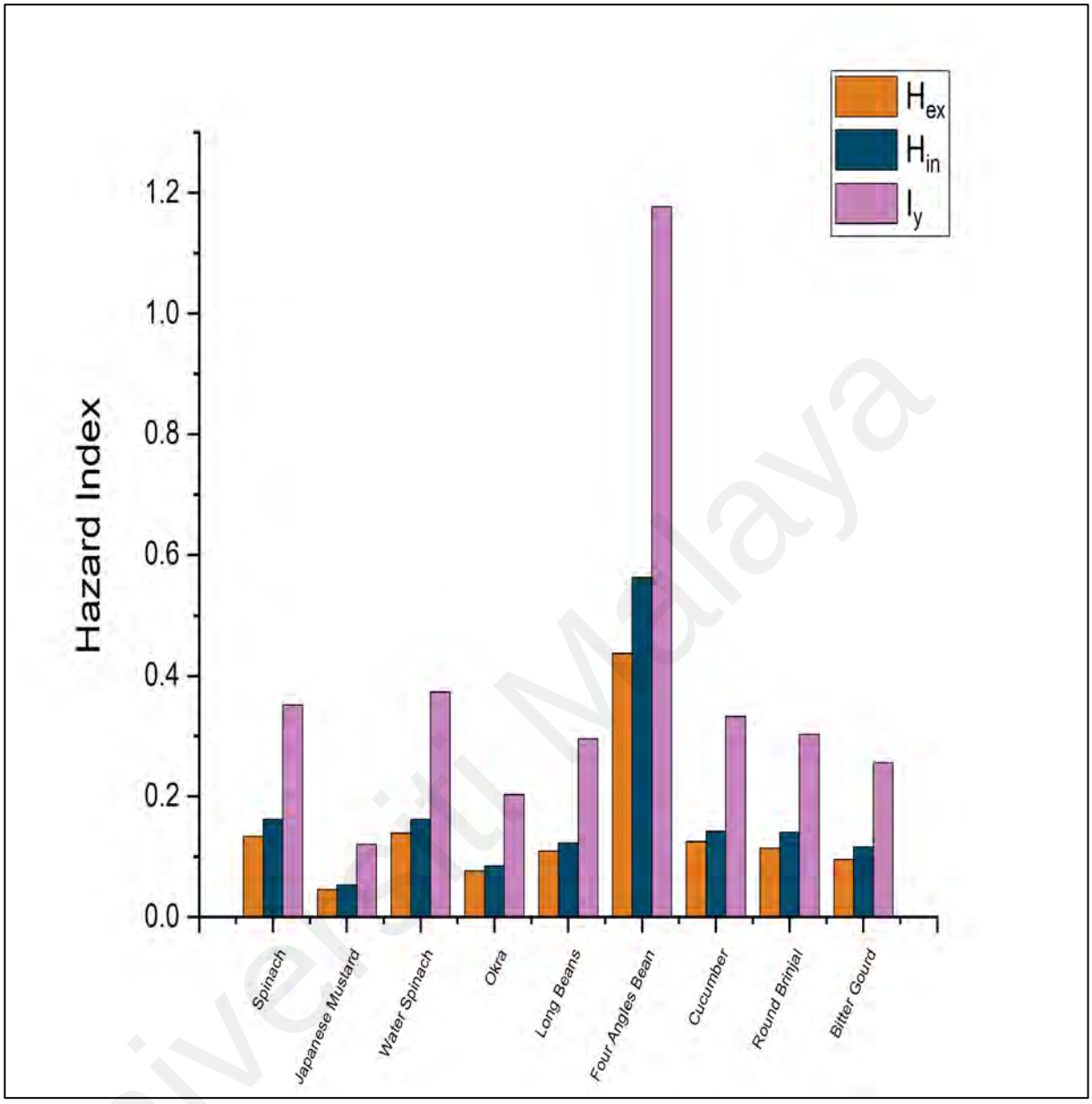

Figure 4.9: External Hazard Index H_{ex}, Internal Hazard Index, H_{in} and Radioactivity Level Index, I_{γ}, for soil surrounding the respective vegetable samples

The comparison of External and Internal Hazard Index (H_{ex} and H_{in}) for the soil of the vegetables are shown in Figure 4.9. The External Hazard Index, H_{ex} is varying from 0.05 to 0.44 with an average value of 0.14. The value of the Internal Hazard Index, H_{in} for the vegetable soil, ranges from 0.05 to 0.56 with an average value of 0.17. The values of H_{ex} and

H_{in} required to be lower than 1 to keep the radiation hazard inconsequential to the surrounding environment, especially to human, since the values obtained for H_{ex} and H_{in} are lower than the limit determined by the ECRP (Commission et al., 1999). Therefore, there is little to no major radiological threat to the general public and agricultural activities from the soil sample from the research area due to the reduced radiation exposure in the environment, especially to the farmers. Soil radioactivity is studied by determining the yearly effective dose and several radiation hazard indicators.

This study shows that the resulting values are significantly less than the bounds of these indices. This indicates that there is very little risk of radiation exposure to the general public. Furthermore, the hazardous effect of carcinogenic radon and its short-lived progeny does not apply to the respiratory system of humans since it is not important to this system.

Table 4.7: Radiological Hazard comparison with the values of some other countries of the world

Countries	H_{ex}	H_{in}	I_{γ}	References
Pakistan	0.26	0.28	0.36	(Qureshi et al., 2013)
India	0.08	-	0.24	(Thangam et al., 2020)
Turkey	-	0.46	0.34	(Turhan et al., 2009)
Brazil	0.03	-	0.09	(Radenković et al., 2009)
Serbia	0.12	-	0.34	(Radenković et al., 2009)
Libya	0.05		0.14	(Radenković et al., 2009)
USA	0.18		0.51	(Radenković et al., 2009)
Montenegro	0.18		0.27	(Radenković et al., 2009)
Current Study	0.14	0.17	0.38	

A comparison of the radiological hazard is shown in table 4.7. It is found that the average amount of the external Hazard Index, H_{ex} in this analysis is higher compared to the value in

India, Brazil, and Libya but lower than the value in Pakistan, USA, and Montenegro. The internal Hazard Index, H_{in} is lower compared to the value in Pakistan and Libya. The Radiological Level Index, Iγ in this study is found to be higher than the value in Pakistan, India, Turkey, Brazil, Serbia, Libya, and Montenegro but lower than the value in USA.

4.7 Annual Ingestion Dose, Absorbed dose rate, Annual Effective dose equivalent and ELCR

Table 4.8: Annual Ingestion Dose, Absorbed dose rate, Annual Effective dose equivalent and ELCR

Vegetable Types	Vegetables	Annual Ingestion Dose, A_{eff} (μSv y^{-1})				Absorbed dose rate, D_n (nGy h^{-1})	AEDE (μSv y^{-1})	ELCR ×10^{-5}
		Ra-226	Th-232	K-40	Total			
Leaf	Spinach	3.32	3.05	0.26	6.63	2.53	3.10	1.16
	Japanese Mustard	6.32	0.29	0.49	7.10	1.75	2.15	0.80
	Water Spinach	11.83	10.15	0.91	22.89	16.94	20.78	7.79
Beans	Okra	4.96	2.75	0.38	8.09	1.79	2.20	0.82
	Long Beans	6.28	10.59	0.48	17.35	8.14	9.98	3.74
	Four Angles Bean	1.63	2.70	0.13	4.45	5.80	7.11	2.66

Table 4.8, continued

Fruit	Cucumber	4.71	0.11	0.36	5.19	6.46	7.92	2.97
	Round Brinjal	8.67	7.92	0.67	17.27	8.45	10.36	3.88
	Bitter Gourd	2.31	0.05	0.18	2.54	8.39	10.29	3.86

Table 4.9: Annual ingestion dosage of vegetable samples compared to other nations' research and world limit

Countries	Annual Ingestion Dose A_{eff} (μSv y^{-1})	References
Turkey	227	(Korkmaz Görür et al., 2011)
Nigeria	270	(Jibiri et al., 2007)
Korea	110	(Choi et al., 2008)
Spain	360	(Cruz da Silva et al., 2020)
Brazil	500	(Silva et al., 2021)
Vietnam	387	(Thien et al., 2020)
WHO	250 - 400	(WHO, 2011)
Current Study	91.52	

4.7.1 Annual Ingestion Dose, A_{eff}

With reference to table 4.8, the highest annual ingestion dose is for Water Spinach which is 22.89 μSv $y^{-1,}$ and the lowest is in the Bitter Gourd, which is 2.54 μSv y^{-1}. The average worldwide A_{eff} from ^{226}Ra and ^{232}Th is 120 μSv y^{-1} and for ^{40}K is 170 μSv y^{-1}. The nine vegetable samples were taken from this study area are found to have much lower than the average world value(WHO, 2011). The comparison of the A_{eff} for ^{226}Ra, ^{232}Th and ^{40}K and the total A_{eff} is shown in Figure 4.10. The A_{eff} calculated in this study is compared with the values reported in other countries, as shown in Table 4.9. The total A_{eff} in this study is found to be lower than the values recommended 250 – 400 μSv y^{-1} as the report by WHO (WHO, 2011). The A_{eff} in this study is close to the same as that in Korea but lower in contrast to the

stated readings in Turkey, Spain, Brazil, Nigeria and Vietnam. The diversity in vegetable intake and the natural environment in different nations may be the cause of this value discrepancy. It may be stated that because the A_{eff} in the vegetable samples in this investigation is low, it is safe for the general public.

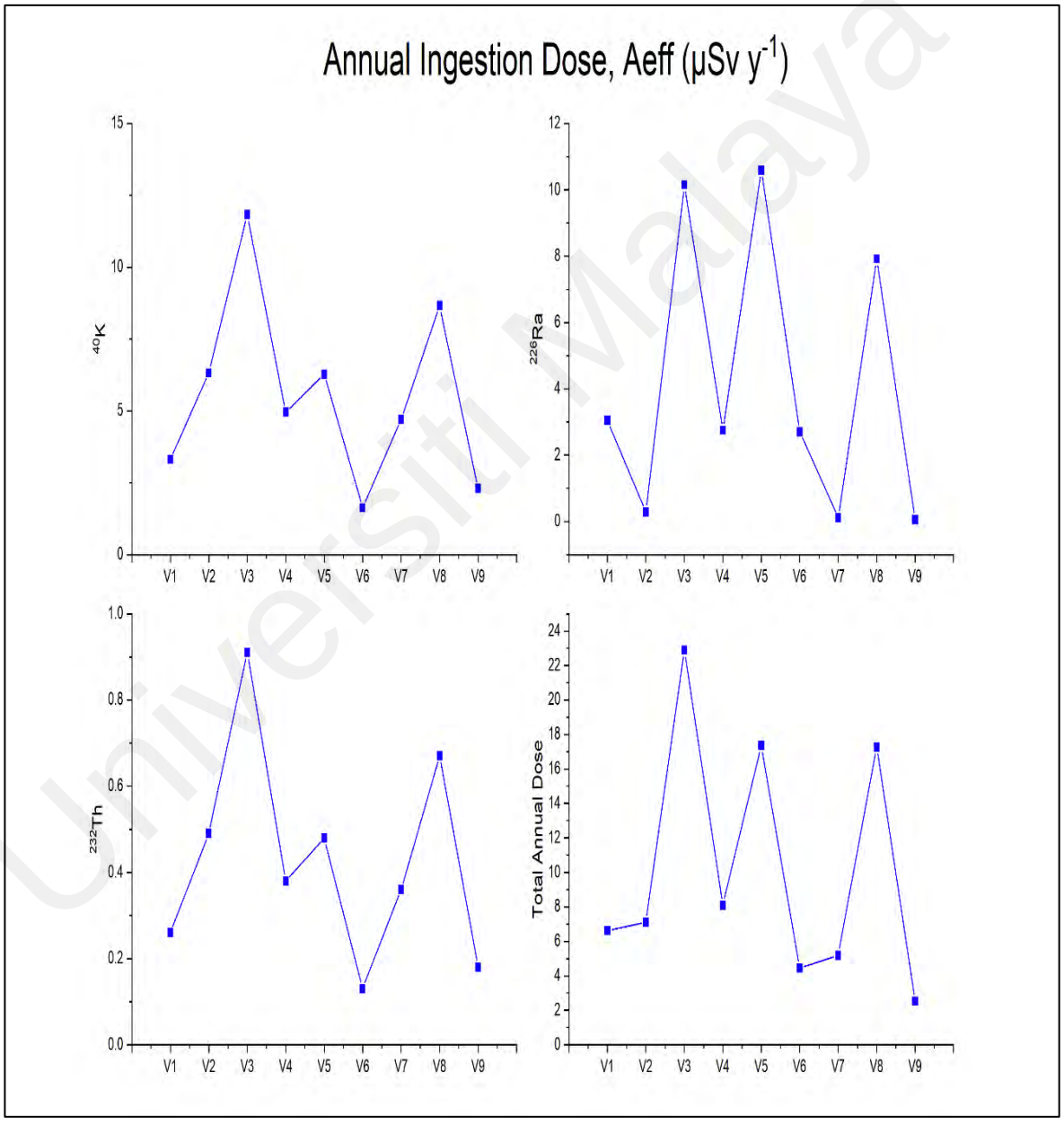

Figure 4.10: Annual Ingestion Dose, A_{eff} for vegetable samples.

4.7.2 Absorbed Dose Rate, D_N and Excess Lifetime Cancer Risk, ELCR

According to the calculated D_N in table 4.08, it is found that the highest D_N value is 16.94 nGy h^{-1} for water spinach, and the lowest is 1.75 nGy h^{-1} for Japanese Mustard. However, the D_N for all the vegetable samples is found to be lower than the recommended value by UNSCEAR (UNSCEAR, 2000), which is 55 nGy h^{-1}. The D_n for the vegetables are compared in Figure 4.11.

According to the statistic by The Global Cancer Observatory, WHO, 9.1% of the total population of Malaysian has a risk of dying from cancer before the age of 75%(Ferlay et al., 2021). Hence, it is important to evaluate the cancer risk due to the consumption of vegetables in this area.

As for the ELCR, it is noticeable from Table 4.8 that the highest ELCR value is 7.79×10^{-5} for water spinach, and the lowest value is 0.80×10^{-5} for Japanese Mustard. However, the ELCR values for all the vegetable samples are lower than the recommended value by UNSCEAR (UNSCEAR, 2000), which is 0.29×10^{-5}. This implies that vegetable grown in this area has a very low cancer risk. Eating fruits and vegetables can help reduce the risk of cancer. Moreover, eating more vegetables and fruits can also reduce the risk of developing obesity which indirectly contributes to lowering the risk of cancer (Rock et al., 2020). The evaluation of ELCR from consumption of vegetable in this study can help to encourage Malaysian to consume more vegetables for a healthier lifestyle.

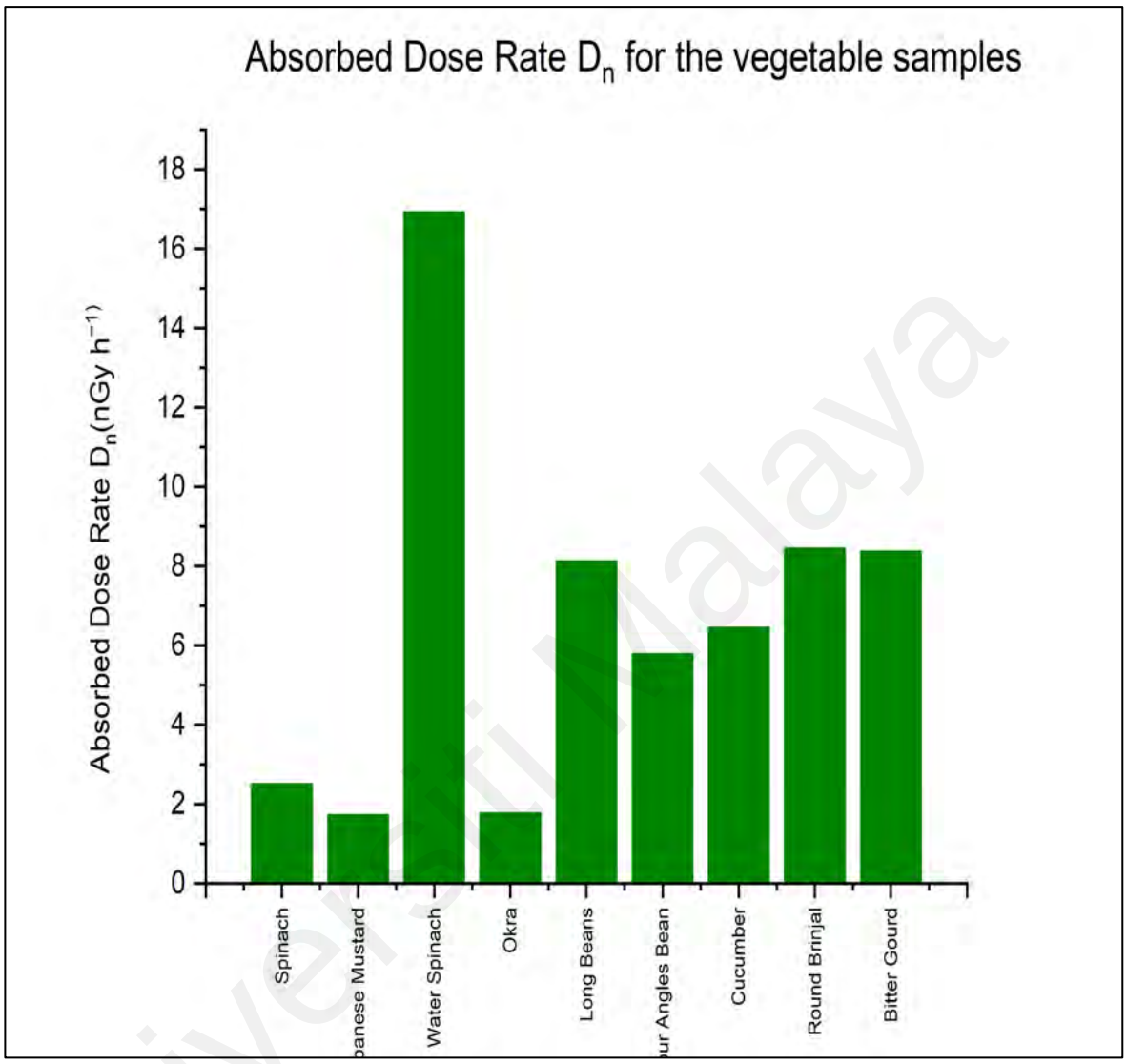

Figure 4.11: Absorbed Dose Rate D_n for the vegetable samples

4.8 ^{137}Cs Activity Concentration, Dose Rate, Annual Effective Dose Rate and Excess Lifetime Cancer Risk for soil samples

Table 4.10: Activity Concentration, Dose Rate, Annual Effective Dose Rate and Excess Lifetime Cancer Risk for soil samples.

Vegetable Farm	Soil Sample	Activity Concentration ($Bqkg^{-1}$)	Dose rate, D_R ($nGyh^{-1}$)	E_{eff} ($\mu Sv\ y^{-1}$)	ELCR $\times 10^{-5}$
Japanese Mustard	S1	3.21±0.17	0.10	11.8	4.45
Water Spinach	S2	0.56±0.17	0.02	2.06	0.77
Spinach	S3	0.55±0.17	0.02	2.02	0.76
Okra	S4	1.02±0.18	0.03	3.75	1.41
Long Bean	S5	0.88±0.18	0.03	3.24	1.22
Four Angles Bean	S6	0.34±0.09	0.01	1.25	0.47
Cucumber	S7	0.59±0.24	0.02	2.16	0.81
Brinjal	S8	1.87±0.17	0.06	6.88	2.58
Bitter Gourd	S9	0.37±0.09	0.01	1.37	0.51
	Mean	1.04±0.21	0.03	3.84	1.44

Soil samples S1 – S9 are taken from the respective vegetable farms presented in the Table 4.10. The activity concentration of ^{137}Cs in the vegetables sample was below the detection threshold. Hence the radiological hazards of ^{137} Cs were not able to determine in this analysis.

The data for ^{137}Cs in the agricultural soil samples gathered from vegetables farms located in the district of Klang, Selangor is given in Table 4.10 indicates significant variability. Activity concentration of ^{137}Cs in the soil varies from 0.34±0.09 to 3.21±0.17 $Bqkg^{-1}$. Dose

rate computed for the corresponding value of activity concentration ranged from 0.01 to 0.10 $nGyh^{-1}$. The soil sample, S6 has the lowest dose rate compared to soil sample S1.

The annual effective dose rate ranged between 1.25 to 11.8 μSv y^{-1}. These determined values are comparatively small when evaluated to the ICRP suggested yearly dose limit of 1.0 mSv and yearly external gamma radiation dose of 0.48 mSv y^{-1}, recommended by UNSCEAR (Cousins et al., 2011; UNSCEAR, 2000).

The values of ELCR ranged between 0.47×10^{-5} to 4.45×10^{-5} which is lower than the safety limit of 0.29×10^{-3}. The highest value of activity concentration and the rate contributed higher value to the annual effective dose rate and excess lifetime cancer risk as for soil sample S1.

These high results might be attributed to anthropogenic radionuclide fallout from earlier worldwide nuclear tests, as well as other nuclear mishaps like the FDNPP and Chernobyl disaster. Because of these nuclear activities, the ^{137}Cs discharged into the air and the fallout radionuclides gathers in the soil, particularly in the agricultural soil in this study.

Table 4.11. Comparison of the current results with data from other countries

Country	Activity Concentration (Bq kg^{1})	References
Turkey	171	(Celik et al., 2010)
Venezuela	5.0	(LaBrecque, 1994)
Bangladesh	7.0	(Miah et al., 1998)
Spain	35	(Gomez et al., 1997)
Egypt	10.4	(Higgy & Pimpl, 1998)
Pakistan	3.2	(Tahir et al., 2005)
USA	31.5	(Karakelle et al., 2002)
Yugoslavia	16	(Vukotić et al., 1998)
Sudan	9.3	(Sam et al., 1997)
Libya	1.3	(Shenber, 2001)
Saudi Arabia	1.0	(Al-Zahrani, 2001)
Taiwan	14.2	(Wang et al., 1997)
India	32.7	(Karunakara et al., 2001)
Indonesia	1.64	(Emlinarti & Buchari, 2003)
Tomioka, Fukushima, Japan	1200	(Kurokawa et al., 2019)
Chernobyl, Russia	284	(Scott, 2001)
Present Study	1.04	

The mean value of this study was compared with the mean value of ^{137}Cs presented in the literature for other countries presented in Table 4.11. The village of Tomioka in the Japanese prefecture of Fukushima had the highest activity concentration of ^{137}Cs. The sample, according to the researchers, was obtained in 2016 from a decontaminated agricultural region.(Kurokawa et al., 2019).

As a result, the elimination of ^{137}Cs-contaminated soils or the imposition of land use restrictions in regions in which elimination is impossible is a pressing matter. The Japanese government, the Japanese general public, and Japanese scientists have all been waiting for information regarding the spatial distributions of ^{137}Cs deposition and its contamination of the soil across the entirety of Japan.

The decontamination exercises were carried out by eliminating the polluted surface soil layer (0-5 cm depth), resurfacing the soil with granitic sand and mixing fresh soil with subsurface soil, the activity concentration of ^{137}Cs was reduced from 9100 Bqkg^{-1} to 1200 Bqkg^{-1}. Similar experiments were carried out 32 years after the Chernobyl nuclear power plant tragedy in the heavily polluted Plavsk radioactive hotspot in the Tula area of Central Russia.

In soil samples taken from an agricultural region, the activity concentration of ^{137}Cs ranges from 67 to 306. The mean value activity concentration in the current study is demonstrated to be among the lowest when compared to data from other regions of the world as well as standards established by the ICRP and UNSCEAR 2000 article. (Cousins et al., 2011; UNSCEAR, 2000).

CHAPTER 5: CONCLUSION

The AC of ^{226}Ra, ^{232}Th, and ^{40}K was determined in the peat soil and three types of vegetables, mainly leaf, beans, and fruits, from a farm located in the state of Selangor, Malaysia. This study's findings show a significant disparity and non-regular distribution in peat soil and vegetable samples for each natural radionuclide. It is essential to understand the behaviour of these natural radionuclides concerning mitigation and changes in soil metabolism, availability for the vegetable uptake, and human in time. The findings that were acquired from these investigations can be regarded as baseline data for total activity levels (TFs) of natural radionuclides in Malaysia. Additionally, they could provide as a guide for the future monitoring and evaluation of naturally occurring radioactive material (NORM) in agricultural soil. In order to take the appropriate radiological and dosimetric steps to decrease the adverse effects of ionising radiation, it is essential to have relevant information such as the distribution of naturally occurring radionuclides in soil and vegetation as well as the transfer ratio.

This experimental study on radionuclides ^{226}Ra, ^{232}Th and ^{40}K allows evaluating the soils' radiological hazards and highly consumed vegetables in the Klang, Selangor. For the hazards of the soils surrounding the vegetable samples, it is found that the Radiological Index Level I_γ surrounding the vegetable Four Angles Bean has a value of 1.18, higher than 1, the recommended value by the European Commission and Radiation Protection. However, both External and Internal Hazards show insignificant exposure to the farmers and the general public living in this area.

Data analysis of the radiological hazards due to the consumption of the vegetables grown in this area shows that the absorbed dose rate, annual effective dose equivalent, annual ingestion dose has an insignificant impact on the consumers and the general public. This study area exhibits a low lifetime risk of cancer due to exposure to natural radionuclides.

The value of ^{137}Cs activity concentration in the agricultural soil in the farm in Klang influenced by the FDNPP where the fallout is due to the atmospheric transport pathways. The activity concentration of ^{137}Cs was used to calculate the dose rate, annual effective dose rate and the excess lifetime cancer risk where it is seldom reported especially for agricultural soil in Malaysia. It was found that the exposure to the ^{137}Cs will not pose any radiological hazards to the general population. Continuous monitoring of the ^{137}Cs activity concentrations in both soil and it's transfer ratio into the vegetables grown in this area should be regularly conducted by the respective governmental agency to ensure the safety of the general population and consumers of these vegetables.

Further works should be focused on:

1. Other types of agricultural soils, such as clay, sand, silt, and loam, should be evaluated for radiological risks.
2. Hydroponic farming is gaining traction with the next generation of farmers. Radiological studies are required to determine the presence of potentially hazardous trace elements in the water supply used in hydroponic farming.
3. Farming in landfills is risky because the soil may include heavy metals and radioactive materials from inappropriate industrial disposal. The authorities should routinely examine radiological risks from the soil and its surroundings.
4. Agricultural land near nuclear reactors should be examined for radioactive risks from the soil and to humans consuming the farm's crops.

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