ACTIVITY LEVELS OF GAMMA RAY EMITTING RADIONUCLIDES IN FOOD CROP SAMPLES IN SELECTED TOBACCO FARMING AREAS IN ARUA AND MARACHA DISTRICTS

BY

ANGUANI EPIPHANY MIKE

A DISSERTATION SUBMITTED TO THE GRADUATE SCHOOL IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF
THE DEGREE OF MASTER OF SCIENCE IN PHYSICS OF

KYAMBOGO UNIVERSITY

DECEMBER, 2017

DECLARATION

I Anguani Epiphany Mike do hereby declare that this is a true record of my original work with respect to my research "The Activity Levels of Gamma Ray Emitting Radionuclides in Food Crop samples in selected Tobacco Farming Areas in Arua and Maracha Districts. The work has not been presented to any University for any academic award.

Signed: ....

Date: 08/12/2017

APPROVAL

This is to certify that this research by Anguani Epiphany Mike was carried out under our supervision. The research report is now ready for submission to the Board of Examiners and the Senate of Kyambogo University with our due approval.

Signed: ....

Supervisor 1: Dr. Jurua Edward

Associate Professor

Department of Physics

Mbarara University of Science and Technology

Date...08/12/2017......

Signed: ....

Supervisor 2: Mr. Oriada Richard

Senior Lecturer Department of Physics

Kyambogo University

Date: December 8th 2017

DEDICATION

To my parents Mr. Mayia Clement Buni (RIP) and Ms. Ayaru Joan (RIP).

ACKNOWLEDGEMENT

First and foremost my gratitude goes to my supervisors Assoc. Professor. Jurua Edward and Mr. Oriada Richard through whose constant guidance and criticism the selection of the researchable topic was possible and the writing of the research proposal and consequently the dissertation was successful.

I thank Hon. Wadri Kassiano Ezati the Member of Parliament of Terego constituency (2001 – 2016) who offered the scholarship for me to pursue this study; to him I am very much delighted.

I also thank the family of Dr. Driwale Alfred and Eng. Edema Robert who offered financial and moral support during the course of this study.

In a special way I thank all the staff members in the Physics Department, Kyambogo University, through whose guidance I was able to make it through in the graduate school.

I recognize the technical support offered to me by our Research methods lecturer Mr. Ben D.D Enjiku who toiled to ensure that we acquired the knowledge of research writing.

To my colleagues Mr. Rutahweire Silver and Mr. Arron Mugaiga who carried out similar researches in Radiation Physics, I am grateful for the exchange of ideas and material during this study.

To my farmers Mr. Atama Tom of Katrini, Mr. Nyara Henry of Bileafe, Mr. Acile William of Oriama, Mr. Aramia Dominic Emmanuel of Omugo, Mr. Adiga Kizito of Odupi, Mr.Ledra Job of Tara, Mr. Ciriga Siraji of Aii-vu and Mr. Ocima Ronald of Yivu and Nyadri sub counties who offered their time and allowed me to use their food crops as samples, to them I am very grateful.

Lastly but not least I wish to acknowledge all that my wife Ms. Ajiyo Stella did in tirelessly supporting the family when I was away for studies at the graduate school.

May the Almighty God bless all those who contributed in one way or the other to support the course of this research abundantly.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The farming activities, especially Tobacco production in Terego East and Terego West in Arua district and Maracha East County in Maracha district employ fertilizers such as NPK, DAP, CAN, TSP and UREA to enhance soil fertility property and to increase Tobacco production. Fertilizers are known to contain radionuclides such as uranium, radium, potassium etc., that originate from phosphate rocks; that could accumulate in the soil over the years and these may be absorbed by food crops grown on such soils. Humans who feed on these food crops may then absorb such radionuclides. As Human cells absorb radiation energy, molecules in them get damaged resulting into malfunction of cells through genetic mutation and this can then be a health risk.

In this study the specific activity levels of gamma ray emitting radionuclides in selected food crop samples (maize, rice, sorghum, cassava, ground nuts, beans and simsim), grown in soils contaminated by fertilizers was determined using Gamma ray spectroscopy technique, that uses NaI(Tl) detector. The samples were obtained from the six Sub Counties of Omugo, Aii-vu, Odupi, Oriama, Katrini and Bileafe in Arua District and three Sub Counties of Tara, Yivu and Nyadri in Maracha District. The sampling technique used was purposive and simple random. In summary, the mean specific activity levels of radium, thorium, uranium and potassium were 64.0 Bqkg^{-1}, 6.0 Bqkg^{-1}, 3.5 Bqkg^{-1} and 185.1 Bqkg^{-1} respectively, in the crop samples considered. The mean specific activity levels for potassium was the highest, followed by radium, thorium and the least level shown by uranium. The mean absorbed dose rate was 40.9 nGy/h and the mean annual effective dose rate was 0.1 mSv/yr., for all the crop samples considered. The mean annual effective dose rate for all crop samples determined in this study were within the range recommended by the International Atomic Energy Agency as having no observable effects in the human body. Therefore it is recommended that consumption of the food crops investigated should continue as it poses no potential radiation hazard. It is further recommended that investigation should be performed on other crops which are not investigated in this study.

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

All heavy elements with Z greater or equal to 83 ($Z \geq 83$) found in nature are radioactive and decay by emission of alpha (α) and beta (β) particles and gamma rays into successive radioactive daughters forming a series of radionuclides that terminate when a stable daughter is produced (Mayer,1906). All Naturally Occurring heavy Radionuclide Materials (NORM) belong to one of the following three decay series in which they may give up energetic radiations:

(i) The Uranium, U-series, begins with ^{238}U and ends with stable ^{206}Pb.

(ii) Thorium, Th-series, which begins with ^{232}Th and ends with ^{208}Pb.

(iii) Actinium series, this begins with ^{235}U and ends with stable ^{207}Pb.

The three decay series give up a wide range of energies that form electromagnetic band of radiation. Radiation describes a process in which energetic particles or waves travel through a medium or space (Harb, 2004). Radiation is classified into two main classes depending on their ability to ionize matter. The two main classes are non-ionising and ionising radiation (IAEA, 2004). These are briefly discussed in the following subsections.

1.1.1 Non - Ionising Radiation

Non ionizing radiation has enough energy that can cause electrons to vibrate within a molecule, but this energy is not enough to remove the electrons completely from matter, they therefore cannot ionize matter because they have very low energy (IAEA, 2004). Instead of producing charged ions when passing through matter, their energy is only sufficient enough to change vibrational and rotational energies of molecules and atoms. Non-ionizing radiation ranges from extremely low frequency radiation in audible wave, microwave and visible portions of the electromagnetic spectrum to the ultraviolet range (IAEA, 2004).

1.1.2 Ionizing Radiation

Radiation that falls within the "ionizing radiation" range has enough energy to remove loosely bound electrons from atoms, thus creating ions. Ionizing radiation is capable of removing electrons from molecules either directly or indirectly (IAEA, 2004), i.e. their energy exceeds the ionization potential of matter. The minimum energy required to ionize an atom ranges from a few electron volts (eV) for alkaline elements to 24eV for helium. X-rays and gamma rays have enough energy to break chemical bonds and are at the upper end of ionising radiation (IAEA, 2004).

During ionization, electrons break away from the atoms. This process results into the formation of two charged particles or ions: a molecule with a net positive charge and a free electron with a negative charge (IAEA, 2003). Particles like electrons, protons and alpha particles are directly ionizing radiation and they deposit energy in the medium through direct coulomb interactions between the direct ionizing charged particles and the orbital electrons in the medium (Randolph, 1996).

Indirectly ionizing radiation such as X-rays and γ-rays deposit energy in the medium in a two-step process:

(i) A charged particle is released in the medium (photons release electrons or positrons and neutrons release protons or heavier ions)

(ii) The released charged particles deposit energy in the medium through direct coulomb interactions with the orbital electrons of the atoms in the medium.(US EPA, 2012)

1.1.3 Sources of Ionizing Radiation

Ionising radiation sources are categorized as Natural and manmade radiation sources, (USNRC, 2014). These are briefly discussed below.

(a) Natural Radiation

There are many natural sources of radiation which have been present since the earth was formed.

The three major sources of naturally occurring radiation are:

(i) **Cosmic radiation**; comes from the sun and outer space, and consists of positively charged particles, as well as gamma radiation. At sea level, the average cosmic radiation dose is about 0.26 mSv per year. At higher altitudes the amount of atmosphere shielding cosmic rays decreases and thus the dose increases (IAEA, 2003). As the earth moves through space it is bombarded by high-energy particles and gamma rays, which add to the background radiation. The earth's atmosphere acts as a shield, absorbing much of the energy from cosmic radiation (Alan at. el 1996).

(ii) **Terrestrial radiation sources**; these include naturally occurring radioactive materials that exist in rocks and soil. The main contributors are the radioactive isotopes that are products of the decay of uranium, thorium and potassium (Alan at. el, 1996). Naturally occurring radioactive materials (NORM) in soil is one of the main components of external gamma-ray exposure to which the public is exposed regularly. Natural environmental radioactivity and the associated external exposure due to gamma radiation depend primarily on the geological and geographical conditions and exist at different levels in the soils of each region in the world (IAEA, 2004).

(iii) **Internal Radiation**; this comes from radioactive materials that exist naturally in the human body. Isotopes of potassium and carbon are the primary sources of internal radiation exposures. Potassium is an essential mineral for life. The Potassium-40 isotope (0.01 percent of all potassium) is naturally radioactive. Carbon makes up about 23 percent, by weight, of the human body. Cosmic radiation creates radioactive Carbon-14, which is an even smaller percentage of all carbon. Potassium and carbon enter the body through the food chain. The average American receives a dose of about 0.4 mSv per year from internal radiation

(b) Man-made Sources (Artificial sources)

The difference between man-made sources of radiation and naturally occurring sources is the source from which the radiation originates (IAEA, 2003). The following information briefly describes some examples of man-made radiation sources.

(i) **Fertilizer**

Commercial fertilizers are designed to provide various concentration levels of potassium, phosphorous, and nitrogen to soils and food crops in order to achieve high production. Such fertilizers can be measurably radioactive for two reasons: potassium is naturally radioactive, and the phosphorous can be derived from phosphate ore that contains elevated levels of uranium and radium. Plant nutrient uptake from the soil may involve these radionuclides introduced through the use of fertilizers. The amount of radioactivity incorporated into the plants is low and does not harm the plant, although this may be a threat to humans (HPS, 2014),

(ii) **Food**

Food contains a variety of different types and amounts of naturally occurring radioactive materials. Since radioactive materials occur everywhere in nature it is inevitable that they get into drinking water and food, giving a global yearly average dose of 0.23 mSv (IAEA, 2014). Where such food samples serve as seeds to be planted, then this may significantly have a multiplying effect on the radionuclides to be introduced to human food chain (EPA, 2013). Potassium-40 in particular is a major source of internal irradiation, but there are others such as uranium, thorium, radium etc. Some foods, for example shellfish and Brazil nuts, concentrate radioactive materials so that, people who consume large quantities receive a radiation dose significantly above average (IAEA, 2014)

(c) Cosmogenic radiation sources

Other naturally occurring radionuclides are of cosmogenic origin. These radioisotopes exist as carbondioxide gas (CO_2) in the atmosphere and are used by plants and become fixed in their structures through photosynthesis. These radionuclides can also be introduced in to the soil through farming activities which practically employ the use of commercial phosphate fertilizers (Akira et al., 2004).

Because of the long-continued application of these inorganic fertilizers, these heavy metals and the radionuclides are being added in the soil and could accumulate in it thereby increasing the soil contaminant levels (Akira et al., 2004). However several lighter elements have naturally occurring radio isotopes such as ^{40}K and ^{14}C which are sources of human internal and external radiation exposure. Potassium and Carbon are constituents of animals and plants which are sources of food to mankind (IAEA, 2003).

In Uganda, agriculture is the backbone of the economy constituting about 80% of the Gross Domestic Product (GDP) in which farmers usually rear animals and grow both cash crops and food crops.

In West Nile region the major cash crop grown is tobacco. Farmers employ commercial inorganic phosphate fertilizers to improve the production of the crop and to enhance soil properties such as fertility, acidity alkalinity etc. Commercial inorganic phosphate fertilizers are known to contain heavy metallic elements such as Cadmium (Cd), Chromium (Cr) and Lead (Pb) and radioactive elements such as ^{238}U, ^{232}Th, ^{40}K and their daughters, which are considered hazardous not only to humans but also to animal health (Jasinski, 2007 and Kauwenbergh, 1997, Schung, 2005; IAEA, 2003; El-Mrabet et al., 2003).

During the past seven decades (1932-2010), Tobacco farming in the two Counties of Terego and Maracha found in the West Nile region has widely expanded causing an escalation in the application of commercial inorganic fertilizers, pesticides and other agricultural chemicals to enhance soil properties such as fertility, PH etc. and to increase tobacco production.

In practice, after harvesting the tobacco, farmers plant both short and long term food crops such as simsim, cassava, groundnuts, millet, sorghum etc. in the field that same farming season or the following seasons. This implies that the crops are likely to have an uptake of these radionuclides which would have accumulated in the soil due to the application of the fertilizers, thus introducing the radionuclides to man's food chain (Mortvedt and Sikora, 1992; Koomblekou and Tabatabai, 1994).

The contaminants accumulation in the soil due to long-continued cultivation of tobacco will much depend on the concentrations of the contaminants in fertilizers, the annual application rate of fertilizers, physical and chemical properties of the soil and to some extend the geochemical properties of the contaminants themselves (Brigden et al., 2002). However the soil contaminants are not only introduced into the soil by farming practices and photosynthesis process, but also through natural radioactivity which is widely spread in the earth's environment. This type of radiation exist in soils, plants, water, air and even in human body and it originates from terrestrial and extraterrestrial radiations (Abdel-Haleem et al., 2001). Therefore the addition of radionuclides to soil increases the activity of Uranium (U), Thorium (Th), and Potassium (^{40}K). Some of these heavy metals and radionuclides may be leached out into ground water that drains from these fields or transferred via the food chain to humans causing radiation related diseases like cancer, cataracts, sterility, which are a threat to the human population leaving in these areas (Abdel-Haleem et al., 2001).

1.2 Problem Statement

The earth and its atmosphere are naturally enveloped in ionizing radiation. Despite this, human activities such as industrialization and commercial farming practices are also known to have contributed relatively high levels of ionizing radiation to our environment. Ionizing radiation is harmful to human health as it can penetrate matter and adversely affect the biophysical and biological processes in the living tissues, (USNRC, 2014).

In the past decades, tobacco farming has expanded widely in the areas of Terego and Maracha Counties with the consequence of increased use of inorganic phosphate fertilizers, pesticides and other agricultural chemicals. These inorganic phosphate fertilizers and agricultural chemicals are known to contain heavy metals such as cadmium (Cd), chromium (Cr) and Lead (Pb) and radioactive elements such as ^{238}U, ^{232}Th, ^{40}K and their daughters (Abrahams, 2002). The accumulation of these in the soil over the years may cause it to be introduced into the man's food chain as the food crops absorb them as source of nutrients. This can then be a health risk to communities consuming such food crops grown in soils contaminated with natural radionuclides (Abrahams, 2002). Therefore it was necessary to carry out this study.

1.3 Purpose of the Study

To determine specific activity levels of gamma ray emitting radionuclides in selected food crop samples grown in tobacco farming areas of Terego and Maracha Counties.

1.4 Objectives of the Study

The objectives of the study were to:

(i) Identify the gamma ray emitting elements in Simsim, Cassava, Beans, Maize, Groundnuts, Rice and Sorghum crop samples grown in tobacco farming areas.

(ii) To determine the Specific Activity (S.A) of each of radionuclides found in the food crop samples grown in post tobacco farming fields.

(iii)To determine the dose levels (Absorbed dose rates and Annual effective dose rates) of the radionuclides found present in all the crop samples grown in different areas within the counties.

1.5 Scope of the Study

The study area covered the six sub-counties of Odupi, Omugo, Aii-vu, Oriama, Bileafe and Katrini all in Terego County and three Sub Counties of Tara, Yivu and Nyadri all in Maracha County. These areas were chosen because the level of the use of fertilizers in them during Tobacco farming was assumed to be high which is evidenced by a good number of curing bans in these areas.

The study was limited to three objectives:
It involved the collection of food crops such as Simsim, Beans, Maize, Cassava, Rice, Sorghum and Groundnuts within randomly selected areas depending on their availability. The crop samples were collected from 5th to 10th of January 2014. These crops were chosen since they form part of the staple foods for the indigenous people and are widely consumed in the country.
However the study had the following limitation:
Obtaining the samples from the farmers was not easy as many did not get the purpose of collecting the crop samples from them and so this made the number of each sample collected not to be representative enough in all the sub counties considered. Activity levels in the most common fertilizers such as Nitrogen Phosphorus and Potassium (NPK), Tri

Supper Phosphate (TSP), UREA, Calcium Ammonium Nitrate (CAN) and Di Ammonium Phosphate (DAP) used by the farmers were not measured to compare findings.

1.6 Significance of the Study

The study was important to determine the specific activity levels and the dose rates in humans consuming the food crops grown in such soils contaminated with gamma ray emitting radionuclides from inorganic phosphate fertilizers by Uganda Atomic Energy Council (UAEC).

The results of this study may be used by Uganda National Bureau of Standard (UNBS) to regulate the excessive use of inorganic phosphate fertilizers.

The study on the specific activity levels of radionuclides in food crop samples due to the use of inorganic phosphate fertilizers can act as guide for government of Uganda to draft policies.

The results of the study may also be used as a base line survey for subsequent related studies.

CHAPTER TWO: THEORY AND REVIEW OF RELATED LITERATURE

2.1 Introduction

This chapter covers the theory of the Gamma ray spectroscopy and review of the related literature. Gamma ray spectrometry is an analytical method that allows the identification and quantification of gamma emitting isotopes in a variety of matrices. In a single measurement, the gamma ray spectrometry allows one to detect several gamma rays emitting radio nuclei in the sample. The measurement gives a spectrum of lines whose amplitude is proportional to the activity of the radionuclide and its position on the horizontal axis gives an idea on its energy (Nafaa, 2006).

2.2 Gamma Ray Spectroscopy

Gamma rays may be treated either as electromagnetic waves or as particles called photons. An electromagnetic wave is characterized by its wave length λ or frequency υ. A photon is a particle having zero charge and zero rest mass, travelling with the speed of light ($3.0\times10^{8}ms^{-1}$) and having energy, $E = h\upsilon$, where h is plank's constant. The wave properties of a photon are used for low-energy measurements only. In all other cases, detection of photons is based on their interactions as particles with matter (Lemeriga, 1998).

Gamma ray spectroscopy systems can be divided into two classes according to whether they use Single- Channel Analyzers (SCAs) or Multichannel Analyzers (MCAs). Both systems begin with a detector, where the gamma ray interaction produces a weak electrical signal that is proportional to the deposited energy (Parker, 2006).The following subsections discuss the major components of a gamma ray spectrometer.

2.2.1 The High Voltage (HV) Bias Supply

Most of the commonly used gamma ray detectors require a high voltage bias supply to provide the electric field that collects the charge generated by gamma-ray interaction in the detector. This is necessary to achieve voltage resolution and low-frequency filtering requirements. It provides a positive or negative voltage required to run the detector system.

Input AC voltage of 230V and output dc voltage in range of +/-15V with current of 500 mA is quite sufficient for this purpose (Matteknik, 1995).

Bias supplies for germanium and silicon detectors usually provide up to 5 kV and 100 μ A. The voltage-resolution and low-frequency filtering requirements are modest because there is no charge amplification in the detector. Battery packs are sometimes used as bias supplies for germanium and silicon detectors because they are portable and do not generate noise. The bias supply requirements for photomultiplier tubes used with scintillation detectors are more stringent than for solid-state diode detectors. The required voltage is typically a few thousand volts, but the required current is usually from 1 to 10 mA. Because the gain of a photomultiplier is a very strong function of the applied voltage, the stability and filtering must be excellent. Bias supplies come in a variety of packages, the common being Nuclear Instrumentation Module (NIM) which plugs in to a frame that supplies the DC voltages to the power module while other bias supplies fit in NIM bins but take power from the normal AC source. It is important to note that detector bias supplies can be lethal (Parker, 2006).

2.2.2 The Detector

The sensitive part of the detector is the Scintillator, which consists of a cylindrical NaI (Tl) crystal with a diameter of 7.5 cm and a height of 7.5 cm. The incoming gamma quanta deposit all their energy, or part of it, to the electrons in the crystal due to collisions (Compton Effect) or photo electric effect. The resulting fast moving electrons collide with the atoms of the crystal, which are excited and subsequently de-excited by emitting photons with a wave length in the region of the visible light. The photons reach the photo cathode of a photo multiplier tube (PM tube), which is optically coupled to the crystal. Here the photons will cause the emission of electrons through the photoelectric effect, whose number is proportional to the energy of the gamma radiation. The electrons are accelerated in the PM tube towards a structure of metal plates (dynodes). The potential difference between each consecutive dynode is about 75 V. The resulting shower of electrons give rise to an electric pulse, of which the amplitude is directly proportional to the amount of light collected on the photo cathode, and thus directly proportional to the energy of the gamma radiation. By measuring the amplitude, the energy of the corresponding gamma quanta can be determined (Matteknik, 1995).

2.2.3 Preamplifier

Preamplifiers are required for germanium and silicon detectors and to improve the performance of NaI scintillation detectors. The detector output signal is usually a low amplitude, short-duration current pulse (typically 10 mV high and 200 ns long). The preamplifier converts this current pulse to a voltage pulse whose amplitude is proportional to the energy deposited in the detector during the gamma ray interactions (Akhtar, 2006). To minimize the signal-to-noise ratio of the output pulse and to preserve the gamma ray energy information, the preamplifier must be placed close to the detector as possible. This minimizes the capacitance at the preamplifier input thereby reducing the output noise level. For single NaI detectors, the preamplifier is often built into a cylindrical housing that holds the photomultiplier tube socket. The preamplifier output pulse is a fast positive or negative step followed by a very slow decay (Adams and Dams, 1970). The amplitude of the fast step is proportional to the charge delivered to the preamplifier input and therefore proportional to the energy deposited in the detector by the gamma ray. The long decay time means that a second pulse often occurs before the tail of the preceding pulse has decayed (Price, 1964).

2.2.4 Amplifier

After leaving the preamplifier, the gamma-ray pulses are amplified and shaped to meet the requirements of the pulse-height- analysis instrumentation that follows the main amplifier. Most spectroscopy-grade amplifiers are single or double NIM modules. Portable MCAs often have a built-in amplifier, which may be adequate for the intended application. The amplifier accepts the low-voltage pulse from the preamplifier and amplifies it into a linear range of 0 to 10 V for most high-quality amplifiers. The maximum output voltage or saturation voltage of most amplifiers is approximately 12V, but the amplifier gain can be adjusted over a wide range, typically 10 to 500 using the two gain controls (coarse and fine) to allow continuous gain adjustments (Nafaa, 2006). The shaping function of the amplifier is vital to the production of high-quality spectra, which then optimizes the signal-to-noise ratio and meets the pulse-shape requirements of the pulse-height-analysis electronics. A typical pulse- type detector signal is as shown in Figure 2.1 (Akhtar, 2006).

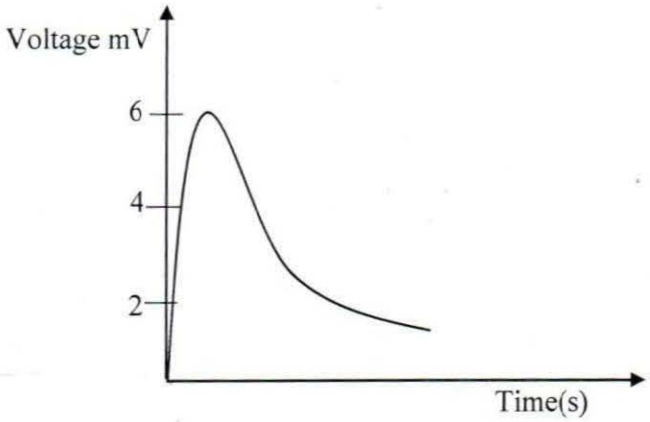

Figure 2.1 A typical pule-type detector signal (Akhtar, 2006)

Because single-channel and multichannel analyzers measure the input pulse amplitude with respect to an internal reference voltage as a function of time. Figure 2.1, shows voltage-time characteristic, in which the amplifier output must return quickly to a stable voltage level, usually zero between gamma ray pulses. The stability of the baseline voltage is extremely important because any baseline fluctuation perturbs the measurement of the gamma ray pulse amplitude and contributes to the broadening of the full-energy peak (Akhtar, 2006).

2.2.5 The Discriminator or Single Channel Analyzer (SCA)

The single channel analyzer is used to eliminate electronic noise and in general to reject unwanted pulses. When a pulse is amplified, the electronic noise that is always present in a circuit is also amplified and so if one attempt to count all the pulses present, the counting rate may be exceedingly high. If the voltage of the amplifier output pulse exceeds the discriminator threshold, the discriminator emits a logic pulse. The logic pulses are used for counting control functions and have fixed amplitude and width, usually 5V and 1 μ s in spectroscopy equipment. Therefore an SCA is essentially a two discriminator system with two independent thresholds of Lower Level Discriminator (LLD) and Upper Level Discriminator (ULD) (Lemeriga, 1998).

2.2.6 Counters, Timers and Rate meters

The counter/timer is the simplest part of the spectroscopy system; its function is to count the SCA output logic pulses. Modern counters operate at maximum count rates of approximately 2×10^7 counts/s and can count two pulses separated by as little as 50 ns. Many counters provide an overflow logic pulse to indicate when the count capacity is exceeded.

The term timer is usually applied to a separate instrument that measures time and can turn on one or more counters for a selected time interval. Timers are counters that count a fixed frequency oscillator to determine the desired time interval. Many counter/timer combinations can either count for a preset time or measure the time required to count a preset number of counts; the latter mode allows all measurements to have the same statistical precision (Adams and Dams, 1970).

A rate meter measures the average pulse rate of the signal applied to its input and may be used in place of, or in conjunction with, a counter. Modern rate meters may be either analog or digital instruments. A digital rate meter is a counter/timer that automatically resets and repeats a count; the count time is often set to 1s so that the digital display shows the number of counts per second. The visual display of a digital rate meter is far more readable than the meter display of an analog rate meter. A digital rate meter is often used to measure the total rate of gamma ray pulses coming from the system amplifier and because the total count rate has an important effect on system performance, the count rate is often monitored continuously (Akhtar, 2006)

2.2.7 Multichannel Analyzer (MCA)

The terms Multichannel Analyzer (MCA) and Pulse- Height Analyzer (PHA) are often used interchangeably in spectroscopy. The multichannel analyzer consists basically of an analogto-digital converter (ADC), control logic, memory and display (Nafaa, 2006). The MCA can operate in several modes, including pulse-height analysis, voltage sampling and multichannel scaling. It sorts and collects the gamma ray pulses coming from the amplifier to build a digital and visual representation of the pulse-height spectrum produced by the detector (Randolph, 1996).

2.2.8 Analog-to-Digital Converter

The Analog to Digital Converter (ADC) performs the fundamental pulse height analysis and is located at the MCA input. The ADC input is the analog voltage pulse from the main amplifier; its output is a binary number that is proportional to the amplitude of the input pulse and this binary output is called the address. The ADC accepts pulses in a given voltage rage, usually 0 to 8 or 10 V, and sorts them into a large number of continuous, equal-width voltage bins or channels. The number of channels into which the voltage range is divided is usually a power of 2 and is called the ADC conversion gain. The required conversion gain varies with detector type and with the energy range being examined (Nafaa, 2006).

The ADC sorts the amplifier output pulses according to voltage; the voltage is proportional to the energy deposited in the detector during the gamma ray interaction. Like the relationship between voltage and energy, the relationship between channel number and energy is linear, and is given by the equation

$$E = mX + b \qquad 2.1$$

Where E is energy in keV, X is channel number, m is slope in keV/channel, b is intercept in keV.

The slope depends on the conversion gain and amplification gain; common values are 0.05 to 1.0 keV/channel. The slope and intercept can be adjusted to fit the energy range of interest into the desired channel range. Most ADCs have both analog and digital controls to adjust the intercept. Because preamplifiers, amplifiers and ADCs are not exactly linear, the relationship shown by Equation 2.1 is not exact. However, with good equipment, gamma ray energies can be readily measured to a tenth of a keV by assuming a linear calibration. ADC linearity is usually specified in terms of integral and differential linearity. A common ADC problem that can influence the quality of results is a slow increase of the differential nonlinearity over time (Akhtar, 2006).

2.2.9 Pulse Shaping

The pulse produced at the output of radiation detector has to be modified or shaped for better performance of the counting system. This is done basically for three reasons:

(i) To prevent overlap. Each pulse should last for as short a period of time as possible and then its effect abolished so that the system is ready for the next pulse. Without pulse shaping, the detector signal will last so long that pulses overlap. If only the number of particles is counted, then pulse overlap leads to loss of counts called dead time loss and this occurrence worsens the resolution of the spectroscopy

(ii) To improve the signal-to-noise ratio. Noise created in the detector and the early amplification stages accompanies the detector signal. Appropriate pulse shaping can enhance the signal and at the same time reduce noise. Thus, the signal-to-noise ratio will improve, which in turn gives a better energy resolution.

(iii)For special pulse manipulation. The detector pulse, in certain applications, need special pulse shaping to satisfy the needs of certain units of counting system as seen in the function of the memory chip of a MCA (Lemeriga, 1998).

2.2.10 Timing

The term timing refers to the determination of the time of arrival of a pulse. In experiments, timing is used to measure the time-development of an event (e.g. measurement of the decay of radioactive elements like Thorium). Timing methods are characterized as "fast" or "slow" depending on the way the signal is derived. Fast timing signals are based on unshaped pulse in the "time-development" of the pulse. Slow timing signals are generated by an integral discriminator or a timing single channel analyzer. In either case, timing is obtained by using a shaped signal at the output of an amplifier (Akhtar, 2006).

2.3 Scintillators

These are materials (solid, liquid or gases) that produce sparks or scintillations of light when ionizing radiation passes through them. The amount of light produced in the Scintillator is very small and is usually amplified before it can be recorded as a pulse. The amplification of the scintillation light is achieved by means of photomultiplier tube (or phototube). The function of a photomultiplier is to accept a small amount of light, amplify it many times and delivers a strong pulse at its output (Lemeriga, 1998). The operation of a scintillation counter may be subdivided into two broad steps:

a) Absorption of incident radiation energy by the Scintillator and production of photons in the visible part of electromagnetic spectrum.

b) Amplification of the light by photomultiplier tube and production of the output pulse (Lemeriga, 1998).

2.3.1 Types of Scintillators

(i) Inorganic Scintillators

(ii) Organic Scintillators

(iii) Gaseous Scintillators

In this study an inorganic Scintillator was used.

2.3.2 Inorganic Scintillators (Crystal Scintillators)

Most inorganic Scintillators are crystals of alkali metal iodides containing small amounts of an impurity. Examples include NaI (Tl), Cs (Tl), CaI (Na), and LiI (Eu). The elements in the parentheses are the impurity or activator. The activator is the agent that gives luminescence of the crystal during the scintillation process. The block detection system using a Scintillator is shown in Figure 2.2.

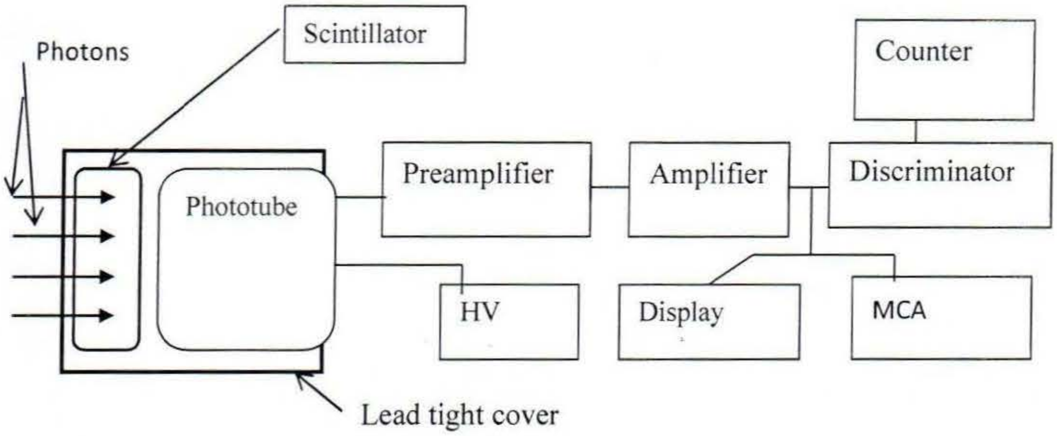

Figure 2.2: A Scintillator detection system (Lemeriga, 1998)

2.3.3 The Mechanism of the Scintillation Process

The mechanism of inorganic Scintillators can be explained in terms of allowed and forbidden energy bands of a crystal. The electronic energy states of an atom are discrete energy levels

(Bohr Theory) represented by discrete lines in the energy level diagram shown in Figure 2.3

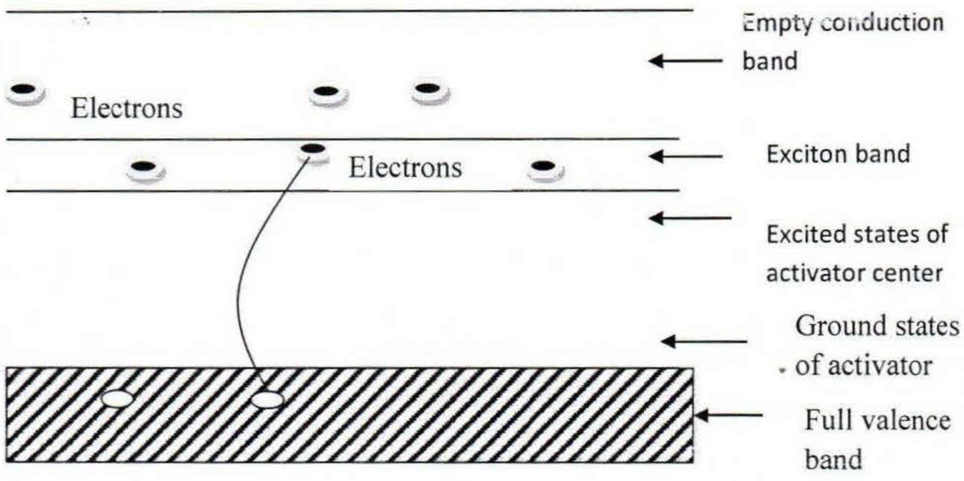

Figure 2.3: Allowed and forbidden discrete energy levels in a crystal

In a ground state, the valence band is fully filled with electrons while the conduction band is empty of electrons as shown in Figure 2.3. When an incident radiation falls on an electron in the valence band, the electron may obtain enough energy to move from the valence band to the conduction band, a process known as excitation. Once the electron is in the conduction band it is free to move anywhere in the lattice of the crystal. In terms of energy states, the excitation band corresponds to elevation of an electron to higher energy states than in the valence band but lower than that of the conduction band leading to the formation of a thin band of exciton states (Randolph, 1996). The width of the exciton band is typically of the order of 1 eV, while the gap between valence and conduction bands is of the order of 8 eV. Energy states may also be created between the valence and conduction bands by the crystal impurities, most important is the energy state created by Thallium activator. The activator atom may exist in a ground state or in one of the excited states. The transition of the impurity atom from the excited state to the ground state, results in the emission of a photon in times of the order of 10^{-8} seconds. If this photon has a wavelength in the visible part of the electromagnetic spectrum, it contributes to scintillation. Thus, production of scintillation takes the following steps:

(i) Ionizing radiation passes through the crystal.
(ii) Electrons are raised to the conduction band.
(iii) Holes are created in the valence band.
(iv) Excitons are formed.
(v) Activation centers are raised to the excited states by absorbing electrons.
(vi) De-excitation is followed by the emission of a photon.

The light emitted by a Scintillator is primarily the result of transitions of the activator atoms and not the crystal. For NaI (Tl) Scintillator, about 12% of the incident energy appears as Thallium luminescence. The magnitude of the light output and wavelength of the emitted light are two important properties of any Scintillators (Lemeriga, 1998)

2.3.4 The Properties of NaI (Tl) Crystal

NaI (Tl) is the most commonly used Scintillator for gamma rays. The crystal has a density of 3.67×10^{3}kg m^{-3} and high atomic number which give it a high efficiency as gamma ray detector. The emission spectra of NaI (Tl) peaks at 410 nm and the light- conversion efficiency is the highest compared to other inorganic Scintillators. The crystal has the disadvantages of being brittle and sensitive to temperature changes, which makes it susceptible to thermal shocks. It always contains a small amount of radioactive potassium, ^{40}K, which creates certain background radiation (Nafaa, 2006)

2.3.5 Radioactivity

Some nuclei spontaneously transform (decay) in to new nuclei by emitting particles. The particles emitted can be alpha (Helium nuclei) or beta (electrons) which may occur by electron capture, where the K-electron of the mother nucleus together with a proton is transformed to a neutron. In radioactive decay the product nuclei often also emit electromagnetic radiation of very high frequency called gamma radiation (Howard, 1963). Therefore, radioactive decay, also known as nuclear decay is a phenomenon in which a nucleus of an unstable atom loses energy by emitting particles of alpha, beta and gamma ray in form of radiation until stable daughter nuclide is formed. The different types of radioactive decay mode are briefly discussed in the following text.

(i) Alpha Decay

This occurs when the nucleus ejects an alpha particle (helium nucleus). This is the most common process of emitting nucleons. Most heavy nuclei where $82\leq Z \leq 92$, decay by emission of an α-particle in which the parent radionuclide loses mass and charge. The α-particle is a helium nucleus of mass number 4 and atomic number 2 represented as ${}^{4}_{2}He$

The Parent radionuclide X decays to nuclide Y when it emits an α-particle according to the Equation:

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha + \gamma \qquad 2.2$$

(ii) Beta Decay

Nuclides which have too many neutrons relative to the number of protons disintegrate by beta decay, i.e. they emit beta particles which are ordinary electrons. This occurs when the nucleus emits an electron or positron and a type of neutrino, in a process that changes a proton to a neutron. The nucleus may capture an orbiting electron, converting a proton into a neutron (electron capture). All of these processes result in nuclear transmutation. A Beta decay takes two forms, β^--particle (electron) and β^+-particle (positron) decays. These beta decay modes are represented by equations 2.3 and 2.4 respectively.

$$ {}_{0}^{1}n \to {}_{1}^{1}P + {}_{-1}^{0}\beta + \bar{\nu}_e \qquad 2.3 $$

$$ {}_{Z}^{A}X \to {}_{Z+1}^{A} + {}_{-1}^{0}\beta + \gamma + \bar{\nu}_e \qquad 2.4 $$

The γ-term allows for the possibility that the daughter nucleus will be formed in an excited state, while some transitions may directly go to the ground state. The energies of the α-particle and γ-ray are discrete and well defined where as that of the β^-- particle is continuous due to the varying amounts of energy taken by the electron anti-neutrino.

In this case, a proton in the nucleus is converted into a neutron, positron and an electron neutrino. The positron decay equation is represented as

$$ {}_{Z}^{A}X \to {}_{Z-1}^{A}Y + {}_{1}^{0}\beta + \gamma + \nu_e \qquad 2.5 $$

(iii) Gamma-Ray (γ) Decay

One or more gamma photons can be emitted from the excited states of daughter nuclei following radioactive decay. Transitions that result in gamma emission leave *Z* and *A* unchanged. The gamma-ray spectrum from a radionuclide is discrete. Furthermore, just as optical spectra are characteristic of the chemical elements, a gamma-ray spectrum is characteristic of the particular radionuclides that are present in a sample. By techniques of gamma-ray spectroscopy, the intensities of photons at various energies can be measured to determine the distribution of radionuclides in a sample (Adams and Dams, 1970).

2.3.6 Decay scheme

A decay scheme is an energy diagram of the decay. It normally includes notations of the mother nucleus (decaying nucleus), the daughter nucleus (resulting nucleus), type of decay, decay paths and their respective percentage distribution, half-life and energy levels of the daughter nucleus as shown in Figure 2.4.The decay scheme can occur through the following processes like Compton scattering, internal conversion and electron capture.

The collision between a gamma quantum and electron is called Compton scattering. The scattering may be treated similarly to the collision between two bodies, which gives a relation between the energy, E and angle, θ of the scattered gamma quantum given as;

$$E' = h\nu' = \frac{h\nu}{1+\frac{h\nu(1-\cos\theta)}{m_0c^2}} \qquad 2.6$$

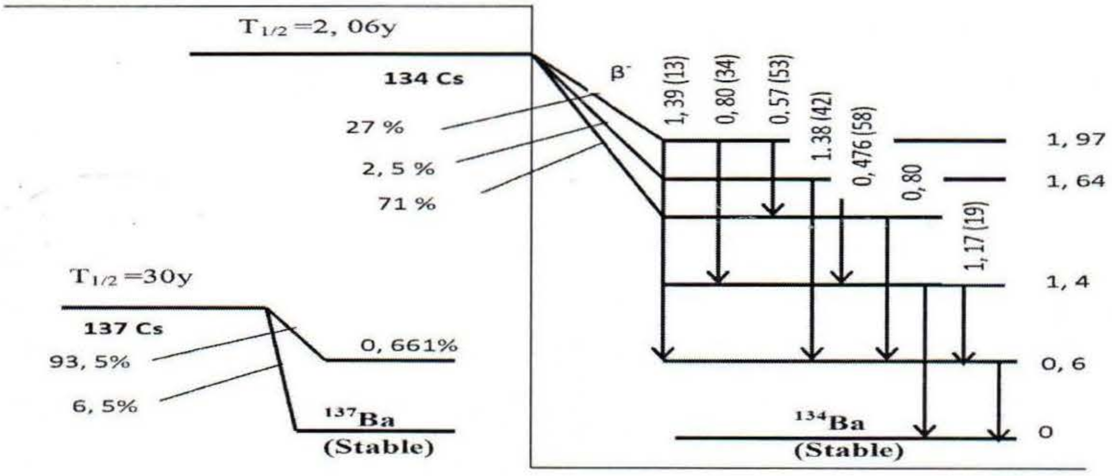

Figure 2.4: Schematic decay series of Cesium (Randolph, 1996)

2.3.7 The Radioactive Decay Law

If there are N radioactive nuclei in a sample, then the rate of decay at a time t seconds is given by the equation

$$\frac{dN}{dt} = -\lambda N \qquad 2.7$$

Where λ is the decay constant and the negative sign shows that N decreases with time. The solution of equation 2.7 is.

$$N = N_0 e^{-\lambda t} \qquad 2.8$$

Where N_0 is the number of unstable nuclei present at $t = 0$. Equation 2.8 describes the exponential radioactive decay law, which states that the rate of decay of a radionuclide is directly proportional to the number of unstable nuclei present at that instant.

2.4 Radiation Quantities and its Units

A physical quantity characterizes a physical phenomenon that is suitable for numeral specifications. For example length, time, volume and absorbed dose of radiation are physical quantities. A unit is a selected reference sample of a quantity. The ICRU recommends the use of SI units for radiation quantities (Schulz, 1695). Some of the quantities associated with radiation are described in the following subsections.

2.4.1 The Activity, *A*

Activity is the rate of decay or transformation of a radionuclide (or is the number of atoms that decay per unit time). The S.I unit of activity is Becquerel (Bq), defined as one disintegration per second (Schulz, 1695). The traditional unit of activity is the curie (Ci) which is related to the Becquerel as, $1\text{Ci} = 3.7\times10^{10}$ Bq 2.9

The activity of a pure radionuclide decreases exponential with time. If the number of atoms in a radionuclide in a sample at a given time, t is N, then the change dN in the number during a short time interval dt is proportional to Ndt .Thus using Equation 2.7 the activity A of a radionuclide is given by

$$A = -\frac{dN}{dt} = \lambda N \qquad 2.10$$

Since the activity of a sample and the number of atoms present are proportional, then

$$A = Ao\exp(-\lambda t) \qquad 2.11$$

Where Ao is activity of sample at time t is zero

During successive half-life of a radionuclide, the activity drops by a factor of one half $(^{A}/_{2})$. The average or mean life, τ of a radionuclide is defined as the average of all the individual life times that the atoms in a sample of radionuclide experience. The mean life, τ is given by

$$\tau = \frac{1}{\lambda} = \frac{T}{0.693} \qquad 2.12$$

2.4.2 Specific Activity

Specific activity is the activity of a radionuclide sample per unit mass. For a pure radionuclide its specific radioactivity, *SA,* is the number of atoms per kilogram of the nuclide N is

$$N = \frac{6.02\times10^{23}}{M} \qquad 2.13$$

Where, M is the Atomic mass of the radionuclide. From equations 2.12 and 2.13, the specific activity can be expressed as;

$$SA = \frac{4.172\times10^{23}}{MT} \qquad 2.14$$

2.4.3 Exposure

An exposure to radiation source is a measure of the health risk that the source poses to humans. Types of radiation exposure can be categorized in to three:

(i) External irradiation: Occurs when all or part of the body is exposed to penetrating radiation from an external source. During exposure this radiation can be absorbed by the body or it can pass completely through e.g. chest x-ray irradiation.

(ii) Contamination: By this it means that radioactive materials in form of gases, liquids or solids when released in the environment contaminate people externally or internally, or both. An external surface of the body, such as the skin, can become contaminated and if radioactive materials get inside the body through the lungs, gut, or wounds, the contaminant can become deposited internally.

(iii)Incorporation: This refers to uptake of radioactive material by body cells, tissues and target organs such as bone, liver, thyroid or kidney. In general radioactive materials are distributed throughout the body based upon their chemical properties. Incorporation cannot occur unless contamination has occurred.

Exposure is measured for gamma, ɤ and x-rays in terms of the amounts of ionization they produce in air. The unit of exposure is Roentgen (R), which was originally defined as the amount of gamma or x-ray radiation that produce ionization in air of 1 esu of charge in a mass of 0.001293g of air of volume 1cm^3 at standard temperature and pressure(STP). This definition of R includes ions produced directly by incident photons as well as ions produced by all the secondary electrons.

Exposure has been defined by Internal Committee of Radiation Union (ICRU) as charge per unit mass, $\frac{\Delta Q}{\Delta m}$ (C Kg^{-1})

Where ΔQ is Charge sum of 1 side produced in air when all the electrons liberated by photons in a mass Δm of air are completely stopped in it.1R = 2.58×10^{-4}C Kg^{-1}

In air at STP 1esu per cubic centimeter is equivalent to 1R of exposure and 1esu= 3.34×10^{10}C (IAEA, 1979)

2.5 Ionizing Radiation Detection and Measurements

Ionizing radiation is not detectable simply by any of the human senses. A number of measuring devices have been developed to detect and measure ionizing radiation. These devices measure the interaction of ionizing radiation on some type of element or media, and convert those interactions into electrical data that may be read on a screen, graph, or monitor. There are two basic types of instruments used for its detection: Particle counting instruments and Dose measuring instruments (Merdanoglu and Altinsoy, 2006). These are discussed in the following subsections.

2.5.1 Particle counting instruments

Particle counting instruments are used to determine the activity of a sample taken from the environment, to measure activity of body fluids, and can be used as portable survey instruments for contamination monitoring. The detector in particle counting instruments can either be a gas, a solid or liquid. In all these types of detectors, passage of an ionizing particle through them results into energy dissipation through a burst of ionization. This burst of ionization is converted into an electrical pulse that activates a readout device, such as a counter or a rate meter, to register a count (Beck et al., 1972). These are discussed as follows.

(a) Gas Filled Detectors

The gas filled detectors resemble a cylindrical condenser, with a central anode for collecting electrons and an outer cathode for collecting positive ions. The ionizing particle passes through the gas that fills the condenser, creating positive ions and electrons. The electric field applied between the anode and the cathode causes electrons and ions created by the incident radiation to migrate to their respective collecting electrodes.

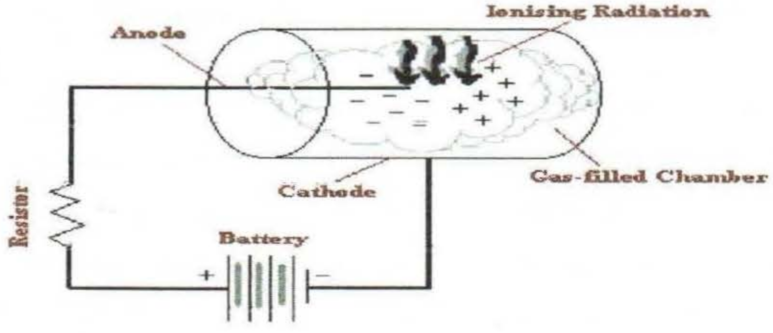

Figure 2.5: Schematic diagram of gas filled Radiation detector (Adopted from www.ehs.utoronto.ca)

As the electric field is increased, the freed electrons are accelerated and achieve sufficient kinetic energy to cause additional ionizations within the detector gas. Thus, the initial ionizing event can lead to a cascade of ionizing events and free electrons. This phenomenon is known as a "Townshend avalanche" after its discoverer. Under proper conditions, the number of secondary ionization events can be kept proportional to the number of primary ion pairs formed, but the total number of ions can be multiplied by a factor of many thousands.

Examples of gas filled particle counting instruments are Ionization chamber counters, Proportional counters and Geiger-Muller counters

(b) Solid and Liquid Scintillation Detectors

A scintillation counter is a transducer that changes the kinetic energy of an ionizing particle into a flash of light. The flashes of light are viewed electronically by photomultiplier tubes. The light sensitive portion of the photomultiplier is its photocathode. The photocathode converts incident light photons into low-energy electrons. The electron multiplier section of the photomultiplier tube acts as an amplifier boosting the electrical signal produced by these electrons sufficiently to be measured. Different scintillation materials (NaI (Tl), CsI (Tl) crystals, plastics, or liquids) are used to detect different types of radiation. Scintillation detectors are used for detecting and measuring gamma photons (Farouk et al., 1982).

(c) Solid-state detectors.

A P-N junction of semiconductors placed under reverse bias has no current flows. An incoming gamma ray (ionizing radiation) causes photoelectric ionization of the material, so an electric current will be formed if a voltage is applied to the material. The electronic counter registers a pulse of current corresponding to the energy entering the solid-state detector. Solid-state detectors are usually made from germanium or cadmium-zinc-telluride (CdZnTe, or CZT) semiconducting material. A High Purity Germanium (HPG) Gamma ray spectrometer uses a solid state detector (germanium) in detecting gamma rays with extremely high resolution (Farouk et al., 1982)

2.5.2 Radiation Dose measuring Instruments

They are based on the effects of accumulated irradiation in the material inside the instrument. Changes in the detector's material electronic state can be stored for later reading of the results. Pocket dosimeters, film badges, and personal thermo luminescent dosimeters are all used to measure radiation doses (USEPA, 2013). The different dosimeters are discussed in the following subsections

(i) Photographic Film Dosimeter (Film Badge)

The Film badge is worn in a holder containing several different filters. When developed the film darkens in proportion to the amount of radiation energy received. Due to the differing amounts of filtration we can gain information on the energy of radiation causing the dose.

Radioactive contamination of the film can be readily identified (UNCEAR, 2012).

(ii) Thermo Luminescent Dosimeter (TLD)

This is a reusable dosimeter which uses lithium fluoride to measure radiation dose. It stores dose information until heated to over 250°C when it gives out light the amount of which is proportional to the dose received. It is environmentally robust and excellent for use in all working environments (Bigu et al., 2000)

(iii) Extremity Dosimeter (Finger TLD)

This is a miniature TLD which can be supplied in different forms to suit once needs (stalls, straps or rings). The finger stall is most commonly used and is worn like the finger of a glove (Bigu et al., 2000)

2.6 Radioactivity in Soil and Phosphate Deposits

Between 1944 to date many nuclear accidents involving radioactive materials have occurred. An accident here refers to a situation where there is an uncontrolled release of radionuclides to the environment. Besides this there has been an escalation of excessive use of inorganic fertilizers that contain heavy metals to enhance crop productivity worldwide. These occurrences are the major human exposure to gamma ray radiation and contamination of the environment by radionuclides (Lemeriga, 1998). These are discussed in the following subsections.

2.6.1 Environmental Radioactivity

Radioactivity is part of nature. All materials alive or dead contain traces of radioactivity, i.e. radioactive elements (radionuclides). These radionuclides have either a natural or artificial origin, and exist in different concentrations and chemical status in all environmental components (lithosphere, hydrosphere and atmosphere), is then referred to as environmental radioactivity or radioecology. Radioecology is an area of science that deals with the understanding of radionuclides origin, how they migrate, react chemically and affect the ecospheres (Kopp and Burkart, 1989). One of the most important aspects of radioecological studies is to provide the scientific basis for predicting the impacts of environmental radioactivity on man and his environment. To assess these impacts quantitatively, it is necessary not only to define the sources of radioactivity and their environmental distribution but also to understand the effect of the environmental parameters and how radionuclides are transferred between the ecological systems (IAEA, 1979). Sources of radiation definition and radioactivity measurements are significant to determine the environmental impacts and to estimate radiation doses (Commission of the European Communities, 1993).

2.6.2 Natural Radioactivity in Soil

Soil is the upper part of the earth's crust and is formed as a result of rock deformation by complex physio-chemical processes, which include weathering decomposition, organic matter addition and water movement. Soil consists of minerals, organic matter, water and air; where their percentages vary widely according to soil type, usage, and particle size (White, 1987).

Soil has always been important to humans and their health, providing a resource that can be used for shelter and food production. Soils significantly influence a variety of functions (e.g. as a plant growth medium; its importance on the cycling of water; as a foundation for buildings) that sustains the human population. Through processes like inhalation and dermal absorption, the mineral, chemical and biological components of soils can either be directly beneficial or detrimental to human health. Specific examples include: cancers caused by the inhalation of fibrous minerals or radon gas derived from the radioactive decay of U and Th from the soil minerals. Human health can also be influenced in more indirect ways as soils interact with the atmosphere, biosphere and hydrosphere. Examples include: the frequent detrimental chemical and biological quality of drinking and recreational waters that are influenced by processes of soil erosion, surface runoff, interflow and leaching; and the transfer of mineral nutrients from soils into the plants and animals that constitute the human food chain (Abrahams, 2002).

The natural radioactivity in soil comes mainly from ^{238}U series, ^{232}Th series and ^{40}K and is one of the components of external gamma-ray exposure to which persons are exposed to regularly. The specific levels of terrestrial environmental radiation are related to the geological composition for each lithologically separated area, and to the content of uranium, thorium and potassium in the rock from which the soil originated in each area (Merdanoglu and Altinsoy, 2006; Chowdhury et al., 2006).

2.6.3 Natural Radioactivity in Phosphate Deposits and Fertilizers

Phosphate rock is the starting material for the production of all phosphate products and is the main source of phosphorus for fertilizers. It can be of sedimentary, volcanic or biological origin (Jasinski, 2007). Concentrations of ^{232}Th and ^{40}K in phosphate rocks of all types are similar to those observed normally in soil, whereas concentrations of ^{238}U and its decay products tend to be elevated in phosphate deposits of sedimentary rocks (UNCEAR 1993). Generally, for uranium a range of 3-400 ppm (37-4900 Bq/kg) and for ^{226}Ra a range of 100-10,000 Bq/kg were reported for the different phosphate deposits (Rossler et al., 1979; IAEA, 1979). ^{238}U and its decay products are generally found in close radioactive equilibrium in phosphate ore.

Most of the rock phosphates mined in the world (about 80%) are used for the production of P-fertilizers and the rest for making detergents (12%), animal feed supplement (5%) and other applications (3%), (Bigu et al., 2000). Phosphate processing operations include mining and milling of phosphate ore and the manufacture of phosphate products by either the wet process or the thermal process. In the wet process, most acidulation (95%) is done with sulphuric acid, which produces phosphoric acid, the starting material for Di Ammonium phosphate (DAP) and Triple Superphosphate (TSP) fertilizers, and phosphogypsum as waste or by product (IAEA, 2003). Varying amounts of heavy metals and radionuclide contaminants in rock phosphates will be transferred into P-fertilizers depending on their concentration in the rock and on the manufacturing processes (Schung, 2005; IAEA, 2003; El-Mrabet et al., 2003). In general, about 80% of the ^{232} Th, 30% of the ^{226}Ra and 14 % of the ^{238}U is left in the phosphogypsum. Uranium and thorium become enriched in the fertilizer to about 150% of their original value as shown in Figure 2.6

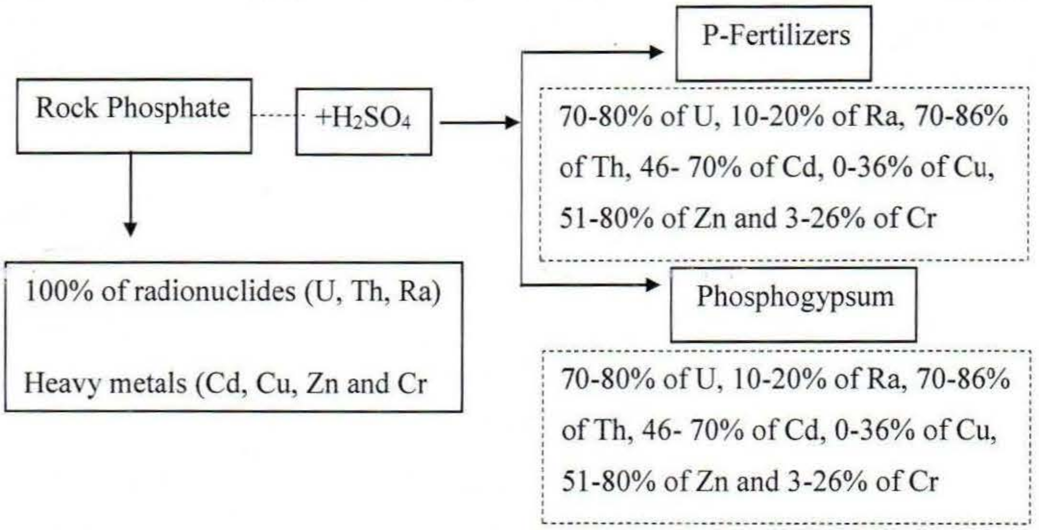

Figure 2.6: Transfer process of radionuclides and heavy metals from rock phosphate to P-fertilizer and phosphogypsum during production (IAEA, 2003)

Figure 2.6 shows the industrial process of P-fertilizer production and its enrichment by percentage composition with the radionuclides of Uranium, Thorium and Radium. The amount of heavy metals and radionuclides in P-fertilizers is primarily due to impurities in phosphate rock, which add continuously due to the long-term agricultural applications of fertilizers. At least 70% of U stays in final products (P-mineral fertilizers). Therefore, the main cause of U discharge to agricultural soils is fertilization with mineral P-fertilizer. High levels of U have negative effects on human health and ecological systems such as sterility, skin reddening in whites, skin blackening in blacks, cataracts etc. (IAEA, 2003).

2.6.4 Behaviour of Long-Lived Radionuclides in Soil

The soil is contaminated either by radionuclide deposition originally discharged into the atmosphere, or on the land surface by direct discharge of wastes. The concentration of radionuclides in soil increases by adsorption with soil particles and their precipitation on soil (Harb, 1983).

Losses of radionuclides from the plant root zone in some cases occur through infiltration process into deeper soil layers and these losses are significant where soil permeability is high and the adsorption of radionuclides to soil particles is low. The low radionuclide adsorption capacity to soil particles leads to relatively high radionuclides uptake by plants (Harb, 2004).

The behaviour of radionuclides in soil is affected by different biochemical processes, when organic matter decomposition changes soil property from an oxidizing to a reducing medium. This will affect the chemical form of the radionuclide present in soil. An example of this is when mobile hexavalent uranium is reduced to the tetravalent immobile form. More so, the rock decomposition is enhanced which results in small soil particle size with more water content, less permeability and high retention of radionuclides in the surface soil (Eisenbud, 1987).

Radionuclides introduced into soil have different behaviours. It could adsorb on the soil particles, undergo ion exchange, form complex organic matter or remain in ionic form (Schulz, 1965).

The distribution of radionuclides between soil particles and soil water is described by the distribution coefficient "K_d". This is defined as "the quantity of radionuclide adsorbed per unit weight of solids divided by the quantity of the radionuclide dissolved per unit volume of water (mkg^{-1}). Smaller multivalent ions usually adsorb more strongly (higher K_d value) than larger univalent ions (IAEA, 2003).

The radionuclide to plant concentration ratio in soil is affected by many factors that control plant uptake. These factors are:

(i) Physio-chemical form of the radionuclide: The Physio-chemical form of the radionuclide strongly affects its retention by the soil particles and its availability for uptake by plants. The most tightly bounded forms of radionuclides (highest K_d value) are also those which exhibit the lowest relative uptake by plant (Harb, 2004).

(ii) Soil characteristics: The soil type affects strongly the behaviour of radionuclides in soil, and soil retention characteristics (Schulz, 1965). Sandy soils do not have the retention capacity of clay soils. Clay soils are composed of smaller particle sizes with larger surface area and negative charge surfaces (El-Reefy, 2006).

(iii)The soil's pH value, affects the plants uptake. In alkaline soils (high pH) insoluble precipitates may be formed with carbonate, hydroxyl, phosphate or sulphide ions. These insoluble precipitates reduce the availability of radionuclides for plants. In acid soils (low pH), hydrogen replace the adsorbed cations which become more available to plants. In highly acidic soils (pH <5.5) some trace elements (particularly iron and manganese) may become toxic to plant growth (Schulz, 1965).

(iv)Fertilizers and agricultural chemicals: They are chemical compounds added to increase the soil fertility and enhance plant production. They strongly affect both the stable element concentration, and soil acidity (El-Reefy at. el., 2006). The effect of lime stone ($CaCO_3$) addition appears to raise soil pH, increasing exchangeable calcium concentration, and decreasing the uptake of strontium. This is possibly due to the decreased solubility of Strontium carbonate ($SrCO_3$) in alkaline conditions (Harb, 2004). Fertilizer with nitrogen in the nitrate form (potassium or calcium nitrates) and phosphate fertilizers may decrease soil acidity (Foth, 1978). Organic fertilizer affects the ion exchange capacity, pH, stable element content of soil, as well as soil retention properties (Blanco Rodrieuez at. et., 2008).

(v) Chelating agents: Chelating agents are organic compounds which increase the ion mobility and reduce soil retention. This increases the plant uptake. Moreover, these agents enhance the translocation ability within the plant itself (Baxter, 1993). In some situations of plants nutrient deficiencies they are useful because they decrease soil retention, therefore increasing plant uptake. Their effectiveness depend upon soil properties (particularly soil pH), chemical form of the radionuclide and the nature and concentration of chelating agent (Harb, 2004).

(vi) Distribution of radionuclides in soil: The distribution of radionuclides in the soil layer equivalent to the depth of plant root zone is an effective factor for radionuclide plant uptake. The root zone layer is dependent on the plant species and the water table depth. The plant uptake of radionuclides is affected by the plant root distribution, and the distribution of radio nuclide with soil depth (Harb, 2004)

2.6.5 Specific Activity Levels of U, Th and K in soils and Food crops

Studies carried out across some African countries showed the following results for the specific activity levels in Bq/kg of U, Th and K in soils and food crops as shown in the table 2.1.

Table 2.1: Activity Levels in Bq/kg of ^{238}U, ^{232}Th, and ^{40}K

Reference	Sample type	^{40}K	^{232}Th	^{238}U (or ^{226}Ra)	Location (Country)
Noureddine et al., (1997)	Soil	93 – 412	7 – 27	5 – 27	Algeria
El–Reefy et al., (2006)	Sand soil	16 – 1379	3 – 117	3 – 101	Egypt
Shenber, (1997)	Soil	265 – 282	7.6 – 9.7	8.7 – 12.8	Libya
Steinhausler and Lettner, (1992)	Food crop	42– 1100	3 – 38	45 – 49	Namibia
Lemeriga, (1998)	Food crop	116 – 338	34.9– 51.2	6.05– 12.67	Uganda

2.7 Biological Effects of Radiation

Radiation effects on biological systems is one of the most widely investigated hazardous agents. As living cells absorb radiation energy, molecules within them get damaged. This damage can either destroy or cause malfunction of the cells through genetic mutation, which can result into multiplication of cells leading to cancerous cell formation. Biological effects of radiation on cells are assumed to result from both direct and indirect results of radiation (Abrahams, 2002).

Depending on the dose, kind of radiation and the observed end point, the biological effects of radiation can differ widely. Some occur relatively rapidly while others may take years to become evident. Therefore biological effects of radiation can be divided in two general categories; and they are discussed in the following subsections (Beretka at. et., 1985).

2.7.1 Stochastic Effects of Radiation (Statistical)

This is the effect that increases with the exposure to radiation. However small the radiation a person is exposed to, it will result in an increased probability of genetic mutations or cancer induction. Stochastic effects occur in statistical manner i.e. if a large population is exposed to a significant amount of radiation, then an elevated chance or incidence of cancer can be expected. Stochastic effects of radiation may not become evident for some considerable time after exposure. Delayed reaction to stochastic effects is expressed by a risk factor called probability coefficient. These factors can be individually assigned to different conditions e.g. leukemia or grouped together to include an overall category e.g. solid cancers of all types i.e. abnormal cellular growth in solid organs like breasts (IAEA, 2003).

2.7.2 Deterministic Effects (Non Stochastic Effects)

This is where the severity of the response to radiation increases with the dose. It shows a clear causal relationship between dose and effect in a given individual e.g. in the case of radiation accident where the doses may well have been appreciable, deterministic effects become evident quite soon after exposure. Examples of deterministic effects of radiation include skin reddening in whites and skin blackening in persons with dark skins, cataract formation etc. (Harb, 2004).

For many years, the genetic effects of radiation were considered to pose the greatest danger to human population exposed to low level of radiation (the major concern today is cancer). It has been found experimentally that a given large dose of radiation delivered accurately, is generally more damaging biologically than the same dose delivered over extended period of time. (IAEA, 2003). The summary of the effects in increase of radiation dose on humans is presented in a Table 2.2

Table 2.2: Radiation Doses and Expected Effects (IAEA, 2003)

Dose (Sv)	Time span	Expected effect
0 – 0.1	Acute or chronic	No observable effect
0.1 – 0.5	Acute or chronic	No observable effect, possible cancer risk
0.5 – 1	Chronic	Increased cancer risk
0.5 – 1	Acute	May see changes in blood cells, but the blood system quickly recovers
1 – 2	chronic	Increased cancer risk
1 – 2	Acute	Nausea and fatigue
2 – 3	Acute	Nausea and vomiting within 24 – 48 hours.
3 – 5	Acute	Nausea, vomiting, and diarrhea within hours.
5 – 12	Acute	Likely lead to death within a few days
>100 Sv	Acute	Death within a few hours.

CHAPTER THREE: EXPERIMENTAL METHOD

3.1 Introduction

This study aimed at determining the specific activity levels and dose rates in food crop samples obtained from selected tobacco farming areas. The areas of Tobacco farming selected in this study in Terego County were Omugo, Odupi, Oriama, Aii-vu, Bileafe and Katrini Sub-couties all in Arua district while the areas considered in Maracha district were Tara, Yivu and Nyadri Sub-counties. These farming areas are shown in Figure 3.1.

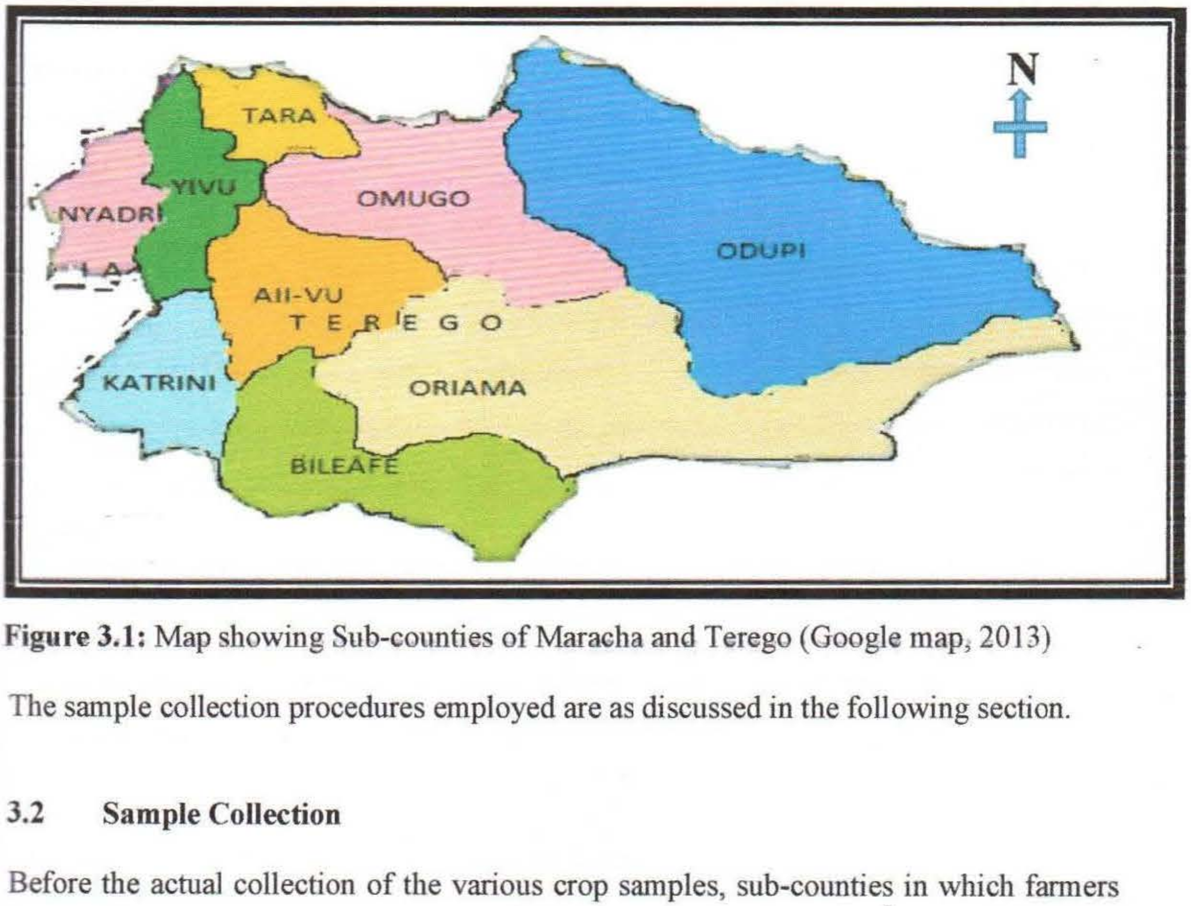

Figure 3.1: Map showing Sub-counties of Maracha and Terego (Google map, 2013)

The sample collection procedures employed are as discussed in the following section.

3.2 Sample Collection

Before the actual collection of the various crop samples, sub-counties in which farmers grow tobacco substantially were identified by moving round the districts while inspecting evidence of growing tobacco farming such as considering the number of bans and asking members of public open and leading questions to establish the level of tobacco farming. Substantial growth means the production of tobacco is at least from 5 tones and above mainly for commercial purpose. The farmers who grow tobacco annually were also identified. This was done by making inquiries in the community population by way of request to know the individuals who grow tobacco annually for purpose of this research. Commonly grown food crops as post tobacco harvest like cassava, beans, simsim, sorghum, maize, rice and groundnuts were also identified by way of observation and selected per sub-county. This selection criterion was done for all the nine sub-counties considered in this study.

The various food crop samples were collected by the researcher from the farmers who had grown them in the fields where tobacco had been harvested either that same season or the previous seasons. This was done by asking the farmers if the food crop was grown as post-harvest of tobacco. The number of crop samples collected very much depended on their availability in a particular sub-county. One to three samples of each crop were obtained from different fields per sub-county. A total of 63 food crop samples were collected for this study. Some crop samples were not found in other sub counties and as such were not collected. It could have been good to also consider crops grown in areas where tobacco has never been grown to compare the finding in this study. In fact with the significant levels of tobacco cultivation in these selected counties, it was not easy to prove which fields have never been used for tobacco cultivation in the past decades (1932 – to-date) and so food crop samples that could have been used as control to compare results in this study were not collected.

During sample collection care was taken to avoid incidences of contamination. This was done by ensuring separate, careful and good packaging in polythene bags for each of the food crop sample collected for the study.

3.3 Sample Preparation

Some crop samples such as rice, groundnuts and cassava were cleaned to remove husks and covers to expose the parts humans usually consume. For rice samples, to remove the husks a locally make pounding motor was used to remove the husks by hand and for cassava the covers were removed by use of hand knives. The husks of groundnuts were removed by means of human hand to expose the seeds. All the samples were dried to remove moisture and crushed into powder form using a local pounding motor by hand; this gave the samples a finite uniform mixture and improved the sample geometry to enhance detection efficiency (Mattetnik 1995). The samples were packed in polythene bags duly labeled using the initials of the Sub-county names and that of the crop sample e.g. OMS for Omugo Simsim, ODS for Odupi Simsim, KAB for Katrini beans etc., this was done to avoid confusion and easy identification of samples during laboratory analysis. Then all the samples collected were transported to the Radiation laboratory for Gamma ray spectrometry analysis.

3.4 Experimental Gamma Ray Spectrometer Set up

In order to measure the specific activity levels of gamma ray emitting radionuclides in the food crop samples grown as post tobacco harvests in these areas, Gamma Ray Spectroscopy Technique (GRST) was employed to detect the gamma ray energies emitted by the crop samples. Gamma ray spectrometer GDM20 module that uses NaI (Tl) as the inorganic Scintillator was used to measure the specific activity levels of the food crop samples.

The simple experimental procedures used to obtain the spectrum for all samples include;

The various components of a Gamma ray spectrometer (GDM20) are shown in Figure 3.2

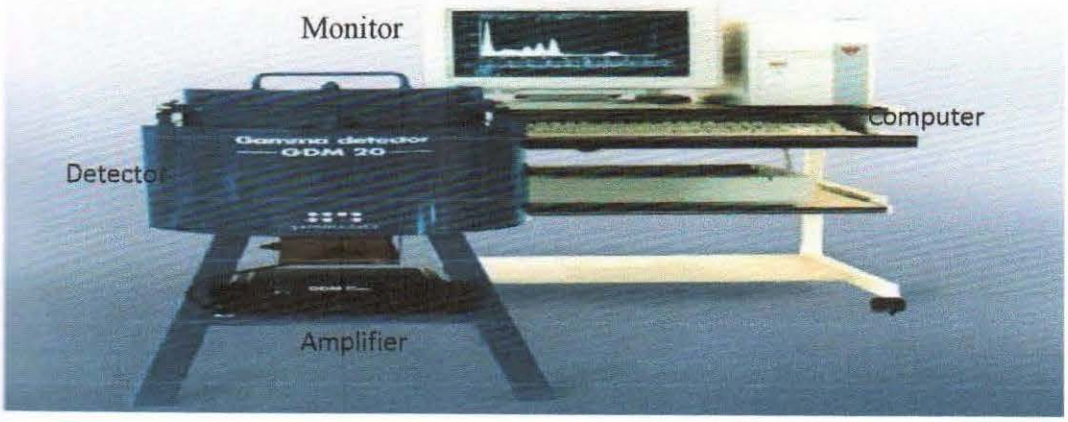

Figure 3.2: Gamma ray spectrometer set up (Mattetnik, 1995)

Figure 3.2 consists of the detector system in which the samples were fed, the amplification unit which amplifies the gamma ray energy pulses and the computer unit from which the input commands are given. It also provides the output where the spectrum being formed is observed on the monitor. The gamma-ray spectrometry set-up is made up of a 7.62 cm by 7.62 cm NaI (Tl) detector housed in a 6 cm thick lead shield (to assist in the reduction of the background radiation). The configuration and geometry was maintained throughout the analysis. A computer based Multichannel Analyser Auto das programme was used for data acquisition and analysis of gamma spectra (Mattetnik, 1995). This required that the spectrometer be energy calibrated and this is discussed in the following subsection.

3.4.1 Energy Calibration using a Eu-152 Source

The energy calibration of the NaI (Tl) detector was done using the ^{152}Eu liquid source which produced prominent peaks with good resolution when run for 6890s. The ^{152}Eu source was placed in the detector and its spectrum obtained. The ^{152}Eu spectrum contained several photo peaks, but for the purpose of energy calibration, the peaks with energies of 0.344 and 1.41 MeV were chosen since this offered a good energy range with prominent photo peaks. The energy calibration was necessary so as to calibrate other spectra of the samples (Mattetnik, 1995). The calibration spectrum obtained is shown in the Figure 3.3

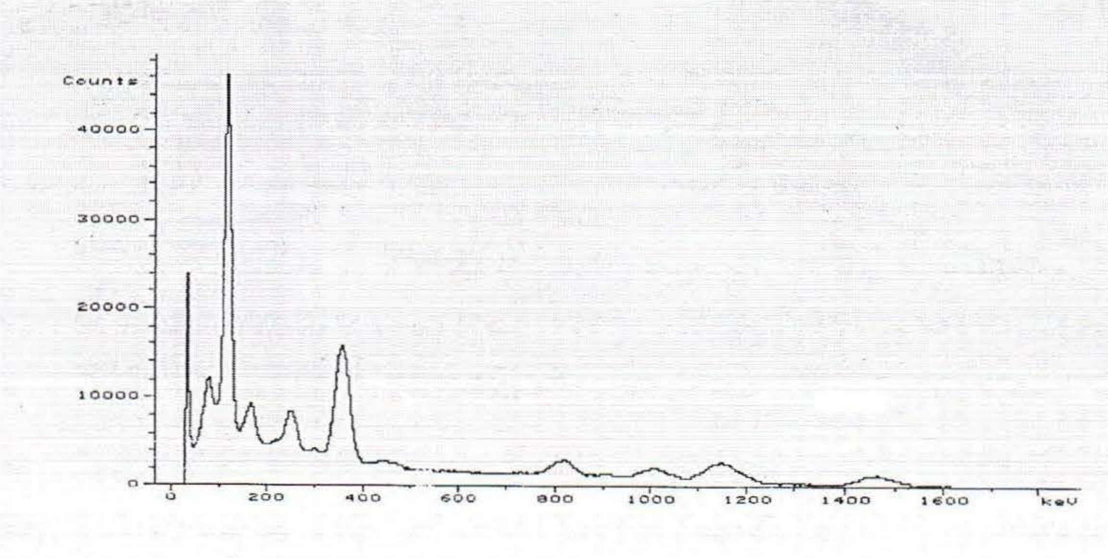

Figure 3.3 Calibration Spectrum of NaI(Tl) Detector using 152-Eu Source

3.4.2 Efficiency calibration

A solution of ^{152}Eu was used to determine the efficiency of the detector at different gamma ray energies. If the solution had a "gamma activity" of A Bq (Becquerel) for the 0.244 MeV transition, i.e. the solution emitted A gamma quanta per second with the energy 0.244 MeV, the activity of the solution measured for a preset time, t, and the area of the corresponding photo peak were determined to Y pulses. The efficiency, ε, of the detector at that energy is computed from the expression

$$\varepsilon = \frac{Y}{At} \qquad 3.1$$

Since the efficiency is dependent on the solid angle at which the detector sees the sample, it was important that the calibration source and the unknown samples be measured with the same geometry (Mattetnik, 1995)

3.5 Measurement of Radionuclides

Samples were weighed using an analog beam balance to establish their exact masses. The mass of empty Marinelli beaker was first determined on the beam balance. The samples were then filled in the Marinelli beaker and weighted and the actual mass of the samples obtained by subtracting the mass of the empty beaker from that containing the samples. The Marinelli beaker was used for feeding the samples into the detector system. Marinelli beakers were chosen because they are specially designed beakers whose three dimension geometry could allow the detector to see through the samples more conveniently. The samples were then placed in the detector, which was housed in a lead shielding.

The crop samples were analyzed for a time ranging from 5011 to 7106 seconds and a spectrum obtained for each sample run in the detector. The activity measurements of all crop samples were done using NaI (TI) detector and autodas software program.

3.6 Obtaining the Gamma Ray Energy

A background file of spectrum acquired without filling a sample in the detector was created (BKGS 2014) after which a spectrum was obtained by running a sample. From the sample spectrum the contribution due to background radiation spectrum was subtracted. Prominent peaks obtained from the spectra were then identified using the radionuclide energy chart and the resulting spectra. Calculations of the areas under the peaks in the spectrum were done for each file created using the Auto das software command.

3.6.1 Correction Coefficients for NaI (Tl) Detector

The correction coefficients for NaI (Tl) is given by the equation;

$$C = \varepsilon \eta, \qquad 3.2$$

where ε, is the detector efficiency and η is the branching ratio for the radionuclides.

Table 3.1: Correction Coefficients for NaI (Tl) Detector (Mattetnik, 1995)

Energy (KeV)	Decay Series	Correction coefficient (C)
84	Th (Th – 228)	0.0286
185	U (Ra - 226)	0.0043
238	Th (Pb – 212)	0.0608
242	U (Pb – 214)	0.0404
295	U (Pb – 214)	0.0237
352	U (Pb – 214)	0.0300
580	Th (Tl – 208)	0.0101
610	U (Bi – 214)	0.0210
780	Eu – 152	0.0296
1170	Co – 60	0.0200
1460	K - 40	2.34×10^{-3}

Table 3.1 shows the correction coefficients for the NaI (Tl) detector with the associated energy of the radioactive decay series. This was used to identify the radionuclide peaks present in the spectra and for calculating the specific activities for each sample analyzed.

3.6.2 The Specific Activities

The specific activities for the radionuclides were calculated using the equation

$$SA = \frac{N}{t \times m \times C}, \tag{3.3}$$

where, C is the correction coefficient for sodium iodide detector, m the mass of sample, N number of photons, t the live time taken to run the sample in the detector.

Residual additional peaks at known energies existed and their activities for the corresponding radionuclides were calculated using the expression

$$SA_{(Ei)} = \frac{N_{(Ei)}}{t \times m \times \eta_{(Ei)} \times \varepsilon_{(Ei)}}, \tag{3.4}$$

where $N_{(Ei)}$ is the area of the residual peak at energy E_i, $\eta_{(Ei)}$ the branching ratio of radionuclides emitting gamma rays with energy E_i, $\varepsilon_{(Ei)}$ the efficiency of the detector for the energy E_i, t the live-time used for running the sample in the detector and m is the mass of the sample.

The error limits in specific activities (ΔSA) in all the samples were calculated using the equation

$$\Delta SA = \left[\frac{\sqrt{N}}{t}\right] \div (m \times C), \tag{3.5}$$

where N, is the number of radionuclides present in the sample and t the live time used to run the sample in the detector, m is the mass of sample and C is the correction coefficient.

3.7 Evaluation of Radiological Hazard Effects

The risk level associated with the eating of food crop samples whose natural radioactivities were measured, were then determined by computing their absorbed dose rate, annual effective dose equivalent. Each of these is discussed in the following subsections.

3.7.1 Absorbed Dose Rate

Radiological clinical effects of ionizing radiation are directly related to the Absorbed Dose Rate, D (Ramasamy *et al*., 2011) since the severity depends on dose level. The measured activity concentrations were converted into doses by applying conversion factors 0.462, 0.604 and 0.0417 for Radium, Thorium and Potassium respectively (UNSCEAR, 2000). This is illustrated by the equation.

$$D = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \qquad 3.6$$

where D is the dose rate in $nGyh^{-1}$ $A_{Ra}, A_{Th},$ and A_K are the activity concentrations ($Bqkg^{-1}$) of ^{226}Ra, ^{232}Th and ^{40}K in the sample respectively.

3.7.2 Annual Effective Dose Equivalent

For samples not to pose a significant carcinogenic threat to the population, the annual effective dose equivalent should not exceed 0.12 mSv year^{-1} (UNSCEAR, 2000).

The annual effective dose equivalent, H (in mSv/y) was computed by use of the dose criterion (UNSCEAR, 1993), given by the equation.

$$H\left(\frac{mSv}{y}\right) = \frac{A_{Ra}}{740} + \frac{A_{Th}}{520} + \frac{A_K}{9620} \qquad 3.7$$

CHAPTER FOUR: RESULTS

4.1 Introduction

This study aimed at obtaining the gamma ray energies for radionuclides present in the food crop samples collected. Samples were weighed using a beam balance to establish their masses and the samples were then run in the detector for a set time interval, after which a spectrum was obtained. The specific activities for all radionuclides identified from the spectrum were computed. The results are as presented in the following sections.

4.2 Sample Spectrum used.

To identify the radionuclides, a sample was run into a detector for a set time and a spectrum obtained. The background radiation was automatically subtracted from the sample spectrum using an autodas command and the resulting spectrum is shown in Figure 4.1. The spectrum was then used to identify all the radionuclides present in the sample. This procedure was followed for all the sample spectra obtained in this study

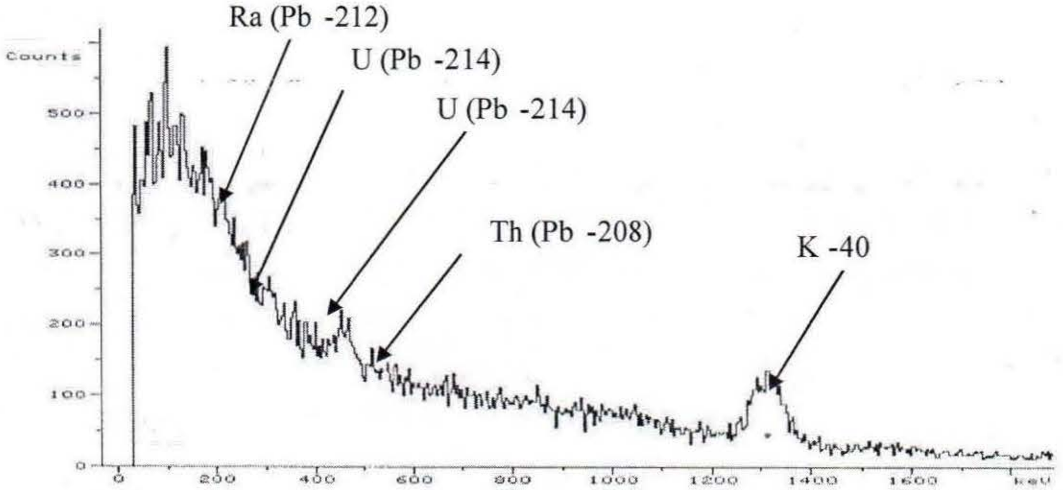

Figure 4.1: A typical Spectrum for Ground nut sample (Omugo sub-county)

From Figure 4.1, five photopeaks of the gamma ray emitting radionuclides were identified and their specific activity (S.A) computed. The radionuclides in the photopeaks shown in Table 4.1 were identified using the correction coefficient (Table 3.1). The sample gamma ray energies obtained from the spectrum shown in Figure 4.1 are presented in Table 4.1

Table 4.1: Gamma Ray Energy for Ground nut Sample -OMG1 (Omugo sub-county)

Mass: 0.31 ± 0.0005 kg									Live time: 6008s
S/n PK	**Radioisotope**	**Coeff (C)**	**Cent (keV)**	**SD (keV)**	**FWHM (keV)**	**SUM (N)**	**Rate (s^{-1})**	**S.A ($Bqkg^{-1}$)**	**Error ($Bqkg^{-1}$)**
1	K-40	0.0023	1315.2	24.1	56.5	1262	0.21	290.5	8.2
2	Th (Tl - 208)	0.0101	516.6	11.2	26.3	179	0.03	9.5	0.7
3	U (Pb - 214)	0.0237	332.1	3.5	8.2	79	0.01	1.8	0.2
4	U (Pb - 214)	0.0300	257.2	8.8	20.8	180	0.03	3.2	0.2
5	U(Ra – 226)	0.0043	192.1	15.1	35.6	603	0.10	75.5	3.1

The details of gamma ray energies for other samples analysed are presented in the Annex D.

4.3 Specific Activity Levels

Using the correction coefficients for NaI (Tl) presented in Table 3.1 and gamma ray energy data presented in Table 4.1, the specific activities of the radionuclides present in the sample was calculated using Equation 3.2. This procedure was followed for all the samples used in this study. The specific activities and mean specific activities computed for all samples are presented in following Tables

In Table 4.3, cassava samples collected from Nyadri sub-county (NYC) showed the highest mean specific activity level of Radium (117.8 Bq/kg) and the least mean specific activity level (44.8 Bq/kg) for Radium was in cassava samples from Bileafe sub-county (BIC). The cassava samples from Omugo sub-county (OMC) had the highest specific activity level of Thorium (12.5 Bq/kg) and the least mean specific activity level (2.9 Bq/kg) for Thorium was observed in cassava samples from Yivu sub-county (YIC). The cassava samples from Oriama sub-county (ORC) had the highest specific activity level of Uranium (4.9

Bq/kg) and the least level (2.4 Bq/kg) for Uranium was showed by cassava samples from Yivu sub-county (YIC). The cassava samples again from Omugo (OMC) presented the highest mean specific activity levels of Potassium (369.9 Bq/kg) while the cassava samples from Yivu (YIC) had the least specific activity level (120.5 Bq/kg) for Potassium. This may be so because, Omugo sub-county is thickly populated and with high level of land fragmentation, there are chances that there could be high annual rate of NPK fertilizer application over the years (UNBS, 2012).

Table 4.2: Specific Activity for Cassava Samples Collected

Sample ID	**MEAN SPECIFIC ACTIVITY (Bq kg^{-1})**			
	Ra-226	Th-232	U-238	K-40
NYC1	128.0 ± 3.8	6.5 ± 0.6	3.1 ± 0.2	141.6 ± 5.5
NYC2	107.5 ± 3.5	3.0 ± 0.4	2.8 ± 0.2	112.1 ± 4.9
OMC1	43.4 ± 2.4	16.2 ± 0.9	4.0 ± 0.3	346.6 ± 9.0
OMC2	68.1 ± 2.9	8.7 ± 0.7	5.1 ± 0.3	393.2 ± 9.6
ODC1	105.8 ± 3.5	4.0 ± 0.4	4.7 ± 0.3	238.1 ± 7.2
ODC2	87.3 ± 3.3	6.8 ± 0.6	2.9 ± 0.2	254.1 ± 7.6
YIC1	96.7 ± 3.6	3.5 ± 0.4	2.7 ± 0.2	179.3 ± 6.6
YIC2	80.9 ± 2.8	2.4 ± 0.3	2.2 ± 0.2	61.7 ± 3.4
BIC1	36.0 ± 2.2	8.6 ± 0.7	4.7 ± 0.3	294.8 ± 8.6
BIC2	53.5 ± 2.5	6.8 ± 0.6	4.0 ± 0.3	327.0 ± 8.4
ORC1	46.6 ± 2.5	7.8 ± 0.7	2.9 ± 0.2	113.1 ± 5.3
ORC2	66.7 ± 2.8	11.8 ± 0.8	6.9 ± 0.4	151.5 ± 5.8

The mean specific activity levels for cassava samples analysed were calculated using their specific activities in Table 4.2 and are presented in the Table 4.3.

Table 4.3: Mean Specific Activity for Cassava Samples

Sample ID	**ACTIVITY CONCENTARATIONS (Bq kg^{-1})**			
	Ra-226	Th-232	U-238	K-40
NYC	117.8 ± 3.7	4.7 ± 0.5	2.9 ± 0.2	126.9 ± 5.2
OMC	55.8 ± 2.7	12.5 ± 0.8	4.5 ± 0.3	369.9 ± 9.3
ODC	96.5 ± 3.4	5.4 ± 0.5	3.8 ± 0.3	246.1 ± 7.4
YIC	88.8 ± 3.2	2.9 ± 0.4	2.4 ± 0.2	120.5 ± 5.0
BIC	44.8 ± 2.4	7.7 ± 0.6	4.4 ± 0.3	310.9 ± 8.5
ORC	56.6 ± 2.7	9.8 ± 0.7	4.9 ± 0.3	132.3 ± 5.5

The mean specific activity levels of cassava samples from the sub-counties where they were collected are graphically presented in the Figure 4.2

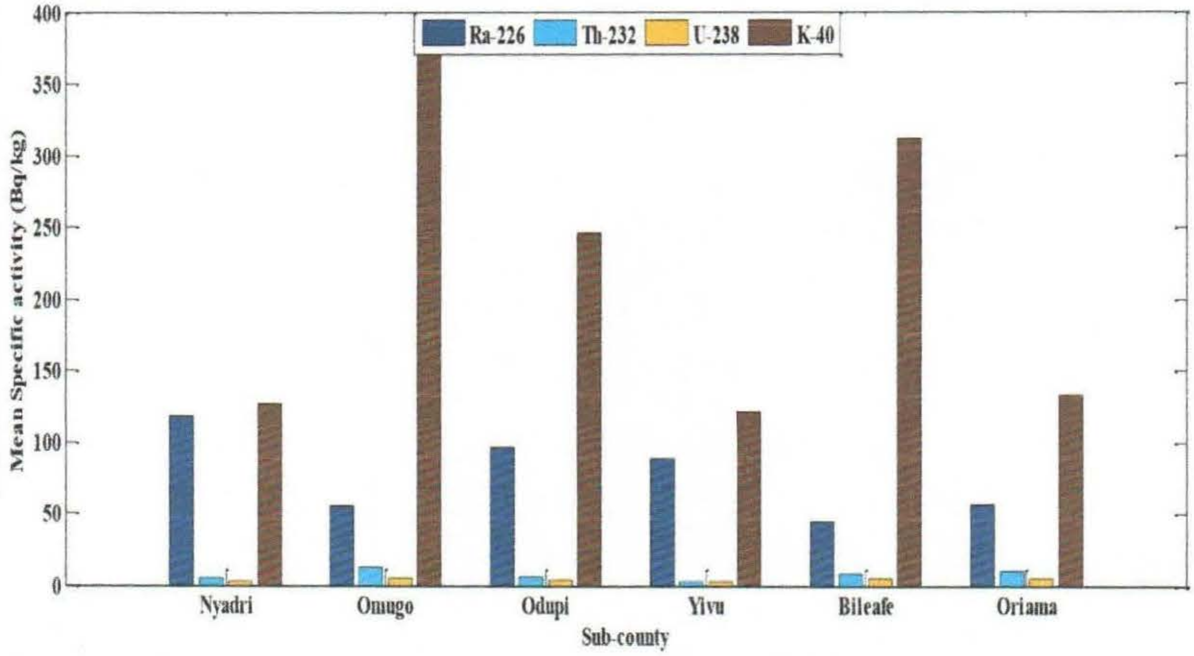

Figure 4.2: Graph of Mean Specific Activity levels in Cassava Samples collected

In Table 4.5, Simsim samples collected from Odupi sub-county (ODS) had the highest mean specific activity level of Radium (153.9 Bq/kg) and least mean specific activity level (26.3 Bq/kg) for Radium was showed by Simsim samples from Aii-vu sub-county (AIS). The Simsim samples from Bileafe sub-county (BIS) presented the highest specific activity level of Thorium (10.1 Bq/kg) and least level (3.7 Bq/kg) for Thorium was observed in Simsim samples from Katrini sub-county (KAS). The Simsim samples again from Katrini (KAS) had the highest mean specific activity level of Uranium (5.1 Bq/kg) while the Simsim samples from Oriama (ORS) showed the least level (2.9 Bq/kg) for Uranium. The Simsim samples from Tara (TAS) had the highest mean specific activity level of Potassium (188.6 Bq/kg) and the least mean specific activity level (78.5 Bq/kg) for Potassium was observed in Simsim samples from Bileafe (BIS).

Table 4.4: Specific Activity level in Simsim Samples collected by Sub-county

Sample ID	**MEAN SPECIFIC ACTIVITY (Bq kg^{-1})**							
	Ra-226		Th-232		U-238		K-40	
AIS1	12.5	± 1.5	7.7	± 0.8	4.2	± 0.3	66.3	± 4.8
AIS2	40.1	± 2.5	4.8	± 0.6	3.9	± 0.3	181.4	± 7.1
KAS1	75.3	± 3.5	5.0	± 0.6	5.1	± 0.4	189.8	± 7.6
KAS2	77.0	± 3.6	2.4	± 0.4	5.0	± 0.3	161.7	± 7.1
ODS1	129.4	± 4.4	8.0	± 0.7	3.1	± 0.3	84.3	± 4.8
ODS2	178.4	± 5.2	5.1	± 0.6	4.2	± 0.3	98.8	± 5.2
TAS1	64.1	± 3.0	9.6	± 0.8	4.5	± 0.3	187.0	± 7.0
TAS2	45.0	± 2.8	4.7	± 0.6	3.9	± 0.3	190.3	± 7.7
BIS1	65.3	± 3.1	11.5	± 0.9	6.0	± 0.4	96.1	± 5.1
BIS2	49.3	± 2.6	8.7	± 0.7	3.5	± 0.3	61.0	± 4.0
ORS1	63.1	± 3.2	7.6	± 0.7	3.1	± 0.3	85.1	± 5.0
ORS2	59.6	± 2.9	10.3	± 0.8	2.8	± 0.2	98.4	± 5.0

The general trend is that the activity levels for a particular radionuclide were in close range for most of the samples analysed except for radium level in the Simsim sample from Aii-vu sub-county that is much lower than values presented by other samples from the rest of the sub-counties.

Table 4.5: Mean Specific Activity for Simsim Samples by Sub-county

Sample ID	**MEAN SPECIFIC ACTIVITY (Bq kg^{-1})**			
	Ra-226	Th-232	U-238	K-40
AIS	26.2914 ± 2.0	6.2 ± 0.7	4.0 ± 0.3	123.8 ± 5.9
KAS	76.1505 ± 3.6	3.7 ± 0.5	5.1 ± 0.4	175.8 ± 7.3
ODS	153.9 ± 4.8	6.5 ± 0.6	3.7 ± 0.3	91.5 ± 5.0
TAS	54.5 ± 2.9	7.1 ± 0.7	4.2 ± 0.3	188.6 ± 7.4
BIS	57.3 ± 2.9	10.1 ± 0.8	4.8 ± 0.3	78.5 ± 4.6
ORS	61.3 ± 3.0	9.0 ± 0.8	2.9 ± 0.3	91.7 ± 5.0

The mean specific activity levels of Simsim samples per sub-county are as graphically presented in the Figure 4.3

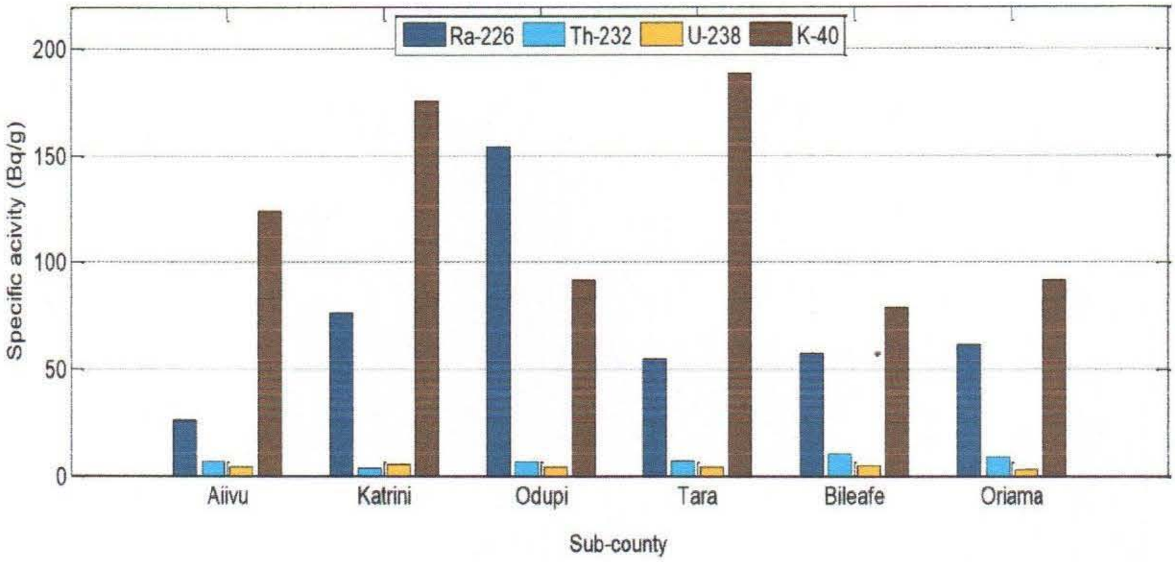

Figure 4.3: Graph of Mean Specific Activity for All Simsim Crop Samples by Sub-county

In Table 4.7, Maize samples collected from Yivu sub-county (YIM) had the highest mean specific activity level of Radium (70.9 Bq/kg) and least mean specific activity level (25.0 Bq/kg) for Radium was showed by Maize samples from Aii-vu (AIM). The Maize samples from Bileafe (BIM2) were observed to have the highest mean specific activity level of Thorium (6.8 Bq/kg) and the least level (2.0 Bq/kg) for Thorium was showed by Maize samples from Yivu sub-county (YIM). The Maize samples again from Bileafe (BIM) had the highest mean specific activity level of Uranium (4.3 Bq/kg) while Maize sample from Aii-vu (AIM) presented the least level (1.9 Bq/kg) for Uranium. The samples from Bileafe (BIM2) showed the highest mean specific activity level of Potassium (102.7 Bq/kg) and the least mean specific activity level (54.4 Bq/kg) for Potassium was observed in Maize sample from Yivu (YIM).

Table 4.6: Specific Activity level for All Maize Crop Samples collected

Sample ID	**MEAN SPECIFIC ACTIVITY (Bq kg^{-1})**			
	Ra-226	Th-232	U-238	K-40
AIM1	24.9 ± 1.6	1.8 ± 0.3	1.9 ± 0.2	96.1 ± 4.2
AIM2	24.9 ± 1.5	3.0 ± 0.3	1.8 ± 0.7	27.9 ± 2.2
KAM1	35.5 ± 1.8	3.0 ± 0.3	2.2 ± 0.2	88.3 ± 3.9
KAM2	22.0 ± 1.5	2.6 ± 0.3	3.7 ± 0.2	91.8 ± 4.0
YIM1	79.6 ± 2.8	2.6 ± 0.3	2.9 ± 0.2	60.5 ± 3.3
YIM2	62.1 ± 2.4	1.5 ± 0.2	1.8 ± 0.2	48.2 ± 2.9
BIM1	17.2 ± 1.2	5.9 ± 0.5	2.8 ± 0.2	52.4 ± 2.9
BIM2	57.2 ± 3.0	7.6 ± 0.7	5.8 ± 0.4	152.9 ± 6.7
ORM1	34.3 ± 1.8	4.8 ± 0.4	2.2 ± 0.2	65.5 ± 3.3
ORM2	69.3 ± 2.5	3.0 ± 0.3	4.0 ± 0.2	73.8 ± 3.5
ORM3	55.9 ± 2.3	3.3 ± 0.4	4.2 ± 0.3	87.3 ± 3.9

The mean specific activity levels of maize samples calculated from specific activity levels in Table 4.6 are presented in Table 4.7

Table 4.7: Mean Specific Activity for Maize Crop Samples collected by Sub-county

Sample ID	MEAN SPECIFIC ACTIVITY ($Bq\ kg^{-1}$)			
	Ra-226	Th-232	U-238	K-40
AIM	24.9 ± 1.5	2.4 ± 0.3	1.9 ± 0.2	62.0 ± 3.2
KAM	28.8 ± 1.6	2.8 ± 0.3	2.9 ± 0.2	90.0 ± 4.0
YIM	70.9 ± 2.6	2.0 ± 0.3	2.3 ± 0.2	54.4 ± 3.1
BIM	37.2 ± 2.1	6.8 ± 0.6	4.3 ± 0.3	102.7 ± 4.8
ORM	53.1 ± 2.2	3.7 ± 0.4	3.5 ± 0.2	75.5 ± 3.6

From Table 4.7 the activity levels for all radionuclides varied significantly from one sub-County to another. This may be so because the samples were collected from different geographical and geological areas. The distances between the fields in these sub-counties from which the samples were collected on average is well over 30 km.

The mean specific activity levels of Maize samples per sub-county are graphically presented in the Figure 4.4

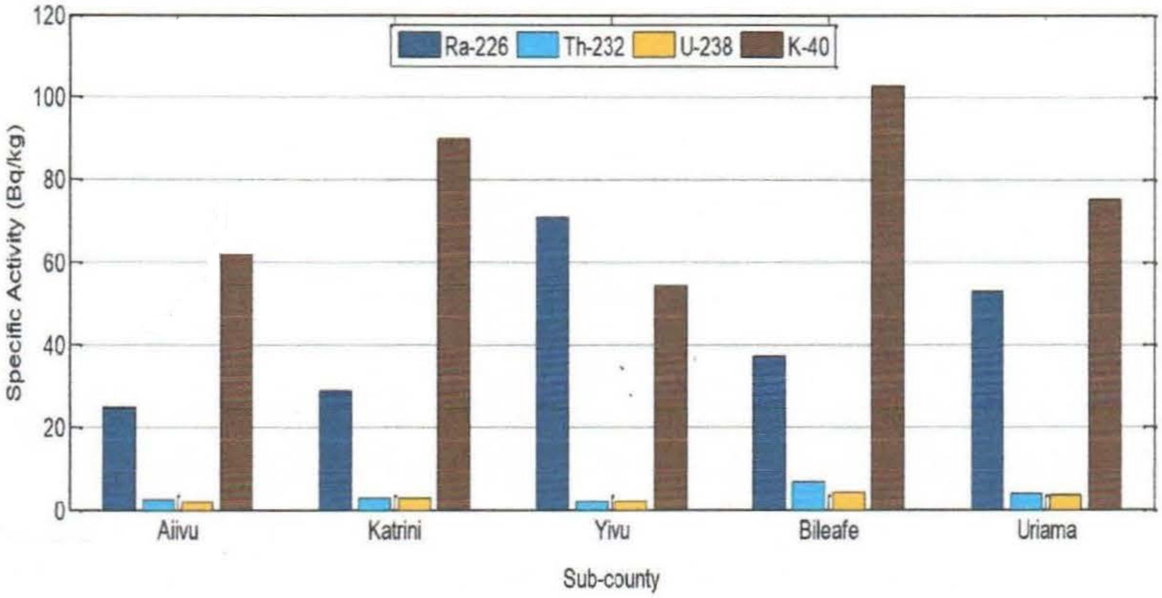

Figure 4.4: Graph of Mean Specific Activity for Maize Samples by Sub-county

Table 4.8: Specific Activity for the Groundnuts Samples collected by Sub-county

Sample ID	**MEAN SPECIFIC ACTIVITY (Bq kg^{-1})**			
	Ra-226	Th-232	U-238	K-40
AIG1	20.3 ± 2.0	6.3 ± 0.7	2.3 ± 0.3	251.6 ± 9.5
AIG2	55.9 ± 2.9	4.4 ± 0.5	3.2 ± 0.3	229.8 ± 8.1
AIG3	64.9 ± 3.2	5.8 ± 0.6	2.5 ± 0.3	234.2 ± 8.3
TAG1	51.8 ± 2.5	6.1 ± 0.6	2.8 ± 0.2	290.3 ± 7.9
TAG2	33.8 ± 2.0	11.2 ± 0.8	4.0 ± 0.3	261.6 ± 7.6
TAG3	61.5 ± 2.5	5.2 ± 0.5	1.6 ± 0.2	111.1 ± 4.5

The mean specific activities for Groundnut per sub-county are presented in Table 4.9.

Table 4.9: Mean Specific Activity for Groundnut Samples by Sub-county

Sample ID	MEAN SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
AIG	47.1 ± 2.7	5.5 ± 0.6	2.7 ± 0.3	238.5 ± 8.6
TAG	49.0 ± 2.3	7.5 ± 0.6	2.8 ± 0.2	221.0 ± 6.7

In table 4.9, groundnut samples from Tara sub-county (TAG) showed the highest mean specific activity level of Radium of 49.0 Bq/kg, Thorium (7.5 Bq/kg) and Uranium (2.8 Bq/kg) while the lowest mean specific activity level of Radium 47.1 Bq/kg, (5.5 Bq/kg) for Thorium and Uranium (2.7 Bq/kg) was observed in samples from Aiivu sub-county (AIG). The samples from Tara (TAG) had the highest mean specific activity level of Potassium (238.5 Bq/kg) and the least mean specific activity level of potassium (221.0 Bq/kg) was showed by groundnut samples from Aii-vu (AIG). The mean specific activity levels of Groundnut samples per sub-county are graphically presented in the Figure 4.5

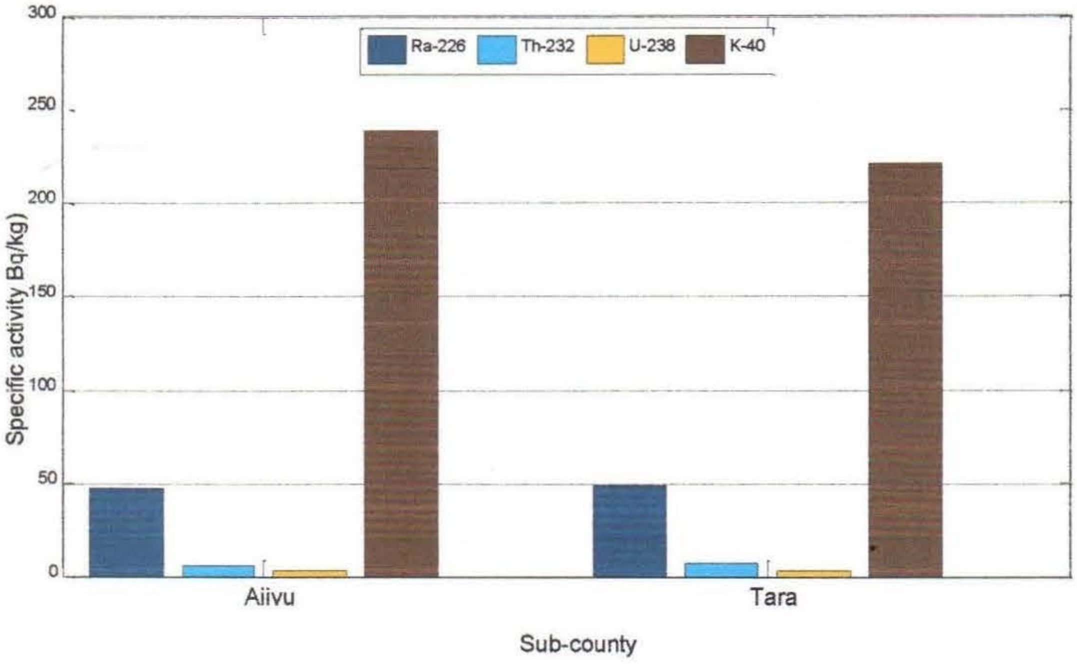

Figure 4.5: Graph of Mean Specific Activity levels in Groundnut Samples by Sub-county

Table 4.10: Specific Activity for Bean Crop Samples by Sub-county

Sample ID	MEAN SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
NYB1	84.1 ± 2.8	7.6 ± 0.5	5.7 ± 0.3	226.8 ± 6.2
NYB2	102.3 ± 3.7	5.4 ± 0.6	3.8 ± 0.9	97.4 ± 4.9
NYB3	64.7 ± 2.3	2.0 ± 0.3	1.9 ± 0.2	56.4 ± 2.9
KAB1	60.3 ± 2.3	11.6 ± 0.7	7.2 ± 0.3	534.8 ± 9.2
KAB2	76.6 ± 2.6	11.3 ± 0.6	3.6 ± 0.2	507.7 ± 9.1
OMB1	30.5 ± 1.7	24.9 ± 1.0	6.1 ± 0.3	580.3 ± 10.0
OMB2	62.5 ± 3.2	8.4 ± 0.8	5.4 ± 0.4	181.8 ± 7.3
YIB1	84.5 ± 2.8	4.7 ± 0.4	3.6 ± 0.2	508.8 ± 9.2
YIB2	108.9 ± 3.1	9.2 ± 0.6	5.2 ± 0.3	498.6 ± 9.1

The mean specific activity levels for all bean samples collected per sub-county are presented in Table 4.11

Table 4.11: Mean Specific Activity for Bean Samples by Sub-county

Sample ID	MEAN SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
NYB	83.7 ± 2.9	5.0 ± 0.5	3.8 ± 0.2	126.8 ± 4.7
KAB	68.5 ± 2.4	11.4 ± 0.7	5.4 ± 0.3	521.3 ± 9.1
OMB	46.5 ± 2.4	16.6 ± 0.9	5.7 ± 0.3	381.1 ± 8.6
YIB	96.7 ± 2.9	7.0 ± 0.5	4.4 ± 0.3	503.7 ± 9.1

In table 4.11, bean samples collected from Yivu (YIB) had the highest mean specific activity level of Radium (96.7 Bq/kg) and least mean specific activity level (46.5 Bq/kg) for Radium was showed by bean samples from Omugo (OMB). The bean samples from

Omugo (OMB) showed the highest mean specific activity level of Thorium (16.6 Bq/kg), Uranium (5.7 Bq/kg) and the least mean specific activity level (5.0 Bq/kg) for Thorium, Uranium (3.8 Bq/kg) was observed in bean samples collected from Nyadri sub-county (NYB). The bean samples from Katrini (KAB) showed the highest mean specific activity level of Potassium (521.3 Bq/kg) and the least mean specific activity level (126.8 Bq/kg) for Potassium was presented by bean samples from again Nyadri (NYB). The mean specific activity levels of Bean samples per sub-county are graphically presented in the Figure 4.6

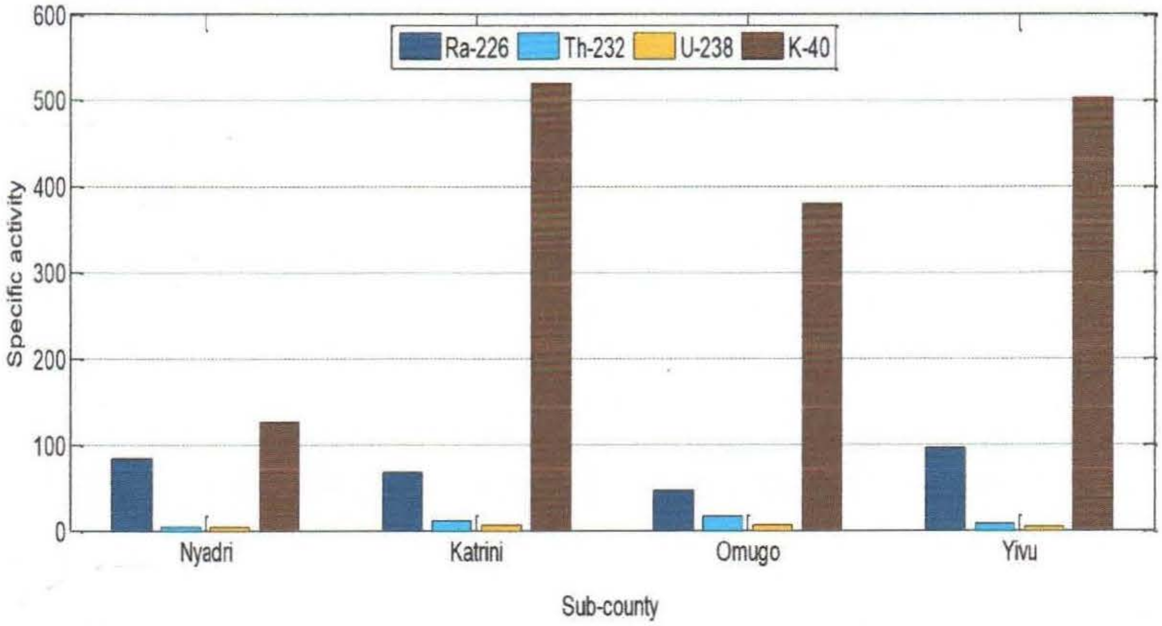

Figure 4.6: Graph of Mean Specific Activity for the Bean Samples Collected by Sub-County

Table 4.12: Specific Activity for Rice Samples collected by Sub-county

Sample ID	**MEAN SPECIFIC ACTIVITY (Bq kg^{-1})**			
	Ra-226	Th-232	U-238	K-40
NYR1	90.2 ± 2.9	4.2 ± 0.4	3.0 ± 0.2	75.3 ± 3.6
NYR2	69.3 ± 2.4	1.0 ± 0.2	2.0 ± 0.2	5.6 ± 0.9
OMR1	75.5 ± 3.1	9.5 ± 0.7	2.5 ± 0.2	290.5 ± 8.2
OMR2	36.9 ± 1.7	4.4 ± 0.4	3.8 ± 0.2	91.9 ± 3.7
OMR3	32.0 ± 1.7	6.5 ± 0.5	3.0 ± 0.2	97.0 ± 4.1
ODR1	75.2 ± 2.6	2.5 ± 0.3	1.5 ± 0.1	11.4 ± 1.4
ODR2	116.0 ± 3.9	6.3 ± 0.6	3.8 ± 0.3	184.5 ± 6.6
KAR1	45.3 ± 2.3	4.1 ± 0.4	2.1 ± 0.2	148.3 ± 5.5
KAR2	74.3 ± 3.1	8.5 ± 0.7	4.6 ± 0.3	594.8 ± 12.0

The mean specific activities for all the rice samples collected per sub-county are presented in Table 4.13.

Table 4.13: Mean Specific Activity for Rice Samples by Sub-county

Sample ID	**MEAN SPECIFIC ACTIVITY (Bq kg^{-1})**			
	Ra-226	Th-232	U-238	K-40
NYR	79.7 ± 2.7	2.6 ± 0.3	2.5 ± 0.2	40.4 ± 2.3
OMR	48.1 ± 2.2	6.8 ± 0.5	3.1 ± 0.2	159.8 ± 5.3
ODR	95.6 ± 3.2	4.4 ± 0.4	2.6 ± 0.2	97.9 ± 4.0
KAR	59.8 ± 2.7	6.3 ± 0.6	3.3 ± 0.3	371.5 ± 8.8

In table 4.13, rice samples collected from Odupi (ODR) had the highest mean specific activity level of Radium (95.6 Bq/kg) and least mean specific activity level (48.1 Bq/kg) for Radium was showed by rice samples from Omugo (OMR). However the rice samples from Omugo (OMR) presented the highest mean specific activity level of Thorium (6.8 Bq/kg) and least mean specific level (2.6 Bq/kg) for Thorium, (2.5 Bq/kg) for Uranium and (40.4 Bq/kg) for Potassium was observed in the same rice samples from Nyadri (NYR). The rice samples from Katrini (KAR) presented the highest mean specific activity level of Uranium (3.3 Bq/kg), Potassium (371.8 Bq/kg). The mean specific activity levels of rice samples per sub-county are graphically presented in the Figure 4.7

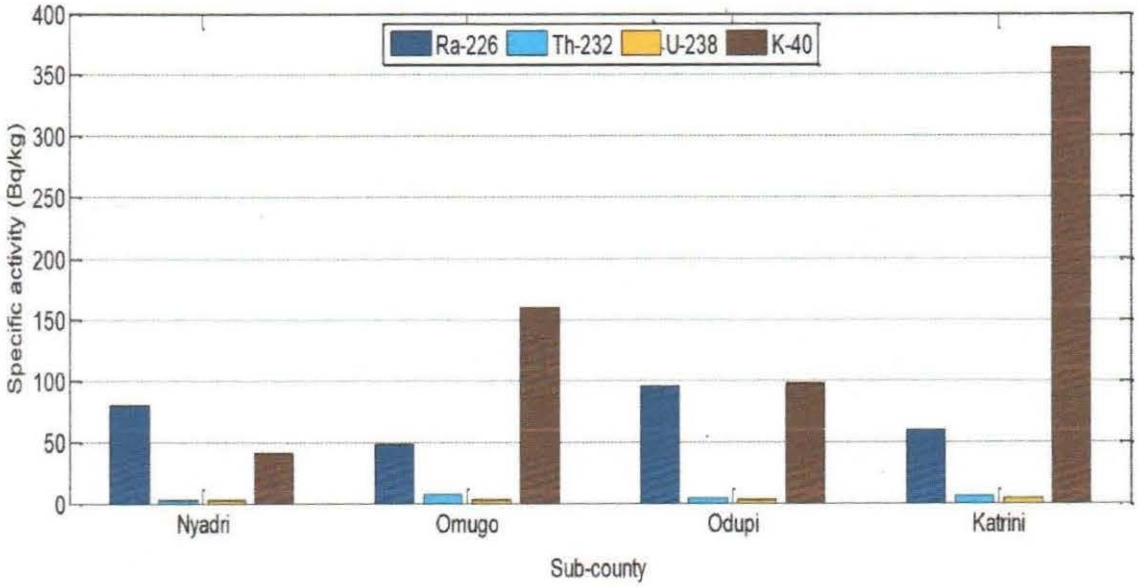

Figure 4.7: Graph of Mean Specific Activity level for Rice Samples by Sub-county

Table 4.14: Specific Activity level for the Sorghum Samples Collected by Sub-county

Sample ID	MEAN SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
KASO1	60.2 ± 2.5	2.7 ± 0.4	2.6 ± 0.2	126.2 ± 5.0
KASO2	41.4 ± 2.1	3.6 ± 0.4	4.4 ± 0.3	172.0 ± 5.7
YISO1	73.5 ± 2.7	2.2 ± 0.3	2.8 ± 0.2	82.8 ± 3.9
YISO2	83.0 ± 3.1	3.4 ± 0.4	4.0 ± 0.3	119.2 ± 5.0

The mean specific activity levels for Sorghum samples collected per sub-county are presented in Table 4.15

Table 4.15: Mean Specific Activity for Sorghum Samples Collected by Sub-county

Sample ID	**MEAN SPECIFIC ACTIVITY (Bq kg^{-1})**			
	Ra-226	Th-232	U-238	K-40
KASO	50.8 ± 2.3	3.1 ± 0.4	3.5 ± 0.2	149.1 ± 5.3
YISO	78.2 ± 2.9	2.8 ± 0.4	3.4 ± 0.2	101.0 ± 4.4

In Table 4.15, sorghum samples collected from Yivu sub-county (YISO) had the highest mean specific activity level of Radium (78.2 Bq/kg) and least mean specific activity level (50.8 Bq/kg) for Radium was showed by sorghum samples from Katrini (KASO). The sorghum samples from Katrini (KASO) presented the highest mean specific activity levels of Thorium (3.1 Bq/kg), Uranium (3.5 Bq/kg) and Potassium (149.1 Bq/kg) while the least mean specific activity level (2.8 Bq/kg) for Thorium, (2.8 Bq/kg) for Uranium and (101.0 Bq/kg) for Potassium was showed by sorghum samples from Yivu (YISO). Generally the mean specific activity levels were in close range except the values for radium in KASO was significantly low compared to that in YISO and that of potassium in KASO was relatively greater than that in YISO. The mean specific activity levels of sorghum samples per sub-county are graphically presented in the Figure 4.8

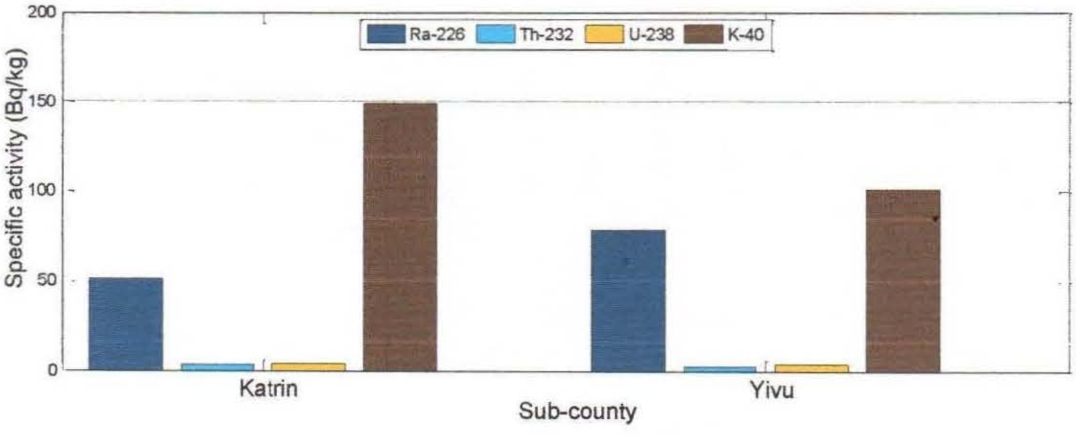

Figure 4.8: Graph of Mean Specific Activity for Sorghum Samples Collected by Sub-County

Table 4.16: Mean Specific Activity for Food Crop Samples Collected

Sample ID	MEAN SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
RICE	68.3 ± 2.6	5.2 ± 0.5	2.9 ± 0.2	166.6 ± 5.1
BEANS	74.9 ± 2.7	9.4 ± 0.6	4.7 ± 0.3	354.7 ± 7.5
G. NUTS	48.1 ± 2.5	6.5 ± 0.6	2.7 ± 0.2	229.8 ± 7.7
SIMSIM	71.6 ± 3.2	7.1 ± 0.7	4.1 ± 0.3	125.0 ± 5.9
SORGHUM	64.5 ± 2.6	2.9 ± 0.4	3.5 ± 0.2	125.1 ± 4.9
MAIZE	43.9 ± 2.0	3.6 ± 0.4	3.0 ± 0.2	76.8 ± 3.7
CASSAVA	76.7 ± 3.0	7.2 ± 0.6	3.8 ± 0.3	217.8 ± 6.8

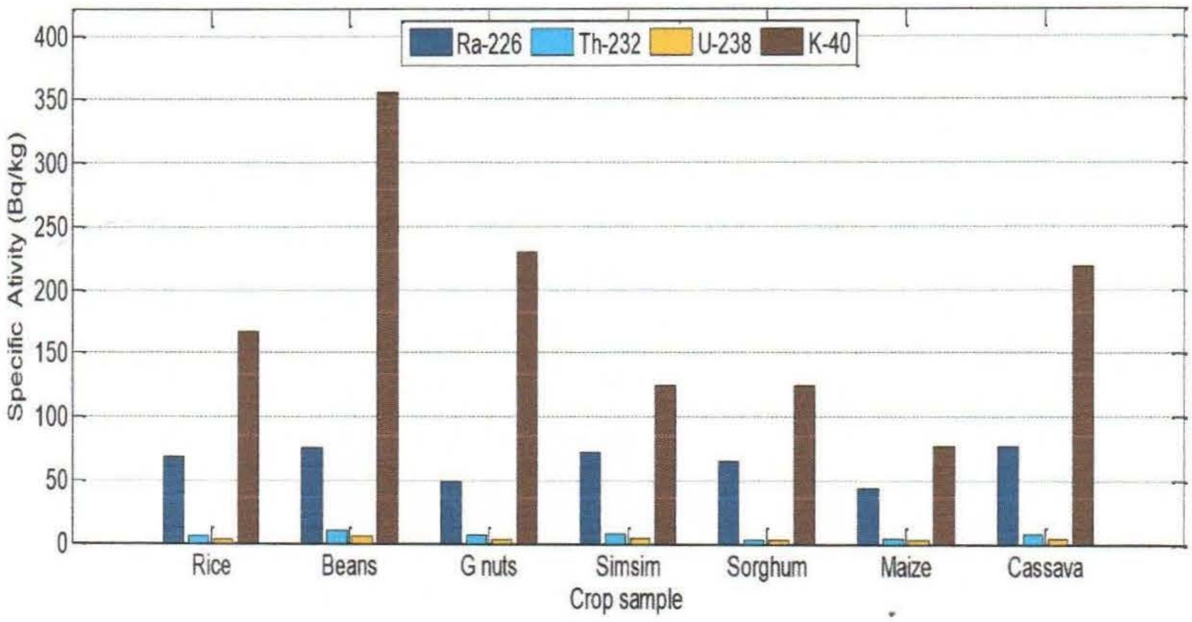

Figure 4.9: Graph of Mean Specific Activity for All Food Crop Samples

In Table 4.16, cassava samples showed the highest mean specific activity levels of Radium (76.7 Bq/kg) while least mean activity (43.9 Bq/kg) for Radium was observed in maize samples. Bean samples presented the highest mean specific activity levels of Thorium (9.4 Bq/kg), Uranium (4.7 Bq/kg) and Potassium (354.7 Bq/kg) while the least mean specific activity level (2.9 Bq/kg) for Thorium and Uranium (2.7 Bq/kg) was showed by sorghum samples and groundnut samples respectively. And the least mean specific activity levels (76.8 Bq/kg) for Potassium was observed in maize samples. The mean specific activity levels of the crop samples are graphically presented in the Figure 4.9

Table 4.17: Mean Absorbed Dose rate (D) and Mean Effective Annual Dose rate (H)

	DOSES	
Crop type	D (nGy/h)	H (mSv/yr)
RICE	41.7 ± 1.7	0.1 ± 0.01
BEANS	55.1 ± 1.9	0.2 ± 0.01
G. NUTS	35.7 ± 1.9	0.1 ± 0.01
SIMSIM	42.6 ± 2.1	0.1 ± 0.01
SORGHUM	36.8 ± 1.6	0.1 ± 0.01
MAIZE	25.6 ± 1.3	0.1 ± 0.01
CASSAVA	48.9 ± 2.0	0.1 ± 0.01

In Table 4.17, the mean absorbed dose rate and the mean annual effective dose rate were calculated from the absorbed dose rates and annual effective dose rates computed for each crop sample collected presented in Table 4.16. Bean samples had the highest absorbed dose rate (55.1. nGy/h) and the annual effective dose rate (0.2. mSv/yr) while maize samples presented the least absorbed dose rate (25.6 nGy/h) and annual effective dose rate (0.1 mSv/yr). Generally the absorbed dose values obtained for close in range and the annual effective dose rate values are close in range to one another for all samples; and are low compared to the world average (0.5 – 1 Sv) known to have increased cancer risk (IAEA, 2014). The dose levels for absorbed dose and the annual effective dose rates are presented graphically in Figures 4.10 and 4.11 respectively.

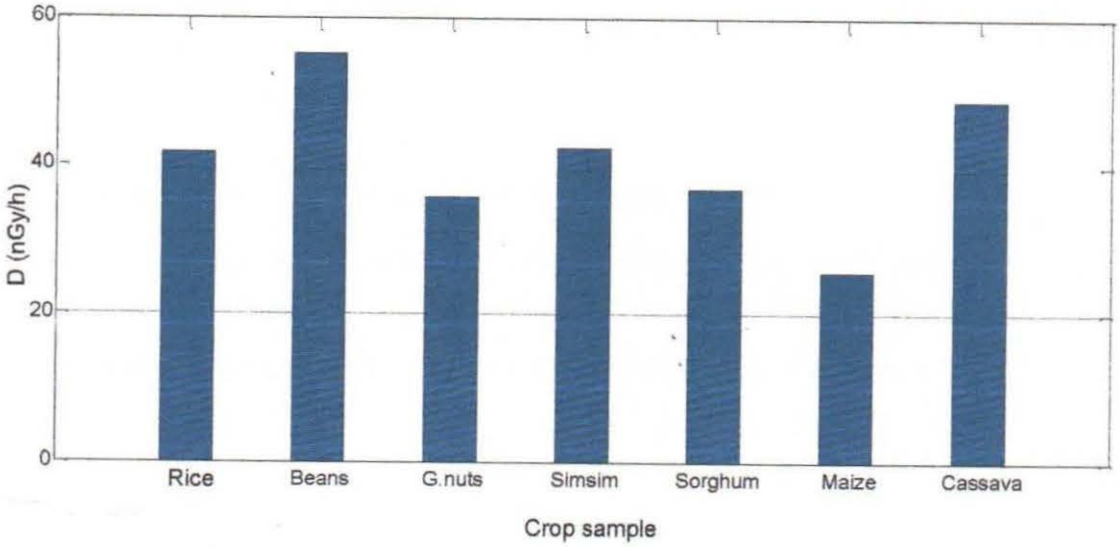

Figure 4.10: Graph of Mean Absorbed Dose rate (D) for All the Samples Collected

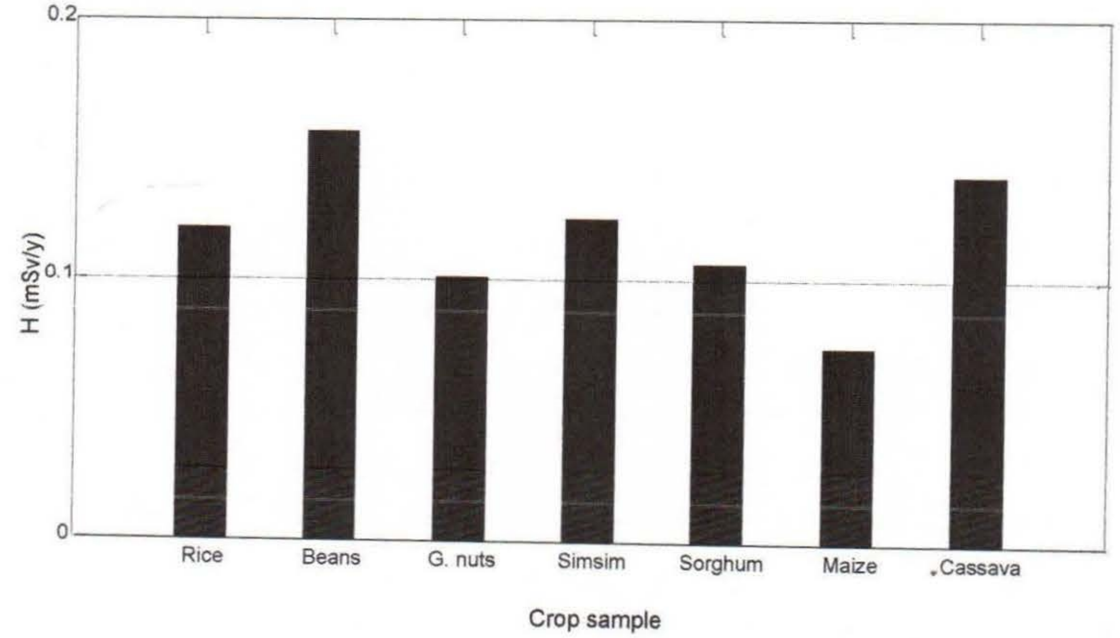

Figure 4.11: Graph of Mean Effective Annual Dose rate (H) for All the Samples

In Tables 4.10, the specific activity levels are high for Bean samples followed by Cassava and the least specific activity is shown by Rice samples. For all the samples analysed, Potassium presented the highest mean specific activity, followed by Radium, Thorium and the least mean specific activity was observed in Uranium.

4.4 Mean Specific Activity in all Food Crop Samples by sub-county

The mean specific activity in all crop samples per sub-county were computed using the specific activities for samples presented in Tables 4.2 – 4.16. The mean specific activities for all the samples considered by sub-county are shown in Table 4.18.

Table 4.18: Mean Specific Activity levels of All Crop Samples by Sub-county

	MEAN SPECIFIC ACTIVITY CONCENTARATIONS (Bq kg^{-1})			
Sub-County	Ra-226	Th-232	U-238	K-40
TARA	51.2 ± 2.5	7.3 ± 0.6	3.4 ± 0.3	208.1 ± 7.0
ODUPI	115.3 ± 3.8	5.4 ± 0.5	3.4 ± 0.3	145.2 ± 5.5
YIVU	83.7 ± 2.9	3.7 ± 0.4	3.2 ± 0.2	194.9 ± 5.4
OMUGO	49.8 ± 2.4	11.2 ± 0.7	4.3 ± 0.3	283.0 ± 7.4
KATRINI	56.8 ± 2.5	5.5 ± 0.5	4.0 ± 0.3	261.6 ± 7.0
AII-VU	34.8 ± 2.2	4.8 ± 0.6	2.8 ± 0.3	155.3 ± 6.3
NYADRI	92.3 ± 3.1	4.3 ± 0.4	3.2 ± 0.2	102.2 ± 4.1
BILEAFE	46.4 ± 2.5	8.2 ± 0.7	4.5 ± 0.3	164.0 ± 6.0
ORIAMA	56.5 ± 2.6	7.0 ± 0.6	3.72 ± 0.3	96.4 ± 4.5

In Table 4.18 the mean specific activity levels of potassium (^{40} K) was the highest in the range (96.4 – 283.0) Bqkg^{-1}, Radium in the range (34.8 – 115.3) Bqkg^{-1} followed by Thorium in the range 3.7 – 11.2 Bqkg^{-1}and the least mean specific activity was observed in Uranium in the range (2.8 – 3.4) Bqkg^{-1}.

Omugo sub-county had the highest mean specific activity levels of potassium (2.8×10^{2} Bqkg^{-1}), Thorium (11.2 Bqkg^{-1}) and the least mean specific activity level of potassium

(1.0×10^2 BqKg^{-1}), Thorium (3.7 Bqkg^{-1}) was observed in samples from Oriama and Yivu sub-counties respectively. Bileafe sub -county presented the highest mean specific activity level of 3.5 Bqkg^{-1} for Uranium and Aii-vu had the least mean specific activity levels of Uranium (2.8 Bqkg^{-1}) and Radium 34.8 Bqkg^{-1}. Odupi sub-county showed the highest level of Radium (115.3 Bqkg^{-1}) in the samples.

The mean specific activity levels varied from one sub-county to another; this may be so due to difference in annual fertilizer application rate.

There were generally high levels of potassium in all the samples. The mean specific activity levels in samples per sub-county are presented graphically in Figure 4.12.

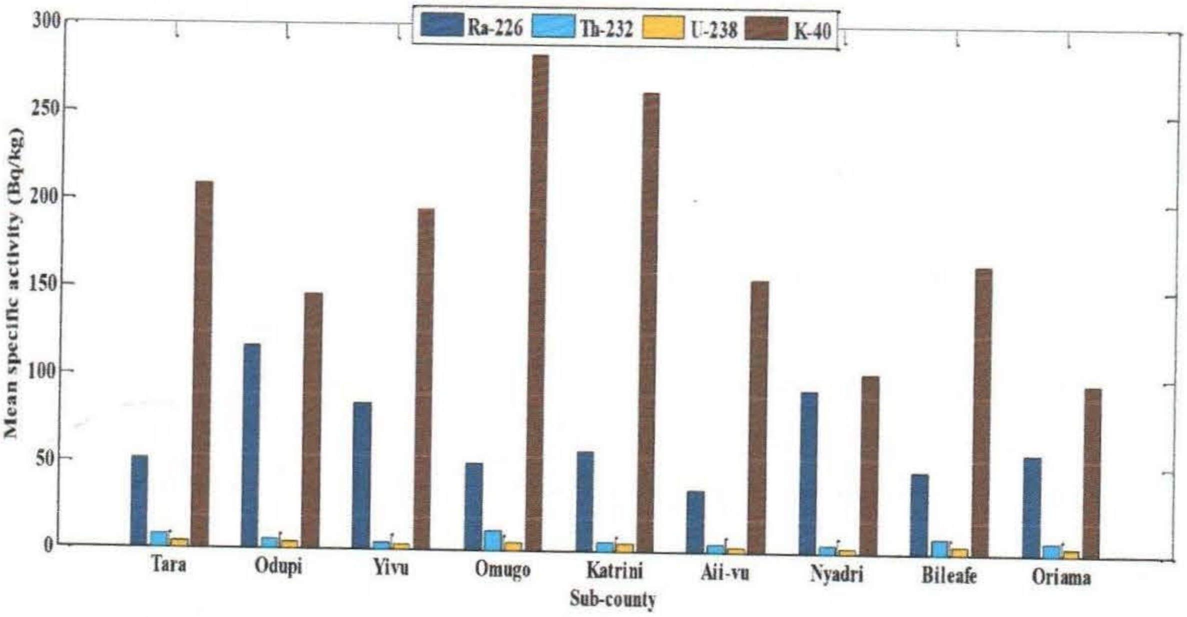

Figure 4.12: Graph of mean specific activity level in samples by sub-county

4.5 Mean Dose Levels in Food crop Samples by Sub County

Using the values of mean specific activity levels in all samples presented in Table 4.18, the mean absorbed dose rate (D) and annual effective dose rate (H) were computed. The mean absorbed dose rate (D) and the annual effective dose rate (H) per Sub County are shown in Tables 4.19.

Table 4.19: Mean Absorbed Dose and Annual Effective Dose Rates by Sub-county

	DOSES					
Sub-county	**D (nGy/h)**			**H (mSv/yr)**		
NYADRI	49.5	±	1.8	0.1	±	0.0
AII-VU	25.5	±	1.6	0.1	±	0.0
KATRINI	40.4	±	1.7	0.1	±	0.0
OMUGO	41.6	±	1.8	0.1	±	0.0
ODUPI	62.6	±	2.3	0.2	±	0.0
TARA	36.8	±	1.8	0.1	±	0.0
YIVU	49.0	±	1.8	0.1	±	0.0
BILEAFE	33.2	±	1.7	0.1	±	0.0
ORIAMA	34.3	±	1.7	0.1	±	0.0

In Table 4.19, the mean absorbed dose rate and the mean annual effective dose rate were calculated from the absorbed dose rates and annual effective dose rates computed for each crop sample collected from each of these sub-counties considered in this study. Odupi sub-county had the highest mean absorbed dose (D) and mean annual effective dose rate (H) of 62.6nGy/h and 0.2mSv/yr respectively. The least mean absorbed dose and the mean annual effective dose rate (25.5nGy/h) and 0.1 mSv/yr was presented by samples from Aii-vu sub-county. The dose levels are presented graphically in Figure 4.13

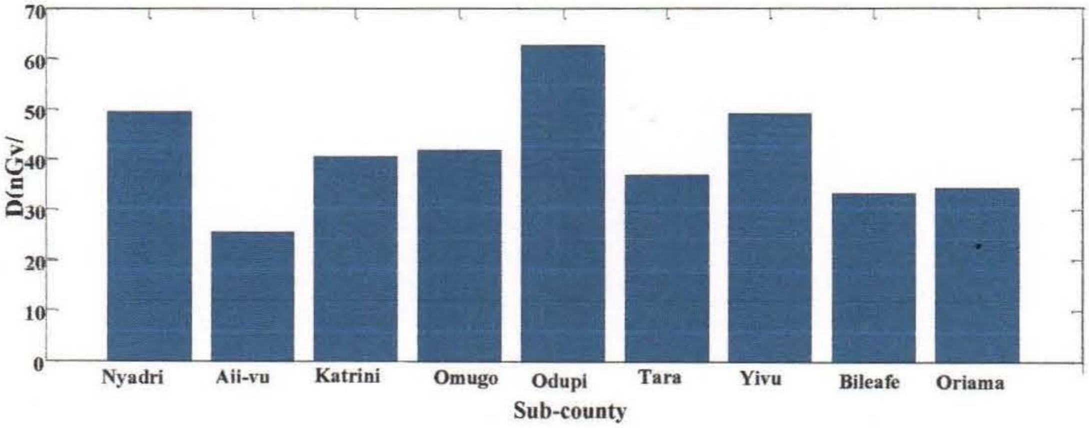

Figure 4.13: A graph of Mean Absorbed Dose by Sub-county

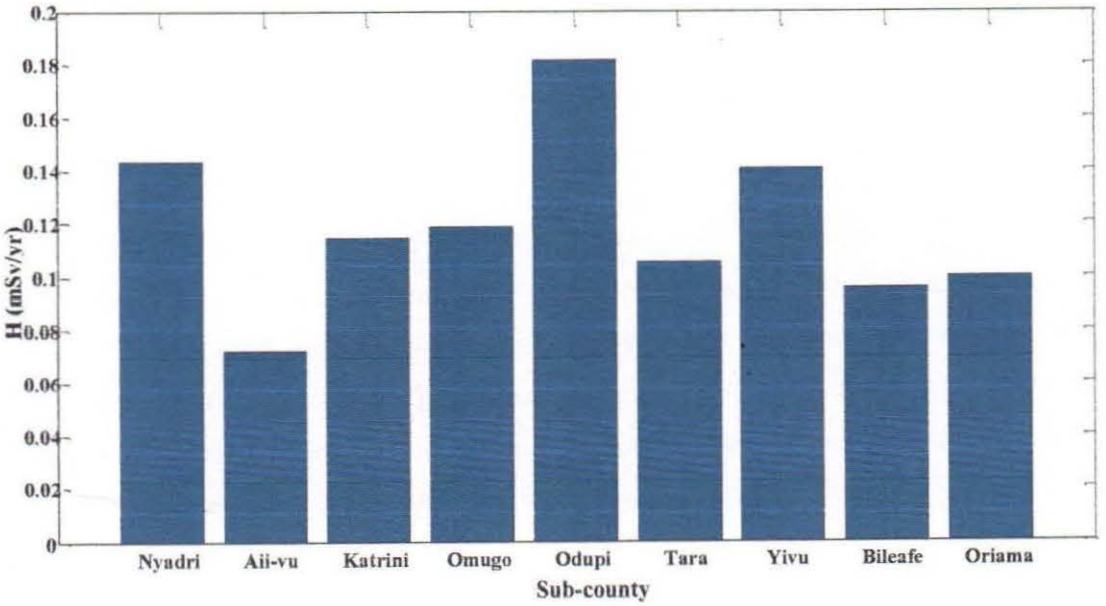

Figure 4.14: A graph of Mean Annual Effective Dose Rate of Samples by Sub-county

CHAPTER FIVE: DISCUSSIONS, CONCLUSION AND RECOMMENDATIONS

5.1 Discussions

The discussion is focused on the specific activity and dose rate levels of ^{40}K, ^{232}Th, ^{238}U and ^{226}Ra in food crop samples of Maize, Sorghum, Beans, Cassava, Simsim, Groundnut and Rice sampled from areas where inorganic phosphate fertilizers were used for production of Tobacco. Specific activity levels and the dose rates due to gamma ray emitting radionuclides varied from one food crop sample to another and from one sub-county to another. The mean specific activities, absorbed dose rate and annual effective dose rates of all the samples analyzed are discussed in the following subsections.

5.1.1 Mean Specific Activities of Samples

The mean specific activity in the samples was found to be mainly due to potassium (^{40}K) (354.7 Bq/kg) and radium (^{226}Ra) (76.7 Bq/kg) and the mean specific activity levels of thorium (9.4 Bq/kg) and uranium (4.7Bq/kg) were relatively in small quantities.

In Table 4.16 the mean specific activity levels of potassium (^{40}K) was the highest in the range 76.8 – 354.7 Bqkg^{-1}, Radium in the range 43.9 – 115.3335 Bqkg^{-1} followed by Thorium in the range 3.0 – 9.4 Bqkg^{-1}and the least mean specific activity was observed in Uranium in the range 3.0 – 4.7 Bqkg^{-1}.

In table 4.11 Omugo Sub County had the highest mean specific activity levels of potassium (2.8304×10^{2}Bqkg^{-1}) and the least mean specific activity level of potassium (0.9639×10^{2} BqKg^{-1}) was obtained from samples collected from Oriama Sub County. Omugo sub-county is thickly populated and with high level of land fragmentation, this might have led to intense NPK fertilizer application over the years since it is the commonest type of inorganic fertilizer used by farmers during tobacco cultivation. Oriama sub-county being a new human settlement area that is sparsely populated, there could be chances that small amounts of potassium have accumulated over the short farming period (UNBS, 2012). It is known that with high population, over cultivation can lead to loss in soil fertility through leaching and nutrient exhaustion (Harb 2004)

In 1998, Lemeriga, found the activity levels in some beans and simsim food crops due to Potassium (^{40}K) sampled in the districts of Mbale and Hoima in Uganda where inorganic phosphate fertilizers were used were in range of 116.86 – 338 Bq/kg. The results in this study are consistent with his finding with a slight variation. This slight variation could be due to differences in plant physiology since more crop samples other than these two mentioned were considered, annual fertilizer application rates and the difference in background radiation brought about by the different geographical areas considered in this study (Schultz at el, 2002).

The high activity of potassium determined in this study is because it is an essential element for plant growth and reproduction. It is also possible that the annual application rate of the NPK fertilizers for growth of tobacco could be high in the county of Maracha East in Maracha and Terego East and West counties of Arua district.

Potassium has a number of functions in plants, which include enzyme activation. It is well established that K^+ is required for protein synthesis in higher plants (IAEA, 1989). The K^+ ion affects photosynthesis in higher plants at various levels and is an important inorganic solute. Potassium plays a key role in osmoregulation. It is also well established that cell expansion is the consequence of the accumulation in the plant cells of K^+, which is required for PH stability in the cytoplasm and to increase osmotic pressure in the vacuoles (Lemeriga, 1998).

In most plant species K^+ has the major responsibility for turgidity changes in the guard cells during stomatal movement. An increase in the concentration of K^+ in guard cells result in the uptake of water from the adjacent cells, this increases the guard cell turgidity thus stomatal opening phenomena. Potassium is also involved in phloem transport and cation-anion balance in the cytoplasm (Marchner, 1986). According to Marchner, 1986 potassium is the most abundant cation in the cytoplasm and radioactive potassium (^{40}K) constitutes about 0.01% of the total potassium available and this explains why its presence in the food crop samples analysed was correspondingly high in this study.

In 2008, Ashraf Khater found the mean specific activity levels of Potassium in foods produced by employing inorganic phosphate fertilizers in Saudi Arabia were in the range 283 – 589 Bq/kg but in this study the activity level of potassium is in the range 76 – 354.7 Bq/kg which is low. This variation may arise from the difference in annual application rate, the fact that these crops considered in this study were grown as post tobacco harvest i.e. as such much of the nutrients in the fertilizers were absorbed by the tobacco as the first harvest.

The specific activities due to ^{226}Ra were high in every food sample considered, ranging between 34.8 ± 2.2 and 115.3 ± 3.8 Bqkg^{-1}. This high specific activity agrees with the findings of the study by (Ashraf Khater *et al,* 2008) on the Radiological quality of ^{226}Ra, ^{232}Th and ^{40}K in food crop samples for radium (75 – 283 Bqkg^{-1}) collected from the Central desert in Iran though the geological components of the two regions might not be alike. There is variation in the values presented in this study; this could be because samples used in this study were grown as post tobacco harvest and those considered by Ashraf were grown directly as first harvest of the fertilizer application.

The low activities of ^{232} Th and ^{238} U in all the samples could be due to the difference in mineral nutrient uptake by plants. Mineral uptake by plants is affected by not only the concentration of these radionuclides in the soil and the fertilizers but also by factors like the plant species, soil PH, metabolic activity and the presence of other elements with which these elements may compete for uptake (Schulz, 2005) This variation may also be due to the differences in plant physiology and crop species, annual fertilizer application rates which was not considered in this study and the difference in the background radiation levels which varies significantly from one geographical area to another. There are possibilities that these elements (^{232}Th and ^{238}U) may exist in soils in forms that cannot be easily absorbed by plants (complex giant molecular structures) (Schulz, 2004). Another factor that could also account for the low activity count for these elements could be substantial leaching of them during high rainfall (Khater, 2008)

The distribution of radionuclides in the soil layer equivalent to the depth of plant root zone is an effective factor for radionuclide plant uptake. The root zone layer is dependent on the plant species and the water table depth (Khater, 2008). The plant uptake of radionuclides is affected by the plant root distribution, and the distribution of radio nuclide with soil depth. There may be possibilities that the uptake of ^{232}Th and ^{238}U could be affected by this absorption factor leading to their low activity levels in this study. According to Baxter, 1993, the average activity in general soil due to ^{238} U is about 24 Bq/kg. This is well far above from 3.6 Bq/kg obtained in this study by a factor of about 6. This may be due to the factors discussed above that affect uptake of nutrients by plants.

According to Lemeriga, 1998, the specific activity of ^{232}Th and ^{238}U in some Beans and Simsim samples collected from districts of Mbale and Hoima in Uganda, the activity levels were in the ranges of 34.9–51.2 Bq/kg and 6.1 – 10.3 Bq/kg for ^{232}Th and ^{238}U respectively. This may be due to accumulation of radionuclides from the mines around the fields from which these samples were obtained. In this study the low activity levels for ^{232}Th (3.0 – 9.4 Bq/kg) and for ^{238}U (2.7 – 4.1 Bq/kg) would mean that the contamination levels due to their accumulation in soil and correspondingly their concentrations in the food crop samples collected were low. There are possibilities that the annual fertilizer application rates and background radiation in the fields from which these samples were collected are low. And in addition effects of leaching of these radionuclides could be high (Khater at el 2008) thus reducing their concentration in the food crops grown as post tobacco harvest in the sub counties of Maracha East and Terego East and West considered in this study.

5.1.2 Mean Absorbed Dose rate and the Annual Effective Dose rate.

The dose limits for practices are intended to ensure that no individual is committed to unacceptable risk due to radiation exposure. For the public the limit is 1 mSv in a year or in special circumstances up to 5 mSv in a single year, provided that the average dose over five consecutive years does not exceed 1 mSv per year (IAEA, 2003). In this study the total absorbed dose rate for all samples was 41.3nGyh^{-1} and the annual effective dose rate for all the samples was 0.1mSvyr^{-1}.

Odupi sub-county had the highest mean absorbed dose rate (62.6 ± 2.3 $nGyh^{-1}$) with Aii-vu sub-county giving the least (25.5 ± 1.6 $nGyh^{-1}$). The mean absorbed dose rate was 41.3 n Gyh^{-1} which is lower than the reference level of 55nGyh^{-1} for all sources of food samples (Abdi *et al.*, 2009).

The mean annual effective dose equivalent in this study was also highest in Odupi sub-county (0.2 ± 0.01 $mSvyr^{-1}$) and lowest in Aii-vu sub-county (0.1 ± 0.00 mSv yr^{-1}). The overall mean annual effective dose for all the nine sub-counties was estimated to be in the range 0.1 – 0.2 mSv yr^{-1}. The upper limit of 0.2 mSv yr^{-1} is slightly higher than the world average value of 0.12 mSv yr^{-1} (**UNSCEAR**, 2000; the **WHO**, 2004) reference limit of 0.1 mSv yr^{-1} but lower than the **UNSCEAR** (2000), **ICRP** (2000) recommended level of 1 mSv yr^{-1} for all sources of food.

In all aspects it is very clear that if an individual is exposed, say at a rate of 0.2mSv/yr, which is the upper limit of annual effective dose rate in this study, then it is possible that over a period of 31 years an individual may cumulatively attain a dose of about 5 mSv. Therefore feeding on such food crops contaminated with these radionuclides for 5 years may likely not pose a health risk for individuals.

5.2 Conclusion

The gamma ray emitting radionuclides of ^{40}K, ^{238}U, ^{232}Th and ^{226}Ra were identified in the crop samples collected. The radionuclides of ^{40}K and ^{226}Ra were more abundant by count than the radionuclides of ^{232}Th and ^{238}U. The activity levels of all radionuclides in the food crop samples were determined. Radioactivity levels varied from one Sub-county to another and from one food crop sample to another. The activity levels of ^{40}K in the nine sub-counties was the highest in the range 76.8–354.7 Bq/kg, that of ^{226}Ra was in the range 43.9 – 76.7 Bq/kg, followed by ^{232}Th in the range 3.0 – 9.4 Bq/kg and the least activity level was shown by ^{235}U in the range 2.7 – 4.7 Bq/kg. The absorbed dose for all samples was measured in the range (25.6 - 55.1. nGy/h) and the annual effective dose rate for all samples was also computed in the range (0.1 - 0.2. mSv/yr). The annual effective doze rates are generally low compared to the average global annual effective doze rate of 1 mSv/yr. This means that their radiological effects on humans consuming these food crops may not be very significant over a short period of time, although over the years the effects may well be significant.

5.3 Recommendations

1. Since radioactivity varied from place to place and also from one crop sample to another, a study should be carried out to measure;
    - (i) The annual application rate of fertilizers during Tobacco farming.
    - (ii) Relative absorption rates for legumes and cereals.
    - (iii) The distribution of radionuclides in the soil layer equivalent to the depth of plant root zone for radionuclide plant uptake.
2. The activity levels in all locally grown and widely consumed foods grown in areas where inorganic fertilizers have never been used should be obtained to establish a data base to compare their activity levels to those grown in soils contaminated by use of inorganic phosphate fertilizers.
3. It would be necessary if similar research is done to compare the findings in this study.
4. It would also be good to carry out a study to establish the concentration levels of contaminants in fertilizers, their physical and chemical properties in the soil.
5. It is recommended that consumption of the food crops investigated should continue as it poses no potential radiation hazard.
6. It is further recommended that investigation should be performed on other crops which are not investigated in this study.

REFERENCES

1. Abdel-Haleem AS, Sroor A, El-Bahi S M, Zohny E (2001) Heavy metals and rare earth elements in phosphate fertilizer components using instrumental neutron activation analysis. Appl. Radiation. Isot. 55: 569-573

2. Abdul-Majid, S., Abulfaraj, W (1992). *Radioactivity concentration in soil in Jeddah area*, Saudi Arabia. J. Environ. Sci. Health A27, 105e116.

3. Abrahams P.W. (2002). *Soils and their implications to human health.* The Science of the Total Environment 291, 1–32

4. Adams. F and Dams.R, Applied Gamma-Ray Spectroscopy (Pergamon Press, Oxford, 1970)

5. Akira Takeda, Kazuhiko Kimura, Shin-ichiYamasak, (2004). *Analysis of 57 elements in Japanese soils, with special reference to soil group and agricultural use.* Geoderma 119, 291–307.

6. Baxter, M.S., (1993), *Environmental radioactivity. A perspective on industrial contribution*, IAEA Bulletin vol.35, No.2, page33, Vienna Austria.

7. Beck H.L., Decampo J., and Gogolok C. "Insitu Ge(Li) and NaI(Tl) gamma ray spectrometry" HASL -258, Health and Safety Laboratory, U.S. Atomic Energy Commission, New York, 1972.

8. Beretka, J., Mathew, P.J., (1985). *Natural radioactivity of Australian building materials, industrial wastes and by-products.* Health Physics 48, 87–95.

9. Bigu J, Hussein M., Hussein AZ (2000) *Radioactivity measurements in Egyptian phosphate mines and their significance in the occupational exposure of mine workers.*

Journal of Environmental Radioactivity 47, 229-243.

10. Blanco Rodriuez, P., Vera Tome, F., Lozano, J.C., Perez-Fernandez, M.A, (2008). *Influence of soil texture on the distribution and availability of ^{238}U, ^{230}Th and ^{226}Ra in soils.* Environmental Radioactivity 99, 1247-1254.

11. Brigden K, Stringer R, Santillo D, (2002). *Heavy metal and radionuclide contamination of fertilizer products and phosphogypsum waste produced by the Lebanese Chemical Company* Greenpeace Research Laboratories Technical Note

13/2002, November 2002:16p. http://www.greenpeace.to/publications_pdf

12. Chowdhury, M.I., Kamal, M., Alam M.N., SalehaYeasmin, Mostafa M.N. (2006). *Distribution of naturally occurring radionuclides in soil of the southern districts of Bangladesh.* Radiation protection and dosimetry 118 (1), 126-130.

13. Commission of the European Communities, (1993). "Radiation protection; Fifth international symposium on the natural radiation environment", Report EUR 14411 EN.

14. Eisenbud, M. (1987), "Environmental Radioactivity from Natural, Industrial and Military Sources" Academic Press, Inc.

15. El-Mrabet R, Abril J, Periáñez R, Manjón G, García-Tenorio R, Delgado A, Andreu L (2003). *Phosphogypsum amendment effect on radionuclide content in drainage water and marsh soils from South-western Spain.* Journal of Environmental Quality 32:1262- 1268.

16. El-Reefy .H.I, Sharshar .T, Zaghloul .R, Badran .H.M., (2006), *Distribution of gamma-ray emitting radionuclides in the environment of Burullus Lake (Soils and vegetations),* Journal of Environmental Radioactivity 87,148-169.

17. Farouk, M. A., Souraya, A. M., (1982). *Ra-226 as standard source for efficiency calibration of Ge (Li) detector.* Nuclear Instruments and Methods 200, 593-595.

18. Foth H.D. "Fundamentals of soil science"; (1978), (John Wiley, New York).

19. Knoll G.F, (1988), *Radiation Detection and Measurement*, second edition, John Wiley and Sons, Inc, New York.

20. Garcia Leon M, Martinez Aguirre A, Perianez R, Bolivar JP, Garcia-Tenorio R, (1995). *Levels and behavior of natural radioactivity in the vicinity of phosphate fertilizer plants.* Journal of Radio analytical and Nuclear Chemistry, 197: 173-184.

21. Guimond, R.J. (1990). *Radium in fertilizers*. Technical Report No. 310 International Atomic Energy Agency (IAEA), Environmental behavior of radium, 113–128.

22. Hamamo H, Landsberger S, Harbottle G, Panno S, (1995). *Studies of radioactivity and heavy metals in phosphate fertilizers.* Journal of radio analytical and nuclear chemistry. Articles. 194 (2), 331-336.

23. Harb .S, 2004. On the human radiation exposure as derived from the analysis of natural and man-made radionuclides in soil. PhD Thesis, VomFachbereich Physik der University Hannover.

24. Howard, R.A. (1963), *Nuclear physics*, Wadsworth publishing company Inc Belmont, California. http://minerals.usgs.gov/minerals/pubs/mcs/, 05.07.2013

25. International Atomic Energy Agency (IAEA), (1979). *Gamma-ray surveys in uranium exploration.* Technical Report Series No. 186, International Atomic Energy Agency.

26. International Atomic Energy Agency (IAEA), (2003). *Extent of environmental contamination by naturally occurring radioactive material (NORM) and technological options for mitigation*. Technical Reports. Series No. 419: 87-107 IAEA, Vienna http://www.pub.iaea.org/MTCD/publications/PDF/TRS419_web.pdf, 04.04.2013.

27. International Atomic Energy Agency (IAEA), (2001). Analysis of U supply to 2050.http://www-pub.iaea.org/MTCD/publications/PDF/Pub1104_scr.pdf.IAEA. Vienna.

28. International Atomic Energy Agency, (1989), "Measurement of radionuclides in food and the environment" Technical report series No. 295.

29. International Atomic Energy Agency, 1979, "Methodology for assessing impacts of radioactivity on Aquatic Ecosystems" Technical Report No. 190.

30. Jasinski SM (2007) *Phosphate rock statistics and information*. U.S. Geological Survey, Mineral commodities summaries,

31. Khater A.E, Higgy R H, Pimpl M, 2001. *Radiological impacts of natural radioactivity in Abu-Tartor phosphate deposits, Egypt.* Journal of Environmental Radioactivity 55.

32. Lemeriga Yasin. M.Sc. Dissertation (1998), *Low level radionuclide counting of Cs, K, U, and Th in selected Ugandan foods and their corresponding soils of growth*, Makerere University.

33. Mattetnik GDM20-*measurement system for Radioactivity, User's Guide version 1.2*, (1995) Gamma Data AB, S-75148 Uppsala SWEDEN.

34. Merdanoglu B., Altinsoy N., (2006). *Radioactivity concentrations and dose assessment for soil samples from Kestanbolgranote area.* Radiation protection and dosimetry 121 (4), 399-405.

35. Nafaa Reguigui, 2006, *Gamma Ray Spectroscopy*- practical information.

36. Nasim Akhatar. Ph.D. Thesis (2006*), Radionuclide pollution due to fertilizer use in some saline soils of the Punjab and their potential risk assessment on human health*, Bahauddin Zakariya University Multan, Pakistan.

37. Schulz, R.K., (1695) "Soil Chemistry of radionuclide" J. Health Physics 11, 13171324.

38. UNSCEAR, (2000), *Radiological Dose Impact Assessment Report in Food Crops on Humans*

39. World Health Organization (WHO, 2004), *Radiation Dose Recommendations in foodstuffs*

APPENDICES

Annex A: Uranium-238 and Thorium-232 decay series

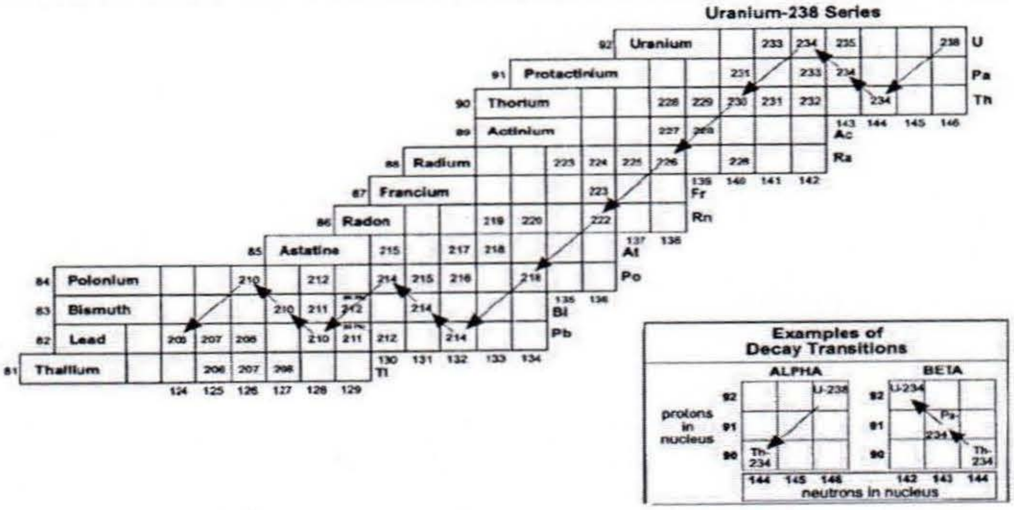

Figure 2.6 A schematic diagram of the Uranium series (Harb, 2004)

Annex B: Thorium 232 series

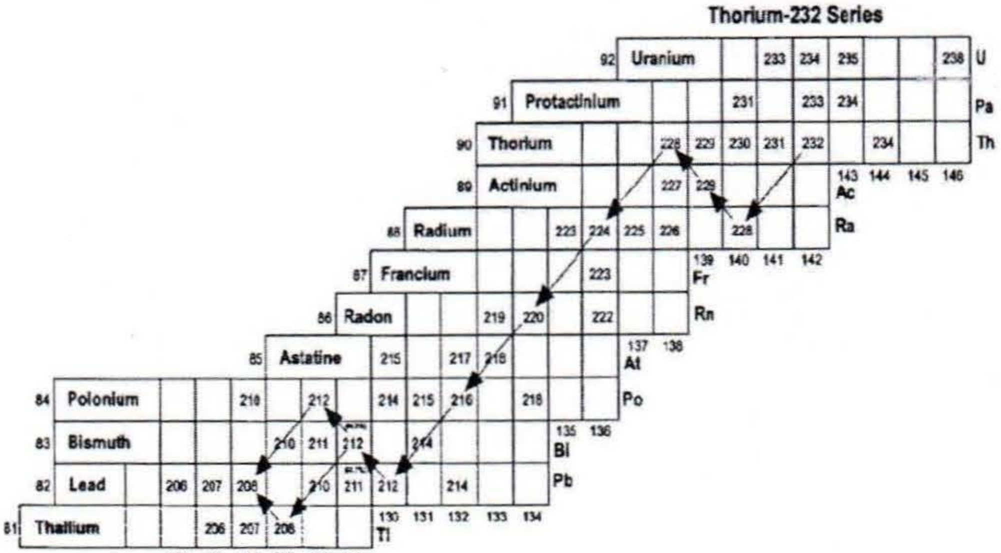

Figure 2.7 A schematic diagram of the Thorium decay series (Harb, 2004)

APPENDICES

Annex A: Uranium-238 and Thorium-232 decay series

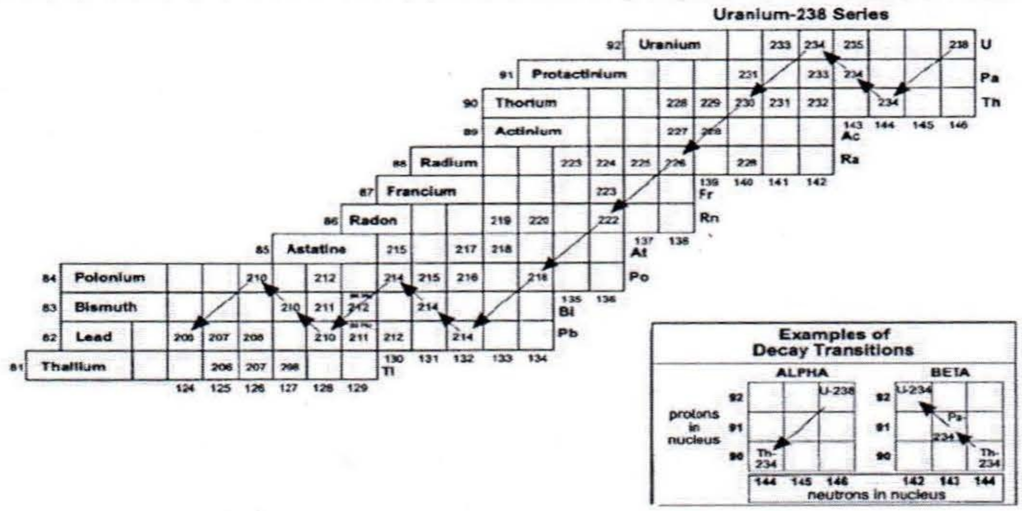

Figure 2.6 A schematic diagram of the Uranium series (Harb, 2004)

Annex B: Thorium 232 series

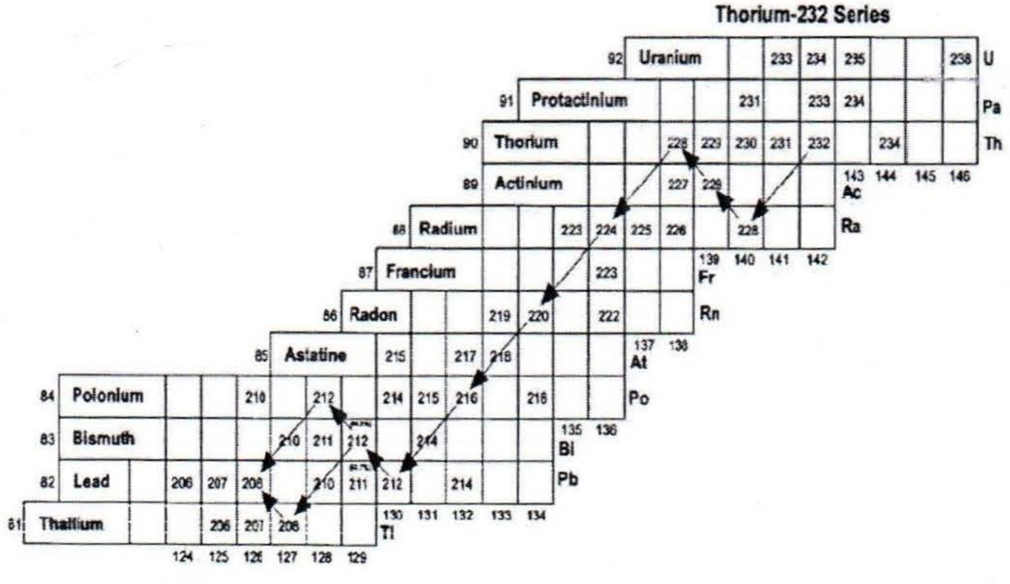

Figure 2.7 A schematic diagram of the Thorium decay series (Harb, 2004)

Annex C: Uranium-235 decay series

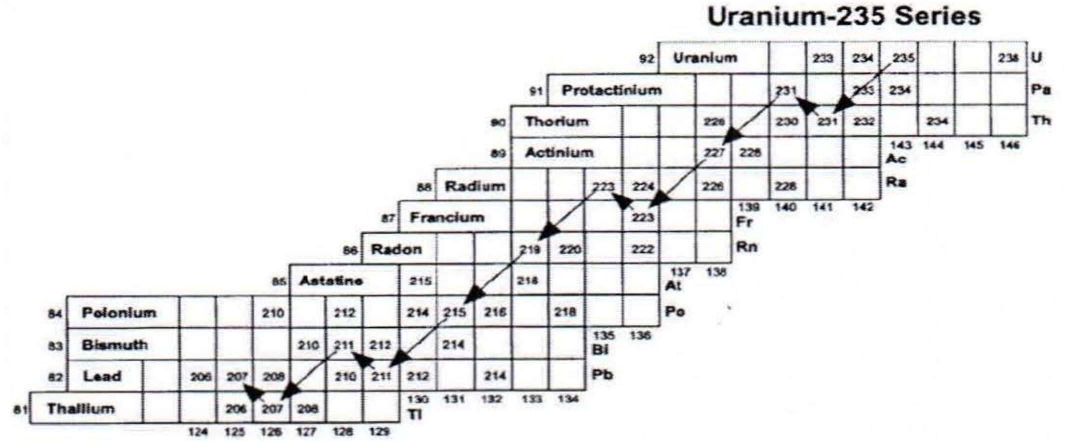

Figure 2.8 A schematic diagram of Uranium-235 (Actinium) decay series (Harb, 2004)

Annex D Results of Gamma Energies for all crop samples Analyzed.

ID	ISOTOPE	PK	M	T	C	CENT	N	S.A	Err
NYC1	40K	1	0.285	7106	0.0023	1309.228	671	141.5913	5.4661
	Th(Tl – 208)	2	0.285	7106	0.0101	512.992	133	6.5022	0.5638
	U(Pb – 214)	3	0.285	7106	0.0237	329.664	180	3.7502	0.2795
	U(Pb – 214)	4	0.285	7106	0.0300	255.404	144	2.3701	0.1975
	U(Ra – 226)	5	0.285	7106	0.0043	185.519	1115	128.0373	3.8344
NYC2	40K	1	0.324	6164	0.0023	1300.829	524	112.1264	4.8983
	Th(Tl – 208)	2	0.324	6164	0.0101	504.562	60	2.9746	0.3840
	U(Pb – 214)	3	0.324	6164	0.0237	337.058	177	3.7395	0.2811
	U(Pb – 214)	4	0.324	6164	0.0300	246.835	110	1.8360	0.1751
	U(Ra – 226)	5	0.324	6164	0.0043	186.429	923	107.4795	3.5377
NYR1	40K	1	0.394	6211	0.0023	1301.712	431	75.2668	3.6255
	Th(Tl – 208)	2	0.394	6211	0.0101	520.664	105	4.2483	0.4146
	U(Pb – 214)	3	0.394	6211	0.0237	331.123	198	3.4140	0.2426
	U(Pb – 214)	4	0.394	6211	0.0300	255.11	190	2.5881	0.1878
	U(Ra – 226)	5	0.394	6211	0.0043	187.390	949	90.1862	2.9276
NYR2	40K	1	0.437	6267	0.0023	1303.662	36	5.6175	0.9363
	Th(Tl – 208)	2	0.437	6267	0.0101	512.709	29	1.0484	0.1947
	U(Pb – 214)	3	0.437	6267	0.0237	330.718	92	1.4174	0.1478
	U(Pb – 214)	4	0.437	6267	0.0300	258.442	210	2.5560	0.1764
	U(Ra – 226)	5	0.437	6267	0.0043	184.646	816	69.2916	2.4257
NYB1	40K	1	0.416	6011	0.0023	1307.485	1327	226.7854	6.2256
	Th(Tl – 208)	2	0.416	6011	0.0101	534.055	192	7.6022	0.5486
	U(Pb – 214)	3	0.416	6011	0.0237	330.327	388	6.5470	0.3324

	U(Pb – 214)	4	0.416	6011	0.0300	257.484	357	4.7589	0.2519
	U(Ra – 226)	5	0.416	6011	0.0043	188.918	904	84.0737	2.7962
NYB2	40K	1	0.285	6007	0.0023	1308.164	390	97.3523	4.9296
	Th(Tl – 208)	2	0.285	6007	0.0101	521.094	94	5.4363	0.5607
	U(Pb – 214)	3	0.285	6007	0.0237	325.717	146	3.5983	0.2978
	U(Pb – 214)	4	0.285	6007	0.0300	251.983	205	3.9914	0.2788
	U(Ra – 226)	5	0.285	6007	0.0043	190.345	753	102.2878	3.7276
NYB3	40K	1	0.435	6620	0.0023	1309.594	380	56.3924	2.8929
	Th(Tl – 208)	2	0.435	6620	0.0101	517.241	58	1.9942	0.2618
	U(Pb – 214)	3	0.435	6620	0.0237	336.855	130	1.9048	0.1671
	U(Pb – 214)	4	0.435	6620	0.0300	252.568	166	1.9215	0.1491
	U(Ra – 226)	5	0.435	6620	0.0043	189.639	801	64.6870	2.2856
AIG1	K -40	1	0.200	6004	0.0023	1316.239	707	251.6129	9.4629
	Th (Tl - 208)	2	0.200	6004	0.0101	535.755	76	6.2664	0.7188
	U (Pb - 214)	3	0.200	6004	0.0237	339.774	64	2.2489	0.2811
	U (Pb - 214)	4	0.200	6004	0.0300	248.839	86	2.3873	0.2574
	U(Ra – 226)	5	0.200	6004	0.0043	212.184	105	20.3353	1.9845
AIG2	K -40	1	0.250	6004	0.0023	1321.229	807	229.7614	8.0880
	Th (Tl - 208)	2	0.250	6004	0.0101	578.658	67	4.4195	0.5399
	U (Pb - 214)	3	0.250	6004	0.0237	348.020	88	2.4737	0.2637
	U (Pb - 214)	4	0.250	6004	0.0300	253.000	180	3.9973	0.2979
	U(Ra – 226)	5	0.250	6004	0.0043	200.676	361	55.9317	2.9438
AIG3	K -40	1	0.240	6013	0.0023	1319.091	791	234.2384	8.3286
	Th (Tl - 208)	2	0.240	6013	0.0101	576.728	85	5.8317	0.6325
	U (Pb - 214)	3	0.240	6013	0.0237	369.482	67	1.9590	0.2393
	U (Pb - 214)	4	0.240	6013	0.0300	250.641	134	3.0951	0.2674
	U(Ra – 226)	5	0.240	6013	0.0043	191.441	403	64.9433	3.2351
AIM1	K -40	1	0.390	6100	0.0023	1326.165	535	96.1044	4.1550
	Th (Tl - 208)	2	0.390	6100	0.0101	541.410	44	1.8312	0.2761
	U (Pb - 214)	3	0.390	6100	0.0237	337.640	81	1.4366	0.1596
	U (Pb - 214)	4	0.390	6100	0.0300	276.706	170	2.3820	0.1827
	U(Ra – 226)	5	0.390	6100	0.0043	196.170	255	24.9274	1.5610
AIM2	K -40	1	0.420	6021	0.0023	1312.456	165	27.8837	2.1707
	Th (Tl - 208)	2	0.420	6021	0.0101	536.694	76	2.9756	0.3413
	U (Pb - 214)	3	0.420	6021	0.0237	338.785	112	1.8688	0.1766
	U (Pb - 214)	4	0.420	6021	0.0300	251.823	138	1.8190	0.1548
	U(Ra – 226)	5	0.420	6021	0.0043	200.716	271	24.9220	1.5139
AIS1	K -40	1	0.200	6159	0.0023	1312.464	191	66.2639	4.7947
	Th (Tl - 208)	2	0.200	6159	0.0101	538.044	96	7.7163	0.7875
	U (Pb - 214)	3	0.200	6159	0.0237	321.883	90	3.0829	0.3250
	U (Pb - 214)	4	0.200	6159	0.0300	231.000	187	5.0603	0.3700
	U(Ra – 226)	5	0.200	6159	0.0043	209.670	66	12.4605	1.5338
AIS2	K -40	1	0.240	6400	0.0023	1316.024	652	181.4014	7.1042
	Th (Tl - 208)	2	0.240	6400	0.0101	541.461	74	4.7700	0.5545
	U (Pb - 214)	3	0.240	6400	0.0237	326.241	165	4.5326	0.3529

	U (Pb - 214)	4	0.240	6400	0.0300	252.465	149	3.2335	0.2649
	U(Ra – 226)	5	0.240	6400	0.0043	206.610	265	40.1223	2.4647
KASO1	K -40	1	0.360	6086	0.0023	1314.263	647	126.1984	4.9614
	Th (Tl - 208)	2	0.360	6086	0.0101	548.371	60	2.7114	0.3500
	U (Pb - 214)	3	0.360	6086	0.0237	317.151	79	1.5214	0.1712
	U (Pb - 214)	4	0.360	6086	0.0300	241.080	242	3.6818	0.2367
	U(Ra – 226)	5	0.360	6086	0.0043	207.864	567	60.1839	2.5275
KASO2	K -40	1	0.360	6258	0.0023	1311.609	907	172.0495	5.7128
	Th (Tl - 208)	2	0.360	6258	0.0101	540.594	81	3.5598	0.3955
	U (Pb - 214)	3	0.360	6258	0.0237	336.820	137	2.5659	0.2192
	U (Pb - 214)	4	0.360	6258	0.0300	268.455	428	6.3326	0.3061
	U(Ra – 226)	5	0.360	6258	0.0043	196.626	401	41.3940	2.0671
KAS1	K -40	1	0.230	6079	0.0023	1318.063	621	189.8085	7.6168
	Th (Tl - 208)	2	0.230	6079	0.0101	540.601	70	4.9570	0.5925
	U (Pb - 214)	3	0.230	6079	0.0237	327.398	170	5.1303	0.3935
	U (Pb - 214)	4	0.230	6079	0.0300	252.091	211	5.0304	0.3463
	U(Ra – 226)	5	0.230	6079	0.0043	198.398	453	75.3477	3.5401
KAS2	K -40	1	0.230	6031	0.0023	1319.744	525	161.7433	7.0591
	Th (Tl - 208)	2	0.230	6031	0.0101	542.482	33	2.3555	0.4100
	U (Pb - 214)	3	0.230	6031	0.0237	310.055	60	1.8251	0.2356
	U (Pb - 214)	4	0.230	6031	0.0300	339.895	344	8.2665	0.4457
	U(Ra – 226)	5	0.230	6031	0.0043	201.823	459	76.9533	3.5919
KAM1	K -40	1	0.411	6114	0.0023	1318.970	519	88.2641	3.8744
	Th (Tl - 208)	2	0.411	6114	0.0101	526.612	76	2.9945	0.3435
	U (Pb - 214)	3	0.411	6114	0.0237	324.333	132	2.2165	0.1929
	U (Pb - 214)	4	0.411	6114	0.0300	251.348	168	2.2285	0.1719
	U(Ra – 226)	5	0.411	6114	0.0043	198.337	384	35.5382	1.8136
KAM2	K -40	1	0.380	6320	0.0023	1320.636	516	91.8191	4.0421
	Th (Tl - 208)	2	0.380	6320	0.0101	553.751	62	2.5561	0.3246
	U (Pb - 214)	3	0.380	6320	0.0237	322.560	132	2.3191	0.2019
	U (Pb - 214)	4	0.380	6320	0.0300	263.923	359	4.9828	0.2630
	U(Ra – 226)	5	0.380	6320	0.0043	196.870	227	21.9815	1.4590
KAB1	K -40	1	0.446	6016	0.0023	1314.357	3358	534.8379	9.2296
	Th (Tl - 208)	2	0.446	6016	0.0101	535.629	313	11.5500	0.6528
	U (Pb - 214)	3	0.446	6016	0.0237	328.415	490	7.7056	0.3481
	U (Pb - 214)	4	0.446	6016	0.0300	264.462	533	6.6216	0.2868
	U(Ra – 226)	5	0.446	6016	0.0043	201.917	696	60.3251	2.2866
KAB2	K -40	1	0.440	6016	0.0023	1311.544	3145	507.7434	9.0539
	Th (Tl - 208)	2	0.440	6016	0.0101	544.850	301	11.2586	0.6489
	U (Pb - 214)	3	0.440	6016	0.0237	321.906	153	2.4388	0.1972
	U (Pb - 214)	4	0.440	6016	0.0300	242.372	372	4.6845	0.2429
	U(Ra – 226)	5	0.440	6016	0.0043	195.324	872	76.6104	2.5944
KAR1	K -40	1	0.380	5415	0.0023	1318.153	714	148.2861	5.5495
	Th (Tl - 208)	2	0.380	5415	0.0101	538.339	85	4.0899	0.4436
	U (Pb - 214)	3	0.380	5415	0.0237	319.697	103	2.1121	0.2081

	U (Pb - 214)	4	0.380	5415	0.0300	253.804	132	2.1383	0.1861
	U(Ra – 226)	5	0.380	5415	0.0043	200.425	401	45.3204	2.2632
KAR2	K -40	1	0.350	5011	0.0023	1307.942	2441	594.7843	12.0386
	Th (Tl - 208)	2	0.350	5011	0.0101	547.757	150	8.4679	0.6914
	U (Pb - 214)	3	0.350	5011	0.0237	333.240	225	5.4130	0.3609
	U (Pb - 214)	4	0.350	5011	0.0300	245.955	196	3.7251	0.2661
	U(Ra – 226)	5	0.350	5011	0.0043	198.094	560	74.2552	3.1379
OMC1	K -40	1	0.300	6037	0.0023	1313.121	1469	346.6279	9.0438
	Th (Tl - 208)	2	0.300	6037	0.0101	524.513	296	16.1818	0.9406
	U (Pb - 214)	3	0.300	6037	0.0237	332.052	179	4.1703	0.3117
	U (Pb - 214)	4	0.300	6037	0.0300	254.729	205	3.7730	0.2635
	U(Ra – 226)	5	0.300	6037	0.0043	199.401	338	43.4016	2.3607
OMC2	K -40	1	0.300	6076	0.0023	1309.489	1677	393.1680	9.6009
	Th (Tl - 208)	2	0.300	6076	0.0101	530.426	161	8.7451	0.6892
	U (Pb - 214)	3	0.300	6076	0.0237	342.749	69	1.5972	0.1923
	U (Pb - 214)	4	0.300	6076	0.0300	266.562	472	8.6314	0.3973
	U(Ra – 226)	5	0.300	6076	0.0043	196.461	534	68.1293	2.9482
OMB1	K -40	1	0.410	6064	0.0023	1311.618	3376	580.2879	9.9872
	Th (Tl - 208)	2	0.410	6064	0.0101	528.165	625	24.8895	0.9956
	U (Pb - 214)	3	0.410	6064	0.0237	329.255	515	8.7401	0.3851
	U (Pb - 214)	4	0.410	6064	0.0300	268.305	253	3.3920	0.2133
	U(Ra – 226)	5	0.410	6064	0.0043	191.393	326	30.4934	1.6889
OMB2	K -40	1	0.240	6062	0.0023	1312.003	619	181.8225	7.3081
	Th (Tl - 208)	2	0.240	6062	0.0101	526.117	123	8.3706	0.7548
	U (Pb - 214)	3	0.240	6062	0.0237	336.769	171	4.9593	0.3792
	U (Pb - 214)	4	0.240	6062	0.0300	239.178	255	5.8424	0.3659
	U(Ra – 226)	5	0.240	6062	0.0043	195.113	391	62.5002	3.1608
OMR1	K -40	1	0.309	6008	0.0023	1315.229	1262	290.5060	8.1776
	Th (Tl - 208)	2	0.309	6008	0.0101	516.565	179	9.5465	0.7135
	U (Pb - 214)	3	0.309	6008	0.0237	332.123	79	1.7955	0.2020
	U (Pb - 214)	4	0.309	6008	0.0300	257.152	180	3.2319	0.2409
	U(Ra – 226)	5	0.309	6008	0.0043	192.095	603	75.5371	3.0761
OMR2	K -40	1	0.454	6226	0.0023	1321.872	608	91.9227	3.7280
	Th (Tl - 208)	2	0.454	6226	0.0101	523.481	126	4.4135	0.3932
	U (Pb - 214)	3	0.454	6226	0.0237	335.268	163	2.4332	0.1906
	U (Pb - 214)	4	0.454	6226	0.0300	242.702	437	5.1534	0.2465
	U(Ra – 226)	5	0.454	6226	0.0043	201.904	448	36.8591	1.7414
OMR3	K -40	1	0.419	6006	0.0023	1314.981	571	96.9663	4.0579
	Th (Tl - 208)	2	0.419	6006	0.0101	543.822	164	6.4524	0.5038
	U (Pb - 214)	3	0.419	6006	0.0237	325.888	120	2.0120	0.1837
	U (Pb - 214)	4	0.419	6006	0.0300	246.218	297	3.9340	0.2283
	U(Ra – 226)	5	0.419	6006	0.0043	196.968	346	31.9748	1.7190
ODS1	40K	1	0.260	6008	0.0023	1309.811	308	84.2620	4.8013
	Th(Tl – 208)	2	0.260	6008	0.0101	527.852	126	7.9863	0.7115
	U(Pb – 214)	3	0.260	6008	0.0237	332.161	129	3.4845	0.3068

	U(Pb – 214)	4	0.260	6008	0.0300	250.359	128	2.7314	0.2414
	U(Ra – 226)	5	0.260	6008	0.0043	186.184	869	129.3743	4.3887
ODS2	40K	1	0.260	6008	0.0023	1310.951	361	98.7616	5.1980
	Th(Tl – 208)	2	0.260	6008	0.0101	541.824	80	5.0707	0.5669
	U(Pb – 214)	3	0.260	6008	0.0237	331.504	110	2.9713	0.2833
	U(Pb – 214)	4	0.260	6008	0.0300	250.645	259	5.5268	0.3434
	U(Ra – 226)	5	0.260	6008	0.0043	189.408	1198	178.3549	5.1530
ODR1	40K	1	0.420	6253	0.0023	1317.291	70	11.3905	1.3614
	Th(Tl – 208)	2	0.420	6253	0.0101	531.030	67	2.5259	0.3086
	U(Pb – 214)	3	0.420	6253	0.0237	335.204	35	0.5623	0.0950
	U(Pb – 214)	4	0.420	6253	0.0300	256.296	190	2.4115	0.1750
	U(Ra – 226)	5	0.420	6253	0.0043	187.240	849	75.1799	2.5802
ODR2	40K	1	0.300	6008	0.0023	1307.701	778	184.4644	6.6134
	Th(Tl – 208)	2	0.300	6008	0.0101	513.903	115	6.3172	0.5891
	U(Pb – 214)	3	0.300	6008	0.0237	332.910	118	2.7624	0.2543
	U(Pb – 214)	4	0.300	6008	0.0300	250.878	259	4.7899	0.2976
	U(Ra – 226)	5	0.300	6008	0.0043	186.160	899	115.9952	3.8687
ODC1	40K	1	0.330	6004	0.0023	1314.469	1104	238.1215	7.1666
	Th(Tl – 208)	2	0.330	6004	0.0101	540.642	80	3.9977	0.4470
	U(Pb – 214)	3	0.330	6004	0.0237	328.870	306	6.5166	0.3725
	U(Pb – 214)	4	0.330	6004	0.0300	252.117	171	2.8769	0.2200
	U(Ra – 226)	5	0.330	6004	0.0043	185.668	901	105.7552	3.5232
ODC2	40K	1	0.310	6021	0.0023	1305.662	1110	254.1422	7.6281
	Th(Tl – 208)	2	0.310	6021	0.0101	541.222	128	6.7898	0.6001
	U(Pb – 214)	3	0.310	6021	0.0237	340.246	137	3.0970	0.2646
	U(Pb – 214)	4	0.310	6021	0.0300	251.518	146	2.6074	0.2158
	U(Ra – 226)	5	0.310	6021	0.0043	185.389	701	87.3412	3.2988
TAG1	40K	1	0.330	6009	0.0023	1310.373	1347	290.2924	7.9096
	Th(Tl – 208)	2	0.330	6009	0.0101	533.684	122	6.0915	0.5515
	U(Pb – 214)	3	0.330	6009	0.0237	320.979	154	3.2768	0.2641
	U(Pb – 214)	4	0.330	6009	0.0300	254.347	137	2.3029	0.1968
	U(Ra – 226)	5	0.330	6009	0.0043	196.798	442	51.8367	2.4656
TAG2	40K	1	0.310	6170	0.0023	1310.044	1171	261.6340	7.6457
	Th(Tl – 208)	2	0.310	6170	0.0101	527.388	216	11.1811	0.7608
	U(Pb – 214)	3	0.310	6170	0.0237	335.081	135	2.9781	0.2563
	U(Pb – 214)	4	0.310	6170	0.0300	241.337	291	5.0714	0.2973
	U(Ra – 226)	5	0.310	6170	0.0043	198.035	278	33.8010	2.0272
TAG1	40K	1	0.390	6014	0.0023	1310.372	610	111.1440	4.5001
	Th(Tl – 208)	2	0.390	6014	0.0101	522.261	123	5.1923	0.4682
	U(Pb – 214)	3	0.390	6014	0.0237	312.039	62	1.1154	0.1417
	U(Pb – 214)	4	0.390	6014	0.0300	252.437	147	2.0891	0.1723
	U(Ra – 226)	5	0.390	6014	0.0043	204.078	620	61.4745	2.4689
TAS1	40K	1	0.260	6178	0.0023	1304.367	703	187.0330	7.0541
	Th(Tl – 208)	2	0.260	6178	0.0101	504.919	156	9.6157	0.7699
	U(Pb – 214)	3	0.260	6178	0.0237	323.094	202	5.3062	0.3733

	U(Pb – 214)	4	0.260	6178	0.0300	253.186	176	3.6523	0.2753
	U(Ra – 226)	5	0.260	6178	0.0043	202.651	443	64.1378	3.0473
TAS2	40K	1	0.230	6006	0.0023	1315.867	615	190.2594	7.6720
	Th(Tl – 208)	2	0.230	6006	0.0101	523.159	65	4.6589	0.5779
	U(Pb – 214)	3	0.230	6006	0.0237	328.705	108	3.2988	0.3174
	U(Pb – 214)	4	0.230	6006	0.0300	253.505	185	4.4641	0.3282
	U(Ra – 226)	5	0.230	6006	0.0043	194.005	267	44.9500	2.7509
YIC1	40K	1	0.290	6007	0.0023	1310.646	731	179.3271	6.6327
	Th(Tl – 208)	2	0.290	6007	0.0101	518.844	61	3.4670	0.4439
	U(Pb – 214)	3	0.290	6007	0.0237	331.153	136	3.2941	0.2825
	U(Pb – 214)	4	0.290	6007	0.0300	253.176	107	2.0474	0.1979
	U(Ra – 226)	5	0.290	6007	0.0043	187.440	724	96.6528	3.5921
YIC2	40K	1	0.390	6006	0.0023	1309.306	338	61.6667	3.3542
	Th(Tl – 208)	2	0.390	6006	0.0101	513.056	56	2.3671	0.3163
	U(Pb – 214)	3	0.390	6006	0.0237	328.541	113	2.0355	0.1915
	U(Pb – 214)	4	0.390	6006	0.0300	249.671	168	2.3908	0.1845
	U(Ra – 226)	5	0.390	6006	0.0043	187.732	815	80.9169	2.8344
YIM1	40K	1	0.390	6027	0.0023	1314.591	333	60.5428	3.3177
	Th(Tl – 208)	2	0.390	6027	0.0101	516.590	61	2.5695	0.3290
	U(Pb – 214)	3	0.390	6027	0.0237	326.875	156	2.8003	0.2242
	U(Pb – 214)	4	0.390	6027	0.0300	254.258	210	2.9781	0.2055
	U(Ra – 226)	5	0.390	6027	0.0043	188.252	805	79.6456	2.8071
YIB1	40K	1	0.420	6117	0.0023	1305.344	3059	508.8337	9.2000
	Th(Tl – 208)	2	0.420	6117	0.0101	529.905	122	4.7017	0.4257
	U(Pb – 214)	3	0.420	6117	0.0237	336.206	244	4.0073	0.2565
	U(Pb – 214)	4	0.420	6117	0.0300	231.519	248	3.2177	0.2043
	U(Ra – 226)	5	0.420	6117	0.0043	185.735	934	84.5455	2.7664
	40K	1	0.430	6014	0.0023	1308.474	3017	498.5716	9.0769
YIB2	Th(Tl – 208)	2	0.430	6014	0.0101	542.324	241	9.2271	0.5944
	U(Pb – 214)	3	0.430	6014	0.0237	328.710	321	5.2375	0.2923
	U(Pb – 214)	4	0.430	6014	0.0300	239.905	398	5.1301	0.2572
	U(Ra – 226)	5	0.430	6014	0.0043	188.750	1211	108.9040	3.1295
YISO1	40K	1	0.390	6009	0.0023	1309.589	454	82.7891	3.8855
	Th(Tl – 208)	2	0.390	6009	0.0101	518.239	51	2.1547	0.3017
	U(Pb – 214)	3	0.390	6009	0.0237	332.204	163	2.9348	0.2299
	U(Pb – 214)	4	0.390	6009	0.0300	252.112	194	2.7594	0.1981
	U(Ra – 226)	5	0.390	6009	0.0043	186.251	741	73.5331	2.7013
YISO2	40K	1	0.325	6322	0.0023	1304.758	573	119.1793	4.9788
	Th(Tl – 208)	2	0.325	6322	0.0101	521.022	70	3.3732	0.4032
	U(Pb – 214)	3	0.325	6322	0.0237	329.184	256	5.2572	0.3286
	U(Pb – 214)	4	0.325	6322	0.0300	246.706	174	2.8229	0.2140
	U(Ra – 226)	5	0.325	6322	0.0043	184.911	733	82.9655	3.0644
YIM2	40K	1	0.401	6141	0.0023	1308.511	278	48.2442	2.8935
	Th(Tl – 208)	2	0.401	6141	0.0101	509.520	38	1.5278	0.2478
	U(Pb – 214)	3	0.401	6141	0.0237	335.608	64	1.0966	0.1371

	U(Pb – 214)	4	0.401	6141	0.0300	255.665	182	2.4636	0.1826
	U(Ra – 226)	5	0.401	6141	0.0043	184.215	658	62.1404	2.4225
BIC1	40K	1	0.286	6007	0.0023	1306.492	1185	294.7670	8.5629
	Th(Tl – 208)	2	0.286	6007	0.0101	527.148	146	8.4141	0.6964
	U(Pb – 214)	3	0.286	6007	0.0237	328.17	127	3.1191	0.2768
	U(Pb – 214)	4	0.286	6007	0.0300	238.007	326	6.3252	0.3503
	U(Ra – 226)	5	0.286	6007	0.0043	191.823	266	36.0072	2.2077
BIC2	40K	1	0.333	6005	0.0023	1304.726	1530	326.9778	8.3594
	Th(Tl – 208)	2	0.333	6005	0.0101	509.855	138	6.8328	0.5816
	U(Pb – 214)	3	0.333	6005	0.0237	327.758	154	3.2495	0.2619
	U(Pb – 214)	4	0.333	6005	0.0300	239.247	288	4.8008	0.2829
	U(Ra – 226)	5	0.333	6005	0.0043	190.303	460	53.4973	2.4943
BIM1	40K	1	0.430	6007	0.0023	1310.08	317	52.4466	2.9457
	Th(Tl – 208)	2	0.430	6007	0.0101	537.859	155	5.9413	0.4772
	U(Pb – 214)	3	0.430	6007	0.0237	329.056	164	2.6790	0.2092
	U(Pb – 214)	4	0.430	6007	0.0300	250.859	223	2.8778	0.1927
	U(Ra – 226)	5	0.430	6007	0.0043	205.898	191	17.1965	1.2443
BIM2	40K	1	0.240	6045	0.0023	1314.542	519	152.8776	6.7106
	Th(Tl – 208)	2	0.240	6045	0.0101	509.865	111	7.5752	0.7190
	U(Pb – 214)	3	0.240	6045	0.0237	322.44	141	4.1007	0.3453
	U(Pb – 214)	4	0.240	6045	0.0300	241.743	323	7.4212	0.4129
	U(Ra – 226)	5	0.240	6045	0.0043	194.254	357	57.2258	3.0287
BIS1	40K	1	0.259	6060	0.0023	1321.806	353	96.1140	5.1156
	Th(Tl – 208)	2	0.259	6060	0.0101	528.292	182	11.4809	0.8510
	U(Pb – 214)	3	0.259	6060	0.0237	336.765	263	7.0703	0.4360
	U(Pb – 214)	4	0.259	6060	0.0300	239.399	235	4.9908	0.3256
	U(Ra – 226)	5	0.259	6060	0.0043	196.24	441	65.3428	3.1116
BIS2	40K	1	0.255	6406	0.0023	1311.699	233	60.9555	3.9933
	Th(Tl – 208)	2	0.255	6406	0.0101	523.65	144	8.7280	0.7273
	U(Pb – 214)	3	0.255	6406	0.0237	338.423	70	1.8081	0.2161
	U(Pb – 214)	4	0.255	6406	0.0300	265.242	255	5.2035	0.3259
	U(Ra – 226)	5	0.255	6406	0.0043	200.115	346	49.2584	2.6481
ORS1	40K	1	0.240	6005	0.0023	1308.381	287	85.1024	5.0234
	Th(Tl – 208)	2	0.240	6005	0.0101	523.972	111	7.6257	0.7238
	U(Pb – 214)	3	0.240	6005	0.0237	333.545	94	2.7520	0.2839
	U(Pb – 214)	4	0.240	6005	0.0300	259.769	149	3.4462	0.2823
	U(Ra – 226)	5	0.240	6005	0.0043	199.709	391	63.0934	3.1908
ORS2	40K	1	0.280	6020	0.0023	1310.762	388	98.3697	4.9940
	Th(Tl – 208)	2	0.280	6020	0.0101	518.361	175	10.2793	0.7770
	U(Pb – 214)	3	0.280	6020	0.0237	329.622	145	3.6297	0.3014
	U(Pb – 214)	4	0.280	6020	0.0300	250.993	98	1.9380	0.1958
	U(Ra – 226)	5	0.280	6020	0.0043	195.864	432	59.6020	2.8676
ORC1	40K	1	0.290	6004	0.0023	1302.249	461	113.1479	5.2698
	Th(Tl – 208)	2	0.290	6004	0.0101	531.323	138	7.8473	0.6680
	U(Pb – 214)	3	0.290	6004	0.0237	328.451	95	2.3022	0.2362

	U(Pb – 214)	4	0.290	6004	0.0300	231.134	182	3.4843	0.2583
	U(Ra – 226)	5	0.290	6004	0.0043	195.919	349	46.6142	2.4952
ORC2	40K	1	0.310	6178	0.0023	1304.112	679	151.5111	5.8145
	Th(Tl – 208)	2	0.310	6178	0.0101	518.952	229	11.8387	0.7823
	U(Pb – 214)	3	0.310	6178	0.0237	329.773	242	5.3316	0.3427
	U(Pb – 214)	4	0.310	6178	0.0300	261.516	484	8.4239	0.3829
	U(Ra – 226)	5	0.310	6178	0.0043	198.886	549	66.6644	2.8452
ORM1	40K	1	0.425	6006	0.0023	1307.042	391	65.4616	3.3105
	Th(Tl – 208)	2	0.425	6006	0.0101	508.358	124	4.8098	0.4319
	U(Pb – 214)	3	0.425	6006	0.0237	323.953	129	2.1324	0.1877
	U(Pb – 214)	4	0.425	6006	0.0300	247.363	177	2.3114	0.1737
	U(Ra – 226)	5	0.425	6006	0.0043	197.814	375	34.1656	1.7643
ORM2	40K	1	0.430	6005	0.0023	1307.562	446	73.8138	3.4952
	Th(Tl – 208)	2	0.430	6005	0.0101	526.193	79	3.0292	0.3408
	U(Pb – 214)	3	0.430	6005	0.0237	328.544	283	4.6244	0.2749
	U(Pb – 214)	4	0.430	6005	0.0300	242.303	256	3.3047	0.2065
	U(Ra – 226)	5	0.430	6005	0.0043	193..254	769	69.2590	2.4975
ORM3	40K	1	0.410	6004	0.0023	1314.654	503	87.3228	3.8935
	Th(Tl – 208)	2	0.410	6004	0.0101	512.065	82	3.2981	0.3642
	U(Pb – 214)	3	0.410	6004	0.0237	327.482	225	3.8566	0.2571
	U(Pb – 214)	4	0.410	6004	0.0300	237.482	342	4.6311	0.2504
	U(Ra – 226)	5	0.410	6004	0.0043	192.253	592	55.9279	2.2986

Annex E: Specific Activity levels in All Crop samples by Sub-county

Table E.1 Specific Activity of Crop Samples from Aii-vu Sub-county

Sample ID	SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
AIC1	20.3 ± 2.0	6.3 ± 0.7	2.3 ± 0.3	251.6 ± 9.5
AIG1	55.9 ± 3.0	4.4 ± 0.5	3.2 ± 0.3	229.8 ± 8.1
AIG2	64.9 ± 3.2	5.8 ± 0.6	2.5 ± 0.3	234.2 ± 8.3
AIM1	24.9 ± 1.6	1.8 ± 0.3	1.9 ± 0.2	96.1 ± 4.2
AIM2	24.9 ± 1.5	3.0 ± 0.3	1.8 ± 0.2	27.9 ± 2.2
AIS1	12.5 ± 1.5	7.7 ± 0.8	4.1 ± 0.3	66.3 ± 4.8
AIS2	40.1 ± 2.5	4.8 ± 0.6	3.98 ± 0.3	181.4 ± 7.1

Table E.2 Specific Activity of Crop Samples from Bileafe Sub-county

Sample ID	SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
BIC1	36.0 ± 2.2	8.6 ± 0.7	4.7 ± 0.3	294.7 ± 8.6
BIC2	53.5 ± 2.5	6.8 ± 0.6	4.0 ± 0.3	327.0 ± 8.4
BIM1	17.2 ± 1.2	5.9 ± 0.5	2.8 ± 0.2	52.4 ± 2.9
BIM2	57.2 ± 3.0	7.6 ± 0.7	5.8 ± 0.4	152.9 ± 6.7
BIS1	65.3 ± 3.1	11.5 ± 0.9	6.0 ± 0.4	96.1 ± 5.1
BIS2	49.3 ± 2.6	8.7 ± 0.7	3.5 ± 0.3	61.0 ± 4.0

Table E.3 Specific Activity of Crop Samples from Katrini Sub-county

Sample ID	SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
KASO1	60.2 ± 2.5	2.7 ± 0.4	2.6 ± 0.2	126.2 ± 5.0
KASO2	41.4 ± 2.1	3.6 ± 0.4	4.4 ± 0.3	172.0 ± 5.7
KAS1	75.3 ± 3.5	5.0 ± 0.6	5.1 ± 0.4	189.8 ± 7.6
KAS2	77.0 ± 3.6	2.3 ± 0.4	5.0 ± 0.3	161.7 ± 7.1
KAM1	35.5 ± 1.8	3.0 ± 0.3	2.2 ± 0.2	88.3 ± 3.9
KAM2	22.0 ± 1.5	2.6 ± 0.3	3.7 ± 0.2	91.8 ± 4.0
KAB1	60.3 ± 2.3	11.6 ± 0.7	7.2 ± 0.3	534.8 ± 9.2
KAB2	76.6 ± 2.6	11.3 ± 0.6	3.6 ± 0.2	507.7 ± 9.1
KASO3	45.3 ± 2.3	4.1 ± 0.4	2.1 ± 0.2	148.3 ± 5.5

Table E.4 Specific Activity of Crop Samples from Tara Sub-county

Sample ID	SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
TAC1	51.8 ± 2.5	6.0 ± 0.6	2.8 ± 0.2	290.3 ± 8.0
TAG1	33.8 ± 2.0	11.2 ± 0.8	4.0 ± 0.3	261.6 ± 7.6
TAM1	61.5 ± 2.5	5.2 ± 0.5	1.6 ± 0.2	111.1 ± 4.5
TAS1	64.1 ± 3.0	9.6 ± 0.8	4.5 ± 0.3	187.0 ± 7.1
TAS2	45.0 ± 3.0	4.7 ± 0.6	3.9 ± 0.3	190.3 ± 7.7

Table E.5 Specific Activity of Crop Samples from Omugo Sub

Sample ID	SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
OMC1	43.4 ± 2.4	16.2 ± 0.9	4.0 ± 0.3	346.6 ± 9.0
OMC2	68.1 ± 2.9	8.7 ± 0.7	5.1 ± 0.3	393.2 ± 9.6
OMB1	30.5 ± 1.7	24.9 ± 1.0	6.1 ± 0.3	580.3 ± 10.0
OMS1	62.5 ± 3.2	8.4 ± 0.8	5.4 ± 0.4	181.8 ± 7.3
OMG1	75.5 ± 3.1	9.5 ± 0.7	2.5 ± 0.2	290.5 ± 8.2
OMM1	36.9 ± 1.7	4.4 ± 0.4	3.8 ± 0.2	92.0 ± 3.7
OMM2	32.0 ± 1.7	6.5 ± 0.5	3.0 ± 0.2	97.0 ± 4.1

Table E.6 Specific Activity of Crop Samples from Odupi Sub-county

Sample ID	SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
ODS1	129.4 ± 4.4	8.0 ± 0.7	3.1 ± 0.3	84.3 ± 4.8
ODS2	178.3 ± 5.2	5.1 ± 0.6	4.2 ± 0.3	98.8 ± 5.2
ODR1	75.2 ± 2.6	2.5 ± 0.3	1.5 ± 0.1	11.4 ± 1.4
ODC1	116.0 ± 3.9	6.3 ± 0.6	3.8 ± 0.3	184.5 ± 6.6
ODC2	105.8 ± 3.5	4.0 ± 0.4	4.7 ± 0.3	238.1 ± 7.2
ODG1	87.3 ± 3.3	7.0 ± 0.6	2.9 ± 0.2	254.1 ± 7.6

Table E.7 Specific Activity of Crop Samples from Oriama Sub

Sample ID	SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
ORS1	63.0934 ± 3.1908	7.6257 ± 0.7238	3.0991 ± 0.2831	85.1024 ± 5.0234
ORS2	59.6020 ± 2.8676	10.2793 ± 0.7770	2.7839 ± 0.2486	98.3697 ± 4.9940
ORS3	46.6142 ± 2.4952	7.8473 ± 0.6680	2.8933 ± 0.2473	113.1479 ± 5.2698
ORC1	66.6644 ± 2.8452	11.8387 ± 0.7823	6.8778 ± 0.3628	151.5111 ± 5.8145
ORM1	34.1656 ± 1.7643	4.8098 ± 0.4319	2.2219 ± 0.1807	65.4616 ± 3.3105
ORM2	69.2590 ± 2.4975	3.0292 ± 0.3408	3.9646 ± 0.2407	73.8138 ± 3.4952
ORM3	55.9279 ± 2.2986	3.2981 ± 0.3642	4.2439 ± 0.2538	87.3228 ± 3.8935

Table E.8 Specific Activity of Crop Samples from Yivu Sub-county

Sample ID	ACTIVITY CONCENTARATIONS (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
YIC1	96.6528 ± 3.5921	3.4670 ± 0.4439	2.6708 ± 0.2402	179.3271 ± 6.6327
YIM1	80.9169 ± 2.8344	2.3671 ± 0.3163	2.2132 ± 0.1880	61.6667 ± 3.3542
YIM2	79.6456 ± 2.8071	2.5695 ± 0.3290	2.8892 ± 0.2149	60.5428 ± 3.3177
YIB1	84.5455 ± 2.7664	4.7017 ± 0.4257	3.6125 ± 0.2304	508.8337 ± 9.2000
YIB2	108.9040 ± 3.1295	9.2271 ± 0.5944	5.1838 ± 0.2748	498.5716 ± 9.0769
YISO1	73.5331 ± 2.7013	2.1547 ± 0.3017	2.8471 ± 0.2140	82.7891 ± 3.8855
YIG1	82.9655 ± 3.0644	3.3732 ± 0.4032	4.0401 ± 0.2713	119.1793 ± 4.9788
YIM2	62.1404 ± 2.4225	1.5278 ± 0.2478	1.7801 ± 0.1599	48.2442 ± 2.8935

Table E.9 Specific Activity of Crop Samples from Nyadri Sub-County

Sample ID	SPECIFIC ACTIVITY (Bq kg^{-1})			
	Ra-226	Th-232	U-238	K-40
NYC1	128.0373 ± 3.8344	6.5022 ± 0.5638	3.0602 ± 0.2385	141.5913 ± 5.4661
NYC2	107.4795 ± 3.5377	2.9746 ± 0.3840	2.7878 ± 0.2281	112.1264 ± 4.8983
NYSO1	90.1862 ± 2.9276	4.2483 ± 0.4146	3.0011 ± 0.2152	75.2668 ± 3.6255
NYR1	69.2916 ± 2.4257	1.0484 ± 0.1947	1.9867 ± 0.1621	5.6175 ± 0.9363
NYB1	84.0737 ± 2.7962	7.6022 ± 0.5486	5.6530 ± 0.2922	226.7854 ± 6.2256
NYG1	102.2878 ± 3.7276	5.4363 ± 0.5607	3.7949 ± 0.2883	97.3523 ± 4.9296
NYM1	64.6870 ± 2.2856	1.9942 ± 0.2618	1.9132 ± 0.1581	56.3924 ± 2.8929