SOIL-TO-PLANT TRANSFER FACTORS OF NATURAL RADIONUCLIDES OF THREE COMMON FOOD CROPS GROWN ON A TIN-MINING IMPACTED SOIL

BY

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CERTIFICATION

I certify that this work was carried out by Nkiruka E. Adesiji in the Department of Physics, University of Ibadan University of Ibadan.

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DEDICATION

This work is dedicated to God, the giver of life, good health and journey mercies.

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ABSTRACT

Tailings produced from tin-mining operations containing elevated levels of Natural Radionuclides (NRs; ^{40}K, ^{238}U, and ^{232}Th) need to be disposed properly to prevent environmental contamination. The knowledge of the mobility of NRs in contaminated farmlands is important because of possible accumulation and their radiological implication in crops grown on such farmlands. The Transfer Factor (TF) of NRs is an important parameter for predicting migration and accumulation of radionuclides through the food chain. However, there is dearth of information on the TFs of NRs in the tropics. This study determined the TFs of NRs in three widely consumed food crops grown on tin mining-impacted soil and Committed Effective Dose (CED) to assess radiological hazards in Nigeria.

Tin-tailings were collected from an abandoned tin-mining site in Alheri, Jos. Soil samples were collected from uncultivated, non-tin-mining site at the Botanical Garden of Redeemer's University, along Lagos-Ibadan Expressway. Three soil sample groups were purposively formulated; group-A (non-tin-mining soil), group-B (tin-tailings) and group-C (tin-tailing and non-tin-mining soil). Cowpea (*Vigna unguiculata*) and maize (*Zea mays*) seeds were obtained from the Institute of Agricultural Research and Training and cassava stems (*Manihot escalenta*) from International Institute of Tropical Agriculture Ibadan. Ten planting pots were prepared for each plant per soil group. The seeds and stems were planted and harvested at their maturity periods. The activity concentrations (AC) of NRs in the formulated samples and plant compartments (seeds, tubers, stems, leaves and roots) were determined using $7.6\,\text{cm} \times 7.6\,\text{cm}$ sodium-iodide thallium activated gamma-detector. The TFs of the NRs and CEDs of the edible parts were evaluated using standard methods. Data were analysed using descriptive statistics and ANOVA at $\alpha_{0.05}$

The mean AC (Bqkg^{-1}) of ^{40}K, ^{238}U and ^{232}Th obtained for the soil groups ranged from 179.65 ± 2.88 (group-A) to 3421.51 ± 3.64 (group-B); 90.35 ± 3.37 (group-A) to 1992.61 ± 1.55 (group-B), and 273.06 ± 5.37 (group-A) to 25232.30 ± 1.33 (group-B), respectively. The mean AC (Bqkg^{-1}) of the plant compartments were 39.39 ± 26.67 (tuber; group-B) to 2400.17 ± 1791.18 (cowpea-leaf; group-A) for ^{40}K; Below Detection Limit (BDL) (maize stems; group-A-B-C) to 717.90 ± 404.86 (cowpea-leaf; group-B) for ^{238}U, and 89.05 ± 110.86 (tuber; group-C) to 15972.92 ± 453.97 (cowpea-seed; group-B) for ^{232}Th. The calculated geometric mean of the TFs of ^{40}K, ^{238}U and ^{232}Th, in cowpea ranged from 1.40 (1.15) (seed) – 9.67 (2.49)(leaf), 0.39 (1.18)(stem) – 2.34(1.23)(root) and 0.77(3.01)(seed) - 9.73(1.45)(leaf) for group-A; 0.05(1.88)(seed) - 0.18(3.09)(leaf), 0.02(3.31)(seed) – 0.33(1.53)(leaf) and 0.05(1.70)(stem) – 0.12(1.53)(root) for group-B; 0.21(2.37)(seed) – 2.56(1.38)(root); BDL(stem, leaf) – 0.21(1.18)(root) and 0.07(1.37)(stem) – 0.31(1.78)(root) for group-C. Those of maize were 0.65(1.31)(seed) – 3.61(1.38)(stem), BDL(seed, stem) – 1.00(5.18)(root) and 0.58(2.79)(seed) – 2.68(2.43)(root) for group-A; 0.03(2,14)(seed) – 0.07(1.88)(stem) – BDL(stem, leaf) – 0.20(2.45)(root) and 0.02(1.97)(stem) – 0.13(1.72)(root) for group-B; 0.23(3.31)(root) – 0.43(2.88)(stem), BDL(seed, stem) – 0.11(2.37)(root) and 0.015(4.00)(seed) – 0.12(2.59)(root) for group-C. And those of cassava were 0.74(1.75)(stem) – 1.46(2.64)(leaf), BDL(tuber) – 0.90(2.21)(leaf) and 0.49(1.87)(tuber) – 1.54(4.26)(leaf) for group-A; 0.01 (1.40)(stem) – 0.12(2.04)(leaf). BDL(tuber, stem, leaf) and 0.03(1.57)(stem) – 0.04(2.23)(tuber) for group-B; 0.11(1.50)(tuber)– 2.91(1.79)(leaf), 0.01(1.11)(stem) – 0.07(2.04)(leaf) and

0.006(2.51)(tuber) – 0.21(1.91)(leaf) for group-C. The transfer factors of the natural radionuclides were observed to be in the order cowpea > maize > cassava. Significant differences occurred in the TFs of theNRs among the soil groups. Cowpea exhibited the highest potential for possible phytoremediation of the natural radionuclides.Cassava tubers had the highest mean CEDs ($mSv.y^{-1}$) (2.19 - 35.7) while cowpea seeds had the least (0.002 - 0.07). The CEDs of tuber and maize seeds exceeded the reference value (0.12 $mSv.y^{-1}$) recommended by the United Nations.

The transfer factor of the natural radionuclides varied across the food crops and soil groups and the cassava and maize grown on tin-mining impacted soil were of radiological concerns.

Keywords: Natural radionuclides, Transfer factor, Committed effective dose, Tin-tailings

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Research

Radionuclides occur naturally in the earth crust as primordial radionuclides. Technological advancement has also led to the production of anthropogenic radionuclides(UNSCEAR, 2000). As a result, humans are constantly exposed to ionising radiation by radionuclides of natural or artificial origin. The existence of the natural radionuclides in the environment vary from one location to anotherdue to difference in geological composition and climate. Therefore, some areas have highbackground radiation. Artificial radionuclides on the other hand, have found great applications in medicine, industries and agriculture. Some human activities and mismanagement of these radionuclides can lead to contamination of the environment.

The mining and milling of ore bodies, have also been identified as one of such activities that could elevate the background radiation as most of the mining wastes often have high concentration of natural radionuclides (Oresegun and Babalola, 1988, Jibiri *et al.,* 2011). The indiscriminate and unregulated disposal of mining wastes has been linked to contamination of the environment both with heavy metals and radionuclides. Contaminated farmlands create a higher chance of uptake of these radionuclides by crops planted on such farmland, as it has been shown that plants have the potential to accumulate toxic heavy metals and radionuclides (Mahon and Mathewes, 1983). Consumption of the harvested crops with elevated activity concentration could lead to internal exposure to ionising radiation (Uchida *et* al., 2007; Adjirackor*et al*., 2017), which had been linked to biological occurrence like cancer.

The transfer of radionuclides from soil to plants is influenced by many processes that affect the mobility and availability of the radionuclides. Some of these factors are soil properties, biological, chemical, structural, hydrological, climatic processes etc. The

transfer of radionuclides could be through the roots or leaves of the plants. Radionuclide uptake can be facilitated by their similarity to plant essential element (Manigandan and Manikanda, 2008). The root system of the plants play a significant role in taking up the available radionuclides (Goldmakani *et al.*, 2008) as well as the presence of competing ions in the soil solution (Shaw *et al.*, 1992).

The transfer of radionuclides is quantified by a parameter called transfer factor (TF), which is define as the ratio of the activity concentration of the radionuclide in the plant to the activity concentration in the soil (Uchida *et al.*, 2007). The many factors affecting the plant uptake of radionuclide introduces high variability in calculated TFs.However, the TFs data could be utilised in the derivation of probability distribution from which a representative values could be obtained for use with screening models.

1.2 Sources of Radionuclide

Radionuclides are found naturally in air, water, soil, plants and even in human beings. All radionuclides identified so far can be placed into three categories;

1. Primordial radionuclides,
2. Cosmic radiation and cosmogenic radionuclides,
3. Anthropogenic radionuclides.

1.2.1 Primordial Radionuclides

These radionuclides are believed to have been existing since the earth was formed some 5 billion years ago. They are typically long lived with half-lives in the order of 10^9 years. The primordial radionuclides include ^{238}U (uranium series), ^{235}U (actinium series) ^{232}Th (thorium series) and some non-series radionuclides like ^{40}K, ^{87}Rb,^{138}La, ^{176}Lu etc. (Cember and Johnson, 2009). The heaviest elements of each series decay into successive radioactive daughters forming series of radionuclides, each series ends when a stable species is produced. The uranium, actinium and thorium series with the respective half-lives of each radionuclide are given from Tables 1.1-1.3.

1.2.2 Cosmic Radiation and Cosmogenic Radionuclides

Cosmic rays are very high-energy particles from extra-terrestrial sources that bombard the earth. One source is the sun, which emits mainly alpha particles and protons. The other radiations, consisting mainly of electrons and protons, originates beyond our solar

system and is called galactic radiation. These primary particles enter the earth's atmosphere and collide with the atmospheric molecules to produce secondary cosmic rays that bombard the earth's surface and have sufficient energy to penetrate deeply into the ground and the sea. Cosmic ray intensity increases with altitude because of the decreased shielding effect of the atmosphere. Interactions that occur between cosmic radiation and the atmosphere lead to the production of numerous cosmogenic radionuclides. They have relativelyvery short half-lives when compared with the primordial radionuclides. Some examples of cosmogenic radionuclide include ^{3}H,^{10}Be,^{14}C,^{26}Al, ^{36}Cl. (Cember and Johnson, 2009).

1.2.3 Anthropogenic Radionuclides

These are radionuclides that do not occur naturally but are produced as a result of some human activities and advancement in technology. They are mostly synthesis in nuclearreactors and other transmutation researches. Some transmutation researches for example, have successfully reported the synthesis of heavier nuclides. These are achieved by the fusion of ions generated from a primary nuclide to the nuclide of a secondary target using laser technology. The heavier nuclides produced are normally left in an excited state. They thereafter, de-excite by emitting gamma radiation e.g. ions produced with laser with^{26}Al as the primary target could fuse with the nuclide of ^{26}Al to produce ^{43}Sc,^{34m}Cl or ^{49}Cr (Magil and Galy, 2005).

Some of the anthropogenic radionuclides have also find immerse use in agricultural and industrial applications. In agriculture, radiations from radionuclides are used to reduce the high losses of food due to insect infestation and spoilage. They are also used in the development of new crop species with better yield and higher resistance to diseases.As tracers, they are used to monitor chemical and physical behaviour at both macroscopic and microscopic levels, e.g. the use of ^{32}P to monitor the uptake of phosphorus in plant. They are also used in leak detection and as a tag to identify oil from different producers in the case of common pipeline usage. They (^{140}La, ^{110m}Ag, or ^{192}Ir) have also find applications as flow pattern and rate tracer and in wear analyses, measuring thickness, finding voids, testing welds and detecting concealed objects etc. In medicine, artificial radionuclides are used for diagnostic and therapeutic purposes. Nuclear diagnostic imaging techniques provide information about physiological and biochemical processes

Table 1.1: The decay series and half-life of Uranium series (Cember and Johnson, 2009)

Nuclide	Mode of Decay	Half Life
^{238}U	α	4.51×10^{9} years
^{234}Th	β^-	24.10 days
^{234m}Pa	β^-	1.175 min
^{234}Pa	β^-	6.66 hours
^{234}U	α	2.48×10^{5}years
^{230}Th	α	8.0×10^{4} years
^{230}Ra	α	1622 years
^{222}Rn	α	3.825 days
^{218}Po	α,β^-	3.05 min
^{218}At	α,β^-	2 sec
^{218}Em	α	0.019 sec
^{214}Pb	β^-	26.8 min
^{214}Bi	β^-,α	19.7 sec
^{214}Po	α	1.64×10^{-4}sec
^{210}Tl	β^-	1.32 min
^{210}Pb	β^-	22.3 years
^{210}Bi	β^-	5.00 days
^{210}Po	α	138.401 days
^{206}Pb	Stable	-

Table 1.2: The decay series and half-life of Actinium series (Cember and Johnson, 2009)

Nuclide	Mode of Decay	Half Life
^{235}U	α	7.13×10^{8} years
^{231}Th	β^{-}	25.64 hours
^{231}Pa	α	3.43×10^{4} years
^{227}Ac	α,β	21.8 years
^{227}Th	α	18.4 days
^{223}Fr	β	21 min
^{223}Ra	α	11.68 days
^{219}Em	α	3.92 sec
^{215}Po	α	1.83×10^{-3} sec
^{211}Pb	β	36.1 min
^{211}Bi	α,β^{-}	2.16 min
^{211}Po	α	0.52 sec
^{207}Tl	β^{-}	4.78 min
^{207}Pb	Stable	-

Table 1.3: The decay series and half-life for Thorium series(Cember and Johnson, 2009)

Nuclide	Mode of Decay	Half Life
^{232}Th	α	1.39×10^{10} years
^{228}Ra	β^-	6.7 years
^{228}Ac	β^-	6.13 hours
^{228}Th	α	1.91 years
^{224}Ra	α	3.64 days
^{220}Rn	α	52 sec
^{216}Po	α	0.158
^{212}Pb	β	10.64 hours
^{212}Bi	α,β^-	60.5 min
^{212}Po	α	3.04×10^{-7} sec
^{208}Tl	β	3.1 min
^{208}Pb	Stable	-

and compliment other imaging methods like conventional radiology, nuclear magnetic resonance, and ultrasound.

They have a very important role to play in identification of heart diseases, brain disorder, lung and kidney function, anda range of cancers. Gamma cameras for example can be used to detect diseases in the heart, brain, lung and thyroid. Some isotopes used for gamma imaging include ^{81m}Kr, ^{99m}Tc, ^{123}I, ^{131}I, ^{111}In, ^{133}Xe etc. In radiotherapy, ^{60}Co is used externally to deliver radiation to a tumour while ^{192}Ir,^{137}Cs, ^{125}I and ^{102}Pd can be implanted near the tumour for treatment in a branch of medicine called Brachytherapy. In radio-Immunotherapy, radionuclide like ^{131}I is chemically attached to an antibody and injected into the bloodstream for tumour treatment. Gamma rays from radionuclides are also used in sterilising surgical dressings, catheters, syringe etc.

Nuclear weapon tests, nuclear power plants, reprocessing of radioactive waste is another major source of anthropogenic radionuclides. Examples are ^{235}U and its fission products, ^{90}Sr (UNSCEAR, 2000).

1.3 Research Problem

Mining activities in Nigeria are not properly regulated. Waste products of tin mining has been found to contain high level of radioactivity (Oresegun and Babalola,1988,1990, 1993; Farai and Jibiri, 2000;Ademola, 2008; Olise *et al.,* 2011).They are either dumped on open land or disposed off indiscriminately in the nearby lands. This indiscriminate disposal of the waste product could contaminate farmlands at close proximity to the mining sites. In some part of the world, population growth and movement, industrial development and food security had resulted in pressure to use lands containing relatively high levels of radioactivity for agricultural activities (UNSCEAR, 2000; Jibiri *et al*., 2007). Radionuclides could then accumulate and enter the food chain as a result of the contamination of the farmlands or farming on the abandoned mining sites. Therefore, there is need to study the accumulation of radionuclides in plants so as to develop regional parameter (transfer factor) that would be useful in calculating radiological consequences or for developing a probability distribution that could be utilized for screening purpose.

1.4 Justification of the Work

Data on the transfer factor of both natural and anthropogenic radionuclides in the tropical ecosystem of Nigeria is very sparse. This is evident in theInternational Atomic Energy Agency(IAEA) handbook (IAEA, 2020),with a compilation of transfer factors from literature for different continents.No African country was represented in the list of countries considered for the tropics. This buttresses the point that much have not been done on the study of this parameter in Africa.

Studying and understanding the behaviour of the uptake of these radionuclides by indigenous plants in our environment would provide data on prediction of radionuclide concentration in agricultural crops. With these data, farmers would also be better advised on the type of crop to manage on a contaminated soil. The study would also generate data that could be used to develop a probability distribution, which would be needed in case of screening purpose. There is also need to develop a model that can predict soil-to-plant transfer factor (TF).

Chakraborty *et al*. (2013) reported a model that was successful in predicting the Chernobyl and weapon test fallout of ^{137}Cs in Europe. Such a model can be developed for the tropical region of Nigeria, but the validation of such model is subject toavailability of regional data and parameters. Hence, the need for this work as very few researches had been done in generating such data that would be needed to validate such model.

1.5 Aim and Objectives

The aim of this work is to determine the soil-to-plant transfer factor of natural radionuclides (^{40}K, ^{238}U and ^{232}Th) in three commonly cultivated and consumed plants (cowpea, maize and cassava),cultivated on mining impacted soils.

The objectives are:

a) To measure the activity concentrations of ^{40}K, ^{238}U and ^{232}Th in

(i) an uncontaminated soil ,

(ii) tailings from a tin mining site and

(iii) the mixture of the tailings with uncontaminated soil.

b) To measure the activity concentrations of ^{40}K, ^{238}U and ^{232}Th in the compartmentsof the plants cultivated on soil samples of (a).

c) To determine the transfer factor of the natural radionuclides from soil to the compartments of the plants (root, stem, leaf and crop).

1.6 Outline of the Thesis

This research work is presented in five chapters. Chapter one gave a brief background information, stated the research problems, justification, aim and objectives of the research work. Chapter two summarised an extensive literature review. Chapter three explained the materials and methods used in this work. Chapter gave the results and discussions while chapter five was on the conclusions, recommendations and contributions to knowledge.

CHAPTER TWO

LITERATURE REVIEW

2.1 Interaction of Ionising Radiation with Matter

The interaction mechanisms of ionising radiations with matter is crucial for the detection and measurement of radiation. It enables the application of appropriate theory for radiation shielding of a particular radiation. The biological effects of radiation on living tissue also depend on the interaction mechanism and deposited energy. The interaction often involves the transfer of energy from the radiation to the matter with which they are interacting. Radiation can interact withthe electrons and nuclei that constitute the atoms of the matter (Turner,2007).

Ionising radiation is subdivided into two classes: direct ionising radiation; whose interactions produce ionisation and excitation of the medium; and indirect ionising radiation that cannot ionise atoms but can produce interactions whose charged products, known as secondary radiation, are directly ionising. Fast moving charged particles, such as alpha particles, beta particles, and fission fragments, can directly ionise matter. Neutral particles, such as photons and neutrons, cannot interact through coulomb force with the electrons of the matter through which they pass; they then, cause interactions that transfer some of their incident kinetic energy to charged secondary particles (Shultis and Faw, 2002). The interaction mechanisms of gamma rays are discussed below.

2.1.1 Interaction of Photons with Matter

Unlike charged particles, photons are electrically neutral and do not lose their energy steadily as they traverse a matter and so can travel a given distance in a material before interaction with an atom in the material. The distance travelled by a photon is

controlled by the probability of interaction per unit distance travelled, which is also dependant on the specific medium traversed and photon energy (Turner, 2007). There are several other ways by which photons interact with matter, but the three most important interaction for detection of photon are;

i. Photoelectric effect

ii. Compton scattering

iii. Pair production

(i) Photoelectric Effect

Photoelectric effect is the ejection of an orbital electron from the surface of a metal as a result of its interaction with a photon. The photon transfers all its energy to the electron and disappear while an electron is ejected, provided the energy of the photon is equal or greater than the work function of the metal. The maximum kinetic energy K_{max}, of the emitted electron is given by equation 2.1. The work function ω, given by equation 2.2, is the minimum energy required to liberate an electron from the metal.

$$K_{\max}=E_{\gamma}-\omega \tag{2.1}$$

$$\omega=hf_o \tag{2.2}$$

where E_γ= energy of the photon and f_o = threshold frequency (Tsoulfanidis and Landsberger, 2015; Turner; 2007).

The probability of photoelectric effect occurring when a photon passes through a matter is called the photoelectric cross section or photoelectric coefficient and is represented by the symbol τ, which is the probability of photoelectric effect occurring per unit distance travelled by the photon. Photoelectric coefficient depends on atomic number Z and on the energy of the photon. It is largest for high-*Z* materials and low-energy photons with frequencies above the threshold value f_o (Cember and Johnson 2009; Turner, 2007).

(ii) Compton Scattering

This is a collision between a photon and a free electron, but in this case, the photon does not disappear. Rather, the energy of the photon is reduced and the direction of motion of the photon changed as illustrated in figure 2.1. The energy lost by the photon which is given to the electron, is derived by application of the laws of conservation of

energy and momentum, with the assumption that the electron was initially stationary. The energy of

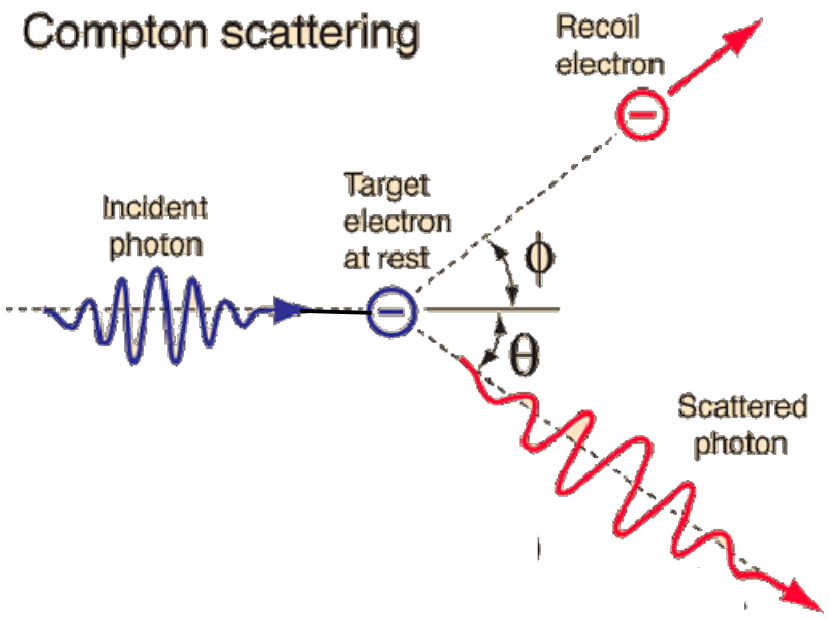

Figure 2.1: An illustration of Compton scattering (HyperPhysic, 2021).

the scattered photon $E_{\gamma'}$ and the kinetic energy of the electron K_e after collision are respectively given by equations 2.3 and 2.4.

$$E_{\gamma'} = \frac{E_\gamma}{1 + (1 - \cos\theta) E_\gamma / mc^2} \tag{2.3}$$

$$K_e = \frac{(1 - \cos\theta) E_\gamma / mc^2}{1 + (1 - \cos\theta) E_\gamma / mc^2} E_\gamma \tag{2.4}$$

Where Eγ is the initial energy of the photon, m is the mass of the electron and c is the speed of light. The minimum and maximum energies of the photon and electron are of paramount importance for radiation measurement. The minimum energy of the scattered photon, which also corresponds to the maximum kinetic energy of the electron, occurs when θ = π. Substituting θ = π into equation 2.3 and 2.4 give rise to equations 2.5 and 2.6.

$$E_{\gamma'_{\min}} = \frac{E_\gamma}{1 + 2E_\gamma / mc^2} \tag{2.5}$$

$$K_{e_{\max}} = \frac{2E_\gamma / mc^2}{1 + 2E_\gamma / mc^2} E_\gamma \tag{2.6}$$

The maximum energy of the scattered photon, also corresponding to the minimum energy of the electron, occurs when θ = 0, $E_{\gamma'_{\max}} = E_\gamma$, $K_{e_{\min}} = 0$, this implies that the collision did not occur.From equation 2.5, it can be concluded that the minimum energy of the scattered photon is more than zero, therefore, it is impossible for all the energy of the photon to be transferred to the electron.

The probability that Compton effect would occur is called the Compton cross-section or Compton coefficient, it is represented by the symbol σ, which is the probability of Compton scattering occurring per unit distance travelled by the photon. It is acomplicated function of Z and E_γ, but is almost independent of Z and varies approximately inversely with E_γ(Attix, 1986; Knoll,2010).

(iii) Pair Production

This is an absorption process in which a photon with at least twice the electron mass ($E_\gamma \geq 2m_ec^2$) interacts with the nucleus, leads to the disappearance of the photon and appearance of an electron-positron pair. The energy requirement for pair production to occur can be derive by applying the law of energy conservation on the kinetic energies of the emitted electron and positron, the rest masses of the electron and positron and the energy of the photon as shown in equation 2.7 (Attix, 1986, Tsoulfanidis and Landsberger, 2015).

$$K_{e^-} + K_{e^+} = E_\gamma - \left(mc^2\right)_{e^-} - \left(mc^2\right)_{e^+} = E_\gamma - 1.022MeV \qquad (2.7)$$

For pair production to occur, the photon energy must be greater than 1.022 MeV. The excess energy is shared between the electron and the positron in a continuous way. When the electron-positron pair annihilate, two photons are produced.

The occurrence probability of pair production is called pair production cross-section or pair production coefficient. It is represented with thesymbolκ, which is the probability of pair production occurring per unit distance travelled by the photon. It is a complicated function of Z and E_γ. Probability for pair production increases with increasing photon energy and when the atomic number is approximately Z^2.

Figure 2.2 shows the relative importance of photoelectric effect, Compton scattering and pair production as E_γ and Z changes. The curves show where two mechanisms are equally probable. Photoelectric effect is most probable when photons with low energy travel in high-Z materials while Compton scattering is most probable for low energy photons travelling through a low-Z material. At photon energy of 1MeV, Compton scattering dominates regardless of Z. For high energy photon travelling through alow-Z material, Compton scattering is the predominate mechanism of interaction, the same photon travelling through a high-Z material will interact through pair production (Attix, 1986; Knoll,2010).The total probability of interaction for photons is called the total linear attenuation coefficient. It is given by the sum of the probabilities of photoelectric, Compton scattering and pair production. The unit can be in m^{-1} or m^2/kg as linear mass attenuation.

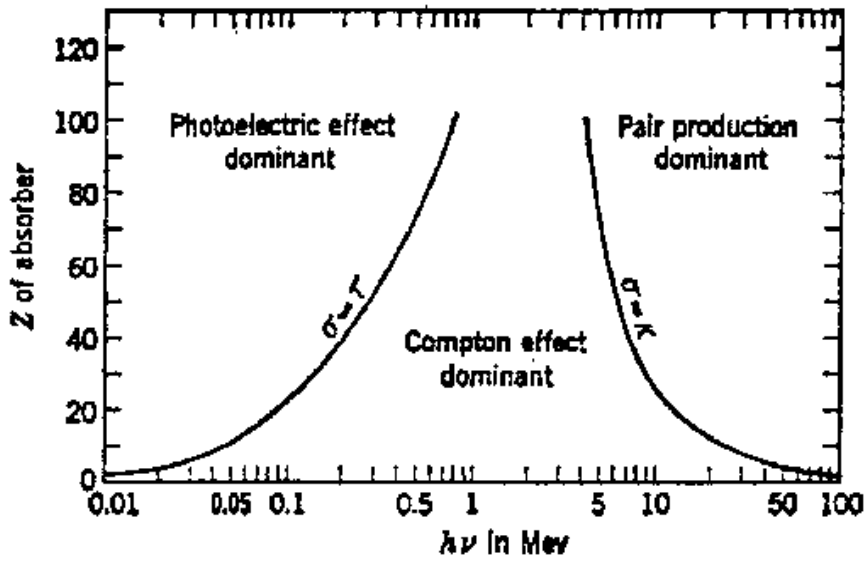

Figure 2.2: Relative importance of the major gamma interactions (Knoll, 2010).

2.2 Chemical and Biological Effect of Ionising Radiations

Most of the biological effects of ionising radiation on mammalian cell are due to the chemical changes on the water molecules that constitute about 70 %(Cember and Johnson 2009) of human cell. When a charge particle passes through a cell, the water molecule irradiated dissociates according to equation 2.8.

$$H_2O \xrightarrow{Radiation} H_2O^+ + e^- \tag{2.8}$$

The positive ionised water molecule breaks down according to equation 2.9 while the electron is picked by a neutral water molecule following equation 2.10.

$$H_2O^+ \rightarrow H^+ + OH \tag{2.9}$$

$$H_2O + e^- \rightarrow H_2O^- \tag{2.10}$$

The negative ionised water molecule dissociates immediately to form H and OH^-

$$H_2O^- \rightarrow H + OH^- \tag{2.11}$$

The products of the reactions in equation 2.9 and 2.10 have very short lives, except for the free radicals (H and OH) which can react with another like molecule or combine with like radical to form hydrogen peroxide (H_2O_2) if the linear energy transfer (LET) of the radiation is large. Hydrogen peroxide is a strong oxidising agent and can affect molecules or cells that did not directly suffer irradiation (Turner, 2007; Cember and Johnson, 2009).

The biological effects on the cell could result from direct or indirect action of radiation. Direct effects occur when the radiation, for example, breaks a strand of the DNA by ionisation. An indirect effect occurs when any of the radicals causes a break in the DNA strand. Radiation effects can occur rapidly or may take several years to manifest depending on the dose, the type of radiation and observed endpoint. It can also be classified into stochastic and deterministic(non-stochastic) effects. Stochastic effect like cancer behaves in a statistical manner while deterministic effects are those that show a clear cause-effect relationship between dose and effect in an exposed individual. A threshold dose is normally associated with the deterministic effect; below the threshold dose, no effect is observed. Effects are seen above the threshold doses and the severity increases with dose.

Most biological effects are non-stochastic in nature. The effect could be somatic; when it affects the exposed individual only, or genetic when the germ cells are affected. A dose-effect relation can be seen in figure 2.3, where the magnitude of effect or the

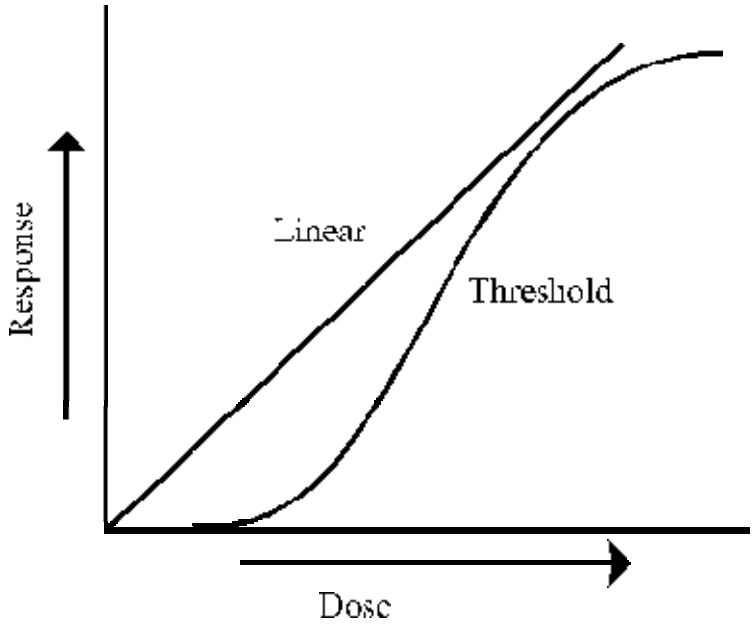

Figure 2.3: The dose-response curve for stochastic (non-threshold) and non-stochastic (threshold) effect(Cember and Johnson 2009).

proportion of individuals who respond to certain dose (Response) is plotted against the dose. The non-stochastic effect showed a threshold dose while the stochastic effect showed a linear, no-threshold (LNT) effect. For epidemiological assessment, the LNT model is adopted; this implies that any amount of dose, no matter how small, has an associated risk (Turner, 2007; Cember and Johnson, 2009). Exposure to radiation could be of chronic or acute type. It is chronic when there is a regular exposure to low level ionising radiation for a long time; and acute when there is a whole-body overexposure to high dose of ionising radiation.

2.3 General Features of a Detector

When any form of radiation interacts with most detectors, the outcome of the interaction is the production of a net charge. The charge is then collected through the use of electric field to form an electrical pulse. A detector can be operated in pulse mode, current mode or mean square voltage mode (MSV). All detectors used to measure the energy of each radiation quanta is operated in the pulse mode. The attached preamplifier is usually operated such that the time constant of the preamp is much greater than the collection time of the detector. Each signal pulse generated from a detector operated in pulse mode represents the interaction of a single photon with the detector. The amplitude of each pulse represents the amount of charge generated by an individual interaction. Such charge can be set to represent the energy deposited by the incident quantum of radiation.

Pulse mode is mostly used in radiation detection because of its better sensitivity over the other modes, and for the extra characteristic of preserving vital information of each pulse generated from individual quantum interaction with the detector. When the eventrate is high, pulse mode becomes impracticable, the time averaging technique of the current mode and MSV are then employed.

For the current mode, the current averaged is given by the product of the event rate and average charge produced per radiation interaction with the detector; this takes care of the random fluctuation in event arrival. The MSV mode is operated in a mixed radiation environment, where the charge produced by one type of radiation is different from other charge types. The derived signal is equal to the square of charge per event. The MSV mode is mostly utilised in reactor instrumentation (Knoll,2010).

2.3.1 Energy Spectra

Energy spectrum of a particle is a function giving the distribution of the particle as a function of energy. It can be represented in differential or integral spectrum. The differential function can be written as n(E) i.e. number of particles with energy from E to E + dE or n(E) dE i.e. number of particle per unit energy interval at energy E. The integral spectrum N(E) gives the number of particles over a certain energy range. The two spectra which are functions of energy can also be expressed in terms of the pulse height (Tsoulfanidis and Landsberger, 2015).

2.3.2 Pulse Height Spectra

The integral spectrum measurement implies counting of all the particles with energy equal to or greater than a certain energy E, or the log of all the particles that produced pulse height equal to or greater than a certain pulse height, V. This can be achieved using a single discriminator.

Measuring the differential energy spectrum means establishing the number of particles within a certain energy interval ΔE for a range of energy, or determining how many pulses fall within a certain interval ΔV for a range of pulse height. This can be done using a single-channel analyser (SCA) operating in differential mode.

Pulses generated by a detector from a monoenergetic incident radiation may not be the same either due to fluctuations in radiation energy or from the variation of the intrinsic response of the detector. For a detector to generate a pulse from any interaction with quantum of radiation, it is expected that the particle deposits all or some known amount of its energy in the detector, the voltage pulse generated should be proportional to the deposited energy and that all possible electronic amplification be equal for all pulse height. But the transformation of the particle energy is statistical in nature; therefore, the output pulses will give a particular distribution for all the particles depositing the same amount of energy in the detector. The observer is therefore required to apply appropriate corrections to the output pulse distribution to produce the actually spectrum of the source. Figure 2.4 shows the source spectrum from a monoenergetic particle (Nikjoo *et* al., 2012; Tsoulfanidisand Landsberger, 2015).

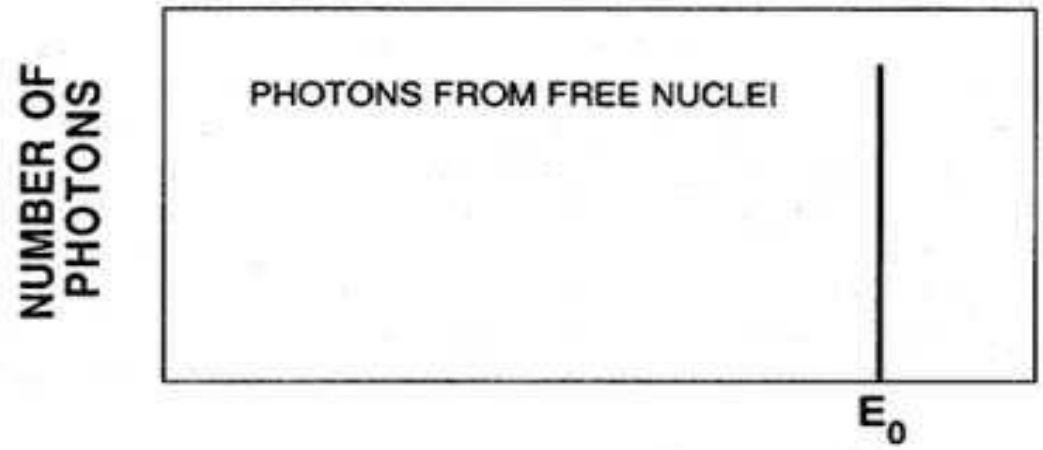

Figure 2.4: Source spectrum with monoenergetic particle (Tsoulfanidis and Landsberger, 2015).

2.3.3 Energy Resolution

The measurement of radiation according to the energy of the incident radiation is termed radiation spectroscopy. The ability of a detector to distinguish photons of different energies is called the energy resolution. The energy resolution of a detector can be judged from the width of the pulse-height distribution obtained from a monoenergetic source of radiation. The larger width is an indication of large variation in one pulse to another deposited by radiation of the same energy on the detector. Lesser fluctuation will give rise to a smaller width with a sharp peak. The fluctuations during measurement could be as a result of drift of operational parameters, random noise from preamplifier and amplifier, statistical noise from discrete nature of the measured signal. From figure 2.5, it can be seen that the width of the pulse height for NaI is wider than that of cadmium zinc telluride (CdZnTe or CZT) detector. The areas under the pulse-height will be the same provided the same number of pulses is recorded. The energy resolution decreases with increasing energy. Figure 2.6 also gives the illustration of how the energy resolution can be calculated. The full width at half maximum (FWHM) is the width of the spectrum at half the height of the maximum peak. The energy resolution R, is a dimensionless fraction of FWHM and peak centroid H_0, as shown in equation 2.12.

$$R = \frac{FWHM}{E_0} \times 100 \tag{2.12}$$

The FWHM measures the number of channels within the width and E_0 is the channel number at the centroid of the photopeak. The smaller the value of R, the better will the detector separate two energy levels that are very close to each other.Generally, detectors are expected to distinguish two energies that are separated by one value of FWHM (Knoll, 2010; Tsoulfanidis and Landsberger, 2015).

2.3.4 Detector Efficiency

The counting efficiency of a detector can be divided into two, namely; absolute and intrinsic efficiencies. The absolute efficiency is given by equation 2.13; it depends majorly on the counting geometry which is determined from the distance of the source to the detector.

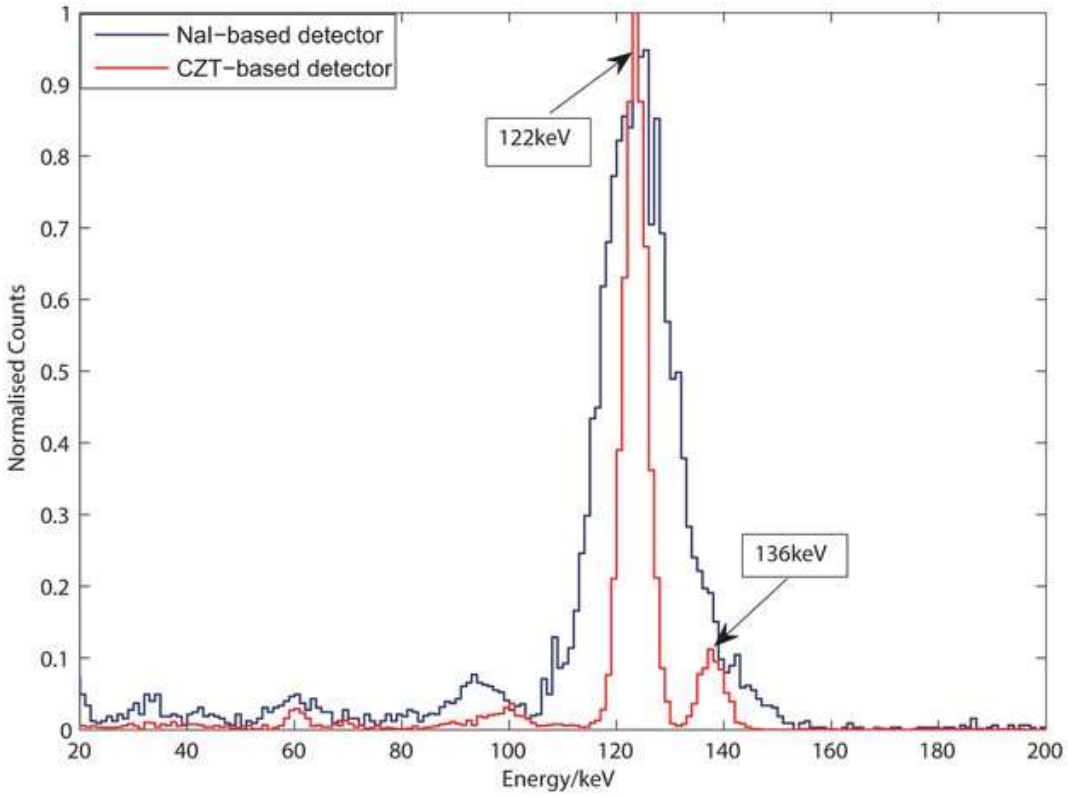

Figure 2.5: Differential energy spectrum showing the energy resolution of two detectors (Weng *et al.*, 2013).

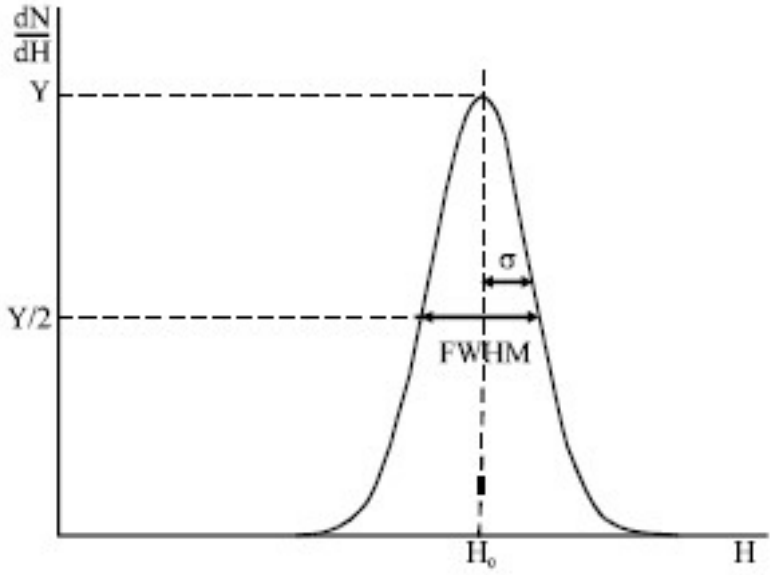

Figure 2.6: Differential energy spectrum showing the parameters for energy resolution (Tsoulfanidis and Landsberger, 2015).

$$E_{abs} = \frac{\text{number of pulses recorded}}{\text{number of emited quanta of radiation from the source}} \qquad (2.13)$$

The intrinsic efficiency is given by equation 2.14. It is primarily dependent on the material making up the detector, the energy of the radiation and detector thickness in the radiation incident direction.

$$E_{\text{int}} = \frac{\text{number of pulses recorded}}{\text{number of quanta of radiation incident on the detector}} \qquad (2.14)$$

2.3.5 Multichannel Analyser

The multichannel analyser (MCA), used in recording the pulse-height distribution from a radioactive source, can be operated in multichannel scaling (MCS) or pulse-height analysis (PHA) mode. Multichannel scaling (MCS) mode is use to count events as a function of timewhile the PHA mode sort out incoming pulses according to their height and save the numberof pulses of a particular height in adequate memory called the channel number.

In PHA mode, MCA works as many SCA arranged adjacent to each other. The incoming pulse enters into a unit called the analogue-to-digital converter(ADC). The ADC digitizes the pulse amplitude: it produces a number proportional to the height of the pulse, a number that determines the channel where the pulse will be stored. Actually, the ADC determines the number of discrete parts into which the pulse height can be subdivided. The memory of the MCA is a data-storage unit arranged in a series of channels. Dead time recorded while using an MCA is the minimum time required to separate two events and store it in the appropriate channel. There is always some probability of losing some events because of the random nature of radioactivity, especially at high counting rate (Tsoulfanidis and Landsberger, 2015).

2.4 Scintillation

Scintillators can be a solid, liquid or gaseous material that generate spark or flash of light when ionising radiation pass through them. The amount of light produced by scintillators is small, and is therefore required to be amplified to be recorded as a pulse. This amplification is achieved through the use of a photomultiplier tube. Two important properties of scintillators are, the light output and the wavelength of the emitted light.

The light output determines the number of photoelectrons to be generated by the photomultiplier tube while the wavelength enables the proper matching of scintillator with a photomultiplier tube. The operation of scintillators is broadly divided into two namely:

(i) Absorption of incident radiation and production of photon in the visible region of electromagnetic spectrum;

(ii) Amplification of pulse by the photomultiplier tube and the production of output pulse.

The three categories of scintillators are; inorganic, organic and gaseous scintillators. The emission of photons by scintillator follow a decay law given by equation 2.15;

$$N(t) = N_0 e^{-t/T} \tag{2.15}$$

where N(t) is the number of photons emitted at time t and T is the decay time of the scintillator. The decay time of most of the excited states is almost the same. Excited states with longer lifetime give rise to afterglow. The current is then fed into the RC circuit to produce a voltage given by equation 2.16.

$$V = V_0\left(1 - e^{-t/T}\right) \tag{2.16}$$

The inorganic scintillators are crystals of alkali metals, especially, the alkali iodides. Common examples are NaI(Tl), CsI(Tl), CaI(Na), LiI(Eu) and CaF_2(Eu). The elements enclosed in the parenthesis are called the impurities or activators. Though their concentrations are small, the activators are responsible for the luminescence of the crystals. The operation of inorganic scintillators is based on the movement of electrons from the valence band of the crystal to either the conduction or exciton band. The exciton band is a band between the valence band and the lower part of the conduction band. Electrons can move from the valence to the exciton band when the absorbed energy is not sufficient to raise it to the conduction band. Additional energy states between the valence and conduction band could also arise as a result of imperfections or impurities.

Organic scintillators of high efficiency belong the class of aromatic compounds, common examples are toluene, trans-stilbene and anthracene. They are classified as

unitary, binary, ternary and so on, depending on the number of compounds in the mixture. Light production in organic scintillators is as a result of molecular transitions. Activators are not needed to improve the luminescence of organic crystals, rather, the presence of impurity reduces the crystal output. Gaseous scintillators are mixtures of noble gases. The scintillations are produced as a result of atomic transitions. Since the light emitted by noble gases belongs to the ultraviolet region, other gases, such as nitrogen, are added to the main gas to act as wavelength shifters.

The photomultiplier tube (PMT) which is an integral part of scintillation detectors, amplifies visible light by a factor of 10^6 or more. It consists of an evacuated glass tube with a photocathode at its entrance and several dynodes, about fifteen (15) dynodes for a typical phototube. The dynodes are successively placed on positive high voltage, with voltage difference between two successive dynodes ranging from 80 - 120 V. The anode at the end of the dynodes serves as electron collector. Photons produced by the scintillator enter the phototube and are impinge on the photocathode. Since the photocathode is made of material that produces electrons when light falls on it e.g Cs-Sb; it emits electrons which are guided by electric field to the first dynode. Each dynode is coated with a substance (Al-Mg or Cs-Sb) which produces secondary electrons when electrons fall on it. This leads to amplification of the photoelectron as each dynode addssome secondary electrons. The schematic diagram of the scintillator that is optically coupled to the PMT is shown in figure 2.7.

For best result, the spectrum of the scintillator should match the spectral sensitivity of the PMT, the cathode should also be cooled to reduce noise due to thermionic emission that give rise to dark current (Birks, 1964; Knoll, 2010;Tsoulfanidis and Landsberger, 2015).

2.4.1 NaI Detector

NaI is the most commonly used inorganic scintillator for gamma ray spectroscopy. The emission spectral is maximum at 410 nm and has the highest light conversion efficiency of all inorganic scintillators. Its other characteristics of high density (3.67×10^3 kg/m^3), high atomic number and large volume makes it a γ-ray detector of high efficiency. It is however, brittle, sensitive to temperature gradient and thermal shock and also hygroscopic, thus it is always enclosed in an air-tight enclosure. The block

diagram of NaI detector is given in figure 2.8 while figure 2.9 shows a typical spectrum of NaI detector consisting of preamplifier, amplifier, MCA.

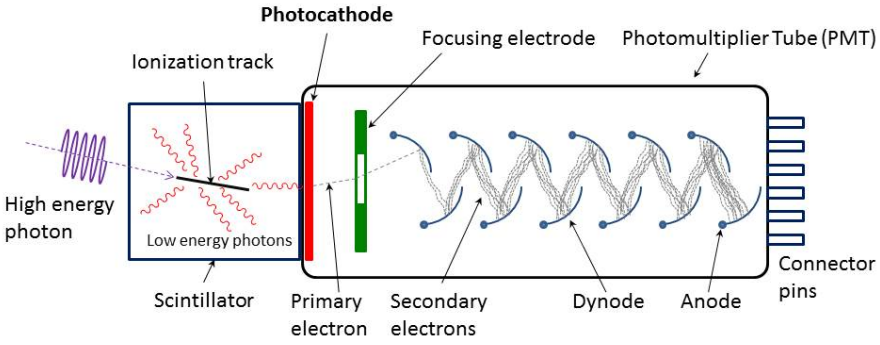

Figure 2.7: Schematic diagram of a scintillation detector comprising of a scintillation material coupled to a photomultiplier tube (Wikipedia. 2018).

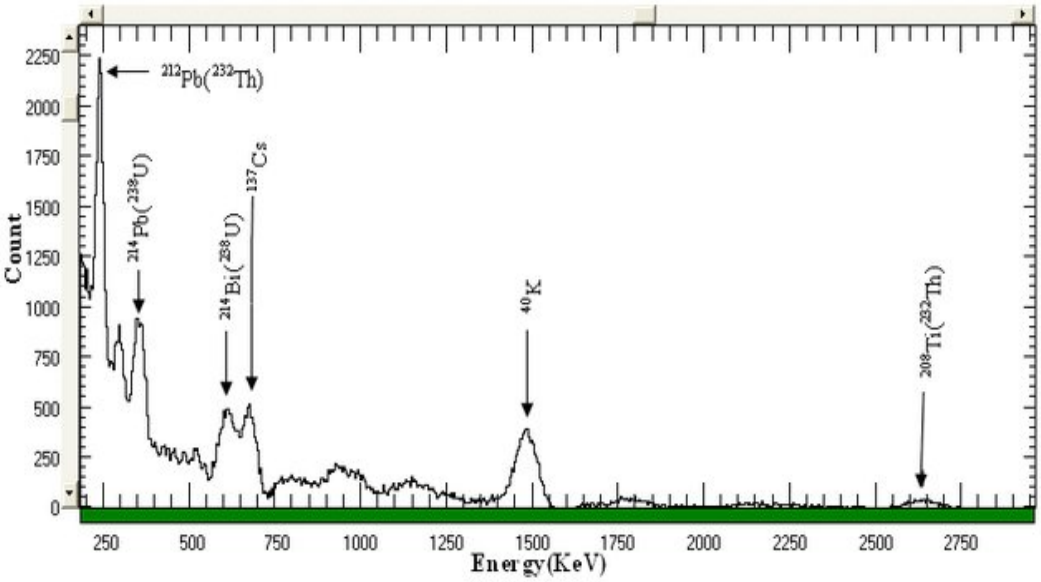

Figure 2.8: Typical NaI spectrum (Abdullah, 2015).

The main purpose of the preamplifier is to provide an ideal coupling between the detector and the parts of the counting system. It also reduces any source of noise that can degrade the energy resolution of the system. The three major categories of preamplifiers are: charge-sensitive, voltage-sensitive and current-sensitive. The voltage-sensitive preamplifier is not used in spectroscopy because of its dependence on the detector's capacitance. The most commonly used is the charge-sensitive preamplifier. The amplifier amplifies the output from the preamplifier and also shapesthe signal. Amplification is expected to be the same for all pulses of all amplitudes without distortion. The advance in electronics and digital processing in recent time has led to the replacement of ADC with modules assembled in a single box (Knoll, 2010; Tsoulfanidis and Landsberger, 2015).

2.5 Photon Spectroscopy

Photons can behave as particles or as electromagnetic waves. The wave nature of photons is employed for low energy measurements while the particle nature is used for in other cases. When photons interact with the material of the detector, they do so through any of the mechanisms discussed in section 2.1.1, and electrons are produced. The electrons produced deposit their energy on the detector and generate voltage pulses, with height proportional to the energy deposited in the detector. Verifying the voltage pulse to know if it is proportional to the energy deposited by the incident photon becomes very important if radiation spectroscopy is the end goal.

Photons with energy E, where $E < 1.022$ MeV, can interact only through photoelectric or Compton scattering. If the former occurs, the energy deposited by the electron is $E - B_e$, where B_e, is the binding energy of the electron. But electronic transition from the outer to lower shell produces an x-ray that compensates for the binding energy of the electronbefore the formation of the voltage pulse. Thus, for photoelectric interaction, the voltage pulse is proportional to the energy deposited by the photon.

But if the mechanism of interaction is Compton scattering, only a certain fraction of the energy is given to the electron while the remaining energy is carried by the scattered photon. The scattered photon may or may not interact with the detector subject to the following; the size of the detector, the position of the first interaction, the energy of the scattered photon and the material of the detector. Except the detector is of infinite size, there is always a chance that the scattered photon will escape. Since the energy of the

Compton electron ranges from 0 to K_e (given by equation 2.6), the pulse produced for Compton scattering ranges from V = 0 to V = K_e. Thus, a monoenergetic source spectrum of the type shown in figure 2.4, interacting with a detector through Compton scattering will produce Compton electrons.

These electrons will produce pulses ranging from zero to a maximum value known as the Compton edge. The continuous range of the pulse from zero to Compton edge is known as the Compton continuum.

Sometimes, the Compton interaction takes place at the edge of the detector leading to the escape of the Compton electron while the scattered photon is reflected back into the detector. The minimum energy of the reflected photon is given by equation 2.5, and this gives rise to the broad peak shown as back scattering. The energy of the photon and size of the detector determine the number of pulse recorded in the Compton continuum. The larger the energy, the higher the probability of Compton interaction occurring, while if a detector size could become infinite, then the Compton continuum would be eliminated (Tsoulfanidis and Landsberger, 2015).

In addition to photoelectric and Compton interaction, pair production becomes possible if the energy of the photon is greater than 1.022 MeV. If a pair production occurs, an electron-positron pair is produced. The energy of the photon is reduced by 1.022 MeV that is transformed to the rest masses of the electron-positron pair. The kinetic energy of the pair is deposited on the detector producing a pulse that is less than the energy of the photon by 1.022 MeV. If the positron reaches its range before pulse formation, it can annihilate with an orbital electron, and produce two gamma radiation each of energy 0.511 MeV. If the two gamma rays are captured in the detector, they will compensate for the energy of the pair's rest masses, and a pulse equal to the energy of the photon will be recorded. If the two gamma rays escape, a pulse that is less by 1.022 MeV, called the double-peak escape, will be recorded. If one gamma ray escapes, the pulse recorded will be 0.511 MeV less than that of the incident photon, this is called single-peak escape.

2.6 Counting Statistics

Radioactive decay is a random process. Consequently, any measurement based on observing the radiation emitted in nuclear decay is subject to some degree of statistical fluctuation. (Knoll, 2010). These fluctuations introduce errors to radiation

measurement, and so statistical analysis is needed to process the counts from radioactivity measurements and to predict the precisions of quantities that will be derived from the measurements.

2.6.1 Error Propagation

The standard deviation for a variable u, derived from independent variables x, y, and z can be estimated from equation 2.17, known as error propagation formula. Equation 2.17 is then applied to different mathematical operations or combinations of the independent variables. For additions/subtractions e.g. the subtraction of background count from the gross count of a sample, the standard deviation is given by equation 2.18;

$$\sigma_u^2 = \left(\frac{\partial u}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial u}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial u}{\partial z}\right)^2 \sigma_z^2 + \ldots\ldots \quad (2.17)$$

$$\sigma_u = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \quad (2.18)$$

When the derived variable is as a result of multiplying/dividing an independent variable by a constant as shown in equation 2.19, the standard deviation is given by equation 2.20 (Martin, 2000; Turner, 2007; Bevington and Robinson, 2003);

$$u = Ax \quad \text{or} \quad v = \frac{y}{B} \quad (2.19)$$

$$\sigma_u = A\sigma_x \quad \text{or} \quad \sigma_v = \frac{\sigma_y}{B} \quad (2.20)$$

If the derived quantity is as a result of multiplication or division of two independent variables as illustrated in equation 2.21, the standard deviation of the derived quantity is given by equation 2.22 (Martin, 2000; Knoll, 2010; Bevington and Robinson, 2003).

$$u = xy \qquad \text{or} \qquad u = \left(\frac{x}{y}\right) \quad (2.21)$$

$$\left(\frac{\sigma_u}{u}\right)^2 = \left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2 \quad (2.22)$$

2.6.2 Geometric Mean and Geometric Standard Deviation

Geometric mean G, of n non-negative quantities $x_1, x_2, ..., x_n$ is given by equation 2.23 or equation 2.24. It is often used when calculating the mean of ratios or group of indices. It only applies to positive numbers and has the advantage of decreasing the influence of outliers on the mean (Dogde, 2008);

$$G = \sqrt[n]{x_1 \cdot x_2 \cdot ... \cdot x_n} \tag{2.23}$$

$$\ln(G) = \frac{\sum_{i=1}^{n} \ln(x_i)}{n} \text{ or } G = \exp\left[\frac{1}{n}\sum_{i=1}^{n} \ln(x_i)\right] \tag{2.24}$$

The geometric standard deviation, which is a measure of dispersion of the observations around a geometric mean, is given by equation 2.25 (Dogde, 2008);

$$\log \sigma_g = \left[\frac{1}{n}\sum_{i=1}^{n} (\log x_i - \log G)^2\right]^{\frac{1}{2}} \tag{2.25}$$

2.6.3 Level of Detection

The sensitivity of a radio-analytical procedure can be characterised as detection level and is often required by many regulatory programs. It serves as a guidepost and not as an absolute level of activity that can or cannot be detected by the counting system. The lower limit of detection (LLD) is one of such guideposts. LLD is defined as the smallest quantity of activity that can be detected with some specified degree of confidence. LLD in counts at 95% confidence level is related to the background count B, as given in the equation 2.26 (Martin,2000);

$$LLD = 2.706 + 4.653\sqrt{B} \tag{2.26}$$

Any sample, whose count above the background count is less or equal to LLD, is considered as being Below Detectable Limit (BDL).

2.6.4 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical technique that verifies if the survey or experimental means results among groups are significantly different, it is very useful in testing of hypothesis. The outcome of ANOVA will help a researcher to either reject the null hypothesis or accept the alternative hypothesis. In ANOVA, the null hypothesis assumes that there is no significant difference in the mean of the groups i.e. all groups are simply random samples of the same population while the alternative hypothesis assumes that there is at least one significant difference in the means of the groups(Dogde, 2008).

ANOVA are basically used in three ways, namely; one-way ANOVA, two-way ANOVA and N-way ANOVA. A one-way ANOVA consist of one independent variable affecting a dependent variable. It is used to compare two means from two groups using the F-distribution. The null hypothesis for the test is that the two means of the two groups are equal. Therefore, a significant result means that the two means are unequal. The shortfall of one-way ANOVA is that, it can only reveal the significant difference but cannot show where the difference among the group lies. A two-way ANOVA refers to an ANOVA consisting of two independent variables affecting one dependent variable, it has an advantage of showing where the difference from the groups lies when there is significant difference among the means of the groups. It can also show the interaction effect of the two independent variables.

When conducting a research with more than two independent variables, the N-way ANOVA is used. Researchers have extended ANOVA in multivariate analysis of variance (MANOVA) and Analysis of covariance (ANCOVA). MANOVA is used when there are two or more dependent variables while ANCOVA is used when the researcher includes one or more covariate variables in the analysis (Keselman *et* al., 1998;Landau and Everitt, 2004;Woodrow, 2014).

A statistical significant result, when the probability or p-value is less than a chosen significant level, leads to the rejection of the null hypothesis. In order to estimate the variance, two estimates are made. The first corresponds to the mean of the variance of the sample and is denoted as s_E^2. The second estimate is based on the variation between the means of the samples and is denoted as s_{Tr}^2. The F ratio is calculated using equation 2.27(Dogde, 2008; Bevington and Robinson, 2003).

$$F = \frac{S_{Tr}^2}{S_E^2} \quad (2.27)$$

If the null hypothesis is verified, the two estimations will be equal, and the F ratio will be equal to 1. The value of the F ratio, which is generally more than 1 because of the variation from the sampling, must be compared to the value in the Fisher table corresponding to the fixed significant level. The decision rule consists of either rejecting the null hypothesis if the calculated F ratio is greater than or equal to the tabulated value, else the means are equal, which shows that the samples come from the same population (Dogde, 2008). A sample of the Fisher table is shown in table 2.1. The SPSS software was used in computing the ANOVA for this work andthe p-value was set at 0.05.

2.7Mining Waste in the Environment and Consequences of Mismanagement

Mining in its broadest sense is the process of obtaining useful minerals from the earth's crust. Mining of all kind degrade the environment, the excavations of ores in mining sites destroy the flora and fauna of the natural ecosystem (Sam and Awad Al-Geed, 2000, Ademola, 2008, Tarras-Wahlberg, 2017, Li *et al.,* 2017, Merem *et al*., 2017). Mining and smelting activities represent the greatest risk for theindividual environmental components, resulting in an increased contaminationof soil/substrate and plants and/or edible plants (Arvay *et al.,* 2017), and soil which has been physically and chemically altered (IAEA, 2002a). The hazards to humans or to the environment posed by mining and milling waste arise not only from its radioactivity but also from the presence of toxic chemicals and other materials in the waste (IAEA, 2002b, Aigbedion and Iyayi, 2007).

The operations and waste disposal methods atthe mining sites are considered one of the main sources of environmental degradation. In a typical metal mining operation, tailings consist of crushed rock and ore, after most of the target metals have beenremoved. Mine tailings are often toxic, and if not contained, are harmful to the environment. The processed solid wastes from some unregulated mining sites areusually disposed off on open land, where they undergo weathering. Waste disposal from processing plants and sediment runoffs from open cut mines are often dumped in rivers and oceans. Smothering of riverbeds and ocean floors, heavy metal contamination and acid mine drainage are some of the consequence of improper mine

waste disposal into the environment. This leads to water discolouration and change in taste of water from river. Toxicity of heavy metals leads to diseases, poisoning and even death (McKinnon, 2002; Carvalho *et al.,* 2007; Ikwuagwu, 2017).

Table 2.1: A section of Fisher's table (Webstat, 2017).

F - Distribution ($\alpha = 0.01$ in the Right Tail)

Denominator Degrees of Freedom (df_2) \ Numerator Degrees of Freedom (df_1)	1	2	3	4	5	6	7	8	9
1	4052.2	4999.5	5403.4	5624.6	5763.6	5859.0	5928.4	5981.1	6022.5
2	98.503	99.000	99.166	99.249	99.299	99.333	99.356	99.374	99.388
3	34.116	30.817	29.457	28.710	28.237	27.911	27.672	27.489	27.345
4	21.198	18.000	16.694	15.977	15.522	15.207	14.976	14.799	14.659
5	16.258	13.274	12.060	11.392	10.967	10.672	10.456	10.289	10.158
6	13.745	10.925	9.7795	9.1483	8.7459	8.4661	8.2600	8.1017	7.9761
7	12.246	9.5466	8.4513	7.8466	7.4604	7.1914	6.9928	6.8400	6.7188
8	11.259	8.6491	7.5910	7.0061	6.6318	6.3707	6.1776	6.0289	5.9106
9	10.561	8.0215	6.9919	6.4221	6.0569	5.8018	5.6129	5.4671	5.3511
10	10.044	7.5594	6.5523	5.9943	5.6363	5.3858	5.2001	5.0567	4.9424
11	9.6460	7.2057	6.2167	5.6683	5.3160	5.0692	4.8861	4.7445	4.6315
12	9.3302	6.9266	5.9525	5.4120	5.0643	4.8206	4.6395	4.4994	4.3875
13	9.0738	6.7010	5.7394	5.2053	4.8616	4.6204	4.4410	4.3021	4.1911
14	8.8616	6.5149	5.5639	5.0354	4.6950	4.4558	4.2779	4.1399	4.0297
15	8.6831	6.3589	5.4170	4.8932	4.5556	4.3183	4.1415	4.0045	3.8948
16	8.5310	6.2262	5.2922	4.7726	4.4374	4.2016	4.0259	3.8896	3.7804
17	8.3997	6.1121	5.1850	4.6690	4.3359	4.1015	3.9267	3.7910	3.6822
18	8.2854	6.0129	5.0919	4.5790	4.2479	4.0146	3.8406	3.7054	3.5971
19	8.1849	5.9259	5.0103	4.5003	4.1708	3.9386	3.7653	3.6305	3.5225
20	8.0960	5.8489	4.9382	4.4307	4.1027	3.8714	3.6987	3.5644	3.4567
21	8.0166	5.7804	4.8740	4.3688	4.0421	3.8117	3.6396	3.5056	3.3981
22	7.9454	5.7190	4.8166	4.3134	3.9880	3.7583	3.5867	3.4530	3.3458
23	7.8811	5.6637	4.7649	4.2636	3.9392	3.7102	3.5390	3.4057	3.2986
24	7.8229	5.6136	4.7181	4.2184	3.8951	3.6667	3.4959	3.3629	3.2560
25	7.7698	5.5680	4.6755	4.1774	3.8550	3.6272	3.4568	3.3239	3.2172
26	7.7213	5.5263	4.6366	4.1400	3.8183	3.5911	3.4210	3.2884	3.1818
27	7.6767	5.4881	4.6009	4.1056	3.7848	3.5580	3.3882	3.2558	3.1494
28	7.6356	5.4529	4.5681	4.0740	3.7539	3.5276	3.3581	3.2259	3.1195
29	7.5977	5.4204	4.5378	4.0449	3.7254	3.4995	3.3303	3.1982	3.0920
30	7.5625	5.3903	4.5097	4.0179	3.6990	3.4735	3.3045	3.1726	3.0665
40	7.3141	5.1785	4.3126	3.8283	3.5138	3.2910	3.1238	2.9930	2.8876
60	7.0771	4.9774	4.1259	3.6490	3.3389	3.1187	2.9530	2.8233	2.7185
120	6.8509	4.7865	3.9491	3.4795	3.1735	2.9559	2.7918	2.6629	2.5586
∞	6.6349	4.6052	3.7816	3.3192	3.0173	2.8020	2.6393	2.5113	2.4073

Akpalu and Normanyo (2017), discussed the effect of gold mining in the environment. Some toxic chemicals like cyanide, mercury and arsenic as well as their harmful compounds , and heavy metals like cadmium, manganese, lead and copper were reported
to be routinely discharged into water bodies. Such pollution of water bodies could lead to respiratory tract infections, cardiovascular diseases, skin infections and cancer in workers and residents.Some other works by Hilson (2000), Akpalu and Parks (2007), Obiri (2007) and Ako *et al.,*(2014) have also corroborated the reports of Akpalu and Normanyo (2017) on the health effects of mining wastes from a gold mining site.Arvay *et al.,*(2017) assessed the environmental and health risk in former polymetallic ore mining and smelting area, in Slovakia. The work revealed the contamination of the environment with several heavy metals especially mercury (Hg). Mercury (Hg) represents one of the most toxic inorganic pollutants due to its wide distribution, high persistency in ecosystems and bioaccumulation ability in food chain.

Aside the chemical and heavy metal contaminants, mining activities have significantly enhanced the radioactivity concentration of the environment (Oresegunand Babalola 1988; Mustapha *et al.,* 2007). Mining often involves the excavation of ores of which mostare classified as naturally occurring radioactive materials (NORM) (Canoba, 2012). NORM is defined as all naturally occurring radioactive materials where human activities have increased the potential risk for radiation exposure in comparison to the unaltered situation (Mas *et al.,* 2006). Because of the high level of natural radionuclides detected in most of the mining wastes as a result of processing, the mining wastes are normally categorized as technologically enhanced naturally occurring radioactive materials (TENORM) (Gaso *et al.,* 2005; Mas *et al.,* 2006).Some non-radioactive or non-uraniumore mining and processing industries like those of tin, phosphate rock, niobium, coal, gold, copper and lead had been reported to increase the doses delivered to the workers and to the population living in the vicinity of the industries (Oresegun and Babalola, 1988,1993, Baxter, 1996, Pires do Rio *et al.,*2002,Righi *et al.,* 2000).

Mas *et al.*(2006) reported the high level of natural radionuclides in the industrial wastes disposal of two phosphate rock processing plants in Spain and further evaluated the restoration processes on the site as a preliminary step to the decommissioning of the site, from the radiological point of view. Their work revealed that the restoration has

reduced the external dose to an appreciable level but however, called for further work on the site.

2.8 Mobility of Natural Radionuclidesin the Soil

The dynamic of radionuclides in the soil is complex, some of the radionuclides are bound to the particles of the soil while some are transported into the soil solution. The radionuclides are regulated by processes that change the mobility of their physicochemical forms. Their transformations are based on sorption interactions in combination with the migration of soil particles and soil solution. The biological availability of radioactive elements in contaminated soils can be lower than that in the background soil owing to their fixation (Rachkova *et al.,* 2010). It is also assumed that the transfer of radionuclide from soil to plant is element specific, as a result, root uptake of all the isotopes of a given element is identical (Sheppard and Evenden, 1988a, Tome *et al.,* 2003). Their mobility can then be classified into two categories, viz., mobile and immobile radionuclides (Manigandan and Manikandan, 2008).

The soil type contributes significantly to the mobility of radionuclides in soil. Sand particles are generally chemically inert and because of their large sizes, water travels through them easily. Silt particles, which are smaller in size, offer larger surface areas while clay particles offer the largest surface area per unit mass and thus hinder water flow. Soluble radionuclides can be adsorbed onto the reactive surfaces of fine soil particles according to their respective distribution coefficients, thus making them less available for uptake. They can also react with organic matter, precipitate as oxides, or undergo ion exchange. Depending on the time that a radionuclide remains in the soil, it can be partitioned into various fractions through these processes. The importance of these processes depends on the radionuclide itself and their removal mechanisms, such as root uptake. The movement of the radionuclide through the soil is hence determined, to a large extent, by these partitioning processes (Golmakani *et al.,* 2008).

2.8.1 Uranium

Uranium is classified among the immobile radionuclides. In the soil, it exists in cationic forms i.e.uranyl cation UO_2^{2+} which is prone to hydration, complexing and hydrolysis (Rachkova *et al.,* 2010). Since soil solids consist of net negative charges, the uranium specie is adsorbed strongly to the soil, especially for fine textured soil (Sheppard and Evenden, 1988a, Vandenhove *et al.,* 2007). Its mobility in soil therefore, depends on the formation of organic complexes and association with the colloids which can increase the mobility of the uranium(Sheppard and Evenden, 1988a; Manigandan and

Manikandan, 2008).Factors affecting uranium sorption include pH, anions, cations, redox state and complexation by organics (Vandenhove *et al.,* 2007).

The uranyl cation can form $UO_2OH^+, UO_2(UO_3)(OH)^+, \mathrm{UO_2}(UO_3)_n(OH)_2$ colloids through hydrolysis (Rachkova *et al.,* 2010). It can form uranyl-carbonate, uranyl-phosphate, hydroxide and sulphate complexes. Uranyl-carbonate was reported to be mostly available for soil uptake (Laroche *et al.,* 2005, Vandenhove *et al.,* 2007) especially for alkaline pH due to the solubility of uranyl-carbonate (Vandenhove *et al.,* 2007).Sheppard *et al.*(2005) also stated that for uranium, there can be substantial mobility in neutral to basic soils as a result of complexation with soluble carbonates. Though contrary report from Roivainen *et al.* (2011), showed that uranium uptake can be greatly facilitated when soil is acidic.Tome *et al.,* (2002) reported that uranium could also interact with stable elements like manganese, magnesium, aluminium, calcium and copper by cation exchange.Vandenhove *et al.*(2007)observed that uranium in soil decreases in this tread sandy > loamy > clay soil.

Sheppard and Evenden (1988b), reported that the mobility of uranium is restricted in plant because of adsorption on the cell wall of the plant. As a result, uranium concentration is normally higher in tissues that are lower on the plant parts like the root surfaces. They also reported that ordinarily,plant concentrations of uranium are lower than soil concentrations, but there could be extraneous contamination of plant samples with soil particle. This may come from atmospheric deposition of dust onto the plant, from splash of soil onto plants during rainfall. And washing may be difficult to remove such contaminations because the radionuclides may have been adsorbed into the plant.

2.8.2 Thorium

Thorium is also classified as immobile radionuclide.Just like uranium, it exists in cationic forms like Th^{4+}, $Th(OH)_2^{2+}$ (Sheppard and Evenden, 1988a;Manigandan and Manikandan, 2008; Rachkova *et al.,* 2010).Ahmed *et al.* (2012), reported that thorium is most soluble in acidic soil (pH = 3.6 – 4.7), its solubility being 5 -14 times greater than the solubility of uranium. According to Rachkova *et al.*(2010), Th^{4+} can only exist in media of pH 2-3. And that the migration of thorium can be in the form of coordination compounds with fluoride, sulfate, phosphate, chloride, nitrate, and carbonate ions. There can be ionic (pH < 2), molecular (pH < 5), colloidal (pH ≅5), and

pseudocolloidal (pH > 5) occurrence forms of extremely small amounts of thorium. The formation of organic complexes and colloids can increase the mobility of thorium (Sheppard and Evenden, 1988a; Rachkova *et al.,* 2010). Rachkova *et al.*(2010) further expatiated that up to 90 % of thorium is associated with the colloidal phase, but this phase decreases with the increase in the concentration of organic substances. At higher organic content at low pH values, mineralization and hardness promote the transportation of thorium with groundwater and inhibit its absorption by the soil.

Sheppard and Evenden(1988a)reported that the mobility of thorium, as it is in uranium, is restricted in plant because of adsorption on the cell wall of the plant. Thus, higher concentrations are found in tissues that are lower on the plant like the root surfaces. The issue of extraneous contamination was also reported for thorium.

2.8.3 Potassium

With the assumption that the transfer of radionuclide from soil to plant is element specific, i.e., during the process of uptake and ion exchange, the radioactive nature of the pollutant is not important, it is the chemical properties of the radionuclide that are important. In practice, therefore, the plant roots do not distinguish between a radionuclide and its stable counterpart (Sheppard and Evenden, 1988a; Laroche *et al.,* 2005). So,the uptake of radioactive potassium can be investigated by the behavior of its stable component that is a macro-nutrient for plant growth.

Potassium (K) belongs to the mobile radionuclides (Manigandan and Manikandan, 2008) and it is one of the macro-nutrients required for the proper development of plant. It is important in photosynthesis, in the regulation of plants responses to light through opening and closing of stomata. Potassium is also important in the biochemical reactions in plants. Basically, potassium (K) is responsible for many other vital processes such as water and nutrient transportation, protein, and starch synthesis (Tajer, 2017).

In soil, it exists in three forms namely; unavailable, slowly available or fixed and readily available. The unavailable potassiumis locked in soil minerals like felspar and mica and are unavailable for plant use. The slowly available K are between the layers of clayed minerals and are thus fixed. The potassium that are dissolved in water or are held on the exchange site of the clay are considered readily available (Kaiser*et al.,* 2016). Some factors that affect the mobility of K are soil factors like

cationexchangeable capacity (CEC), soil moisture, soil temperature, tillage system, soil aeration and oxygen level; and plant factors like plant variety, root structure of the plants and plant population.

2.9 Effects of Mining Waste on Agriculture

The effects of mining on agriculture have been basically the degradation and contamination of agricultural lands with pollutants discussed in section 2.10. Soil at and around the mining sites are often characterised with low soil nutrients, which leads to reduction in crop yield and alsodiversity in plant species (Jibiri *et al.,* 2011; Woch *et al.,* 2017). Roy *et al.*(2012) investigation on the imparts of gold mill tailings dumps on agriculture lands, showed that the increment in the tailing content of an agricultural soil lead to decrease in the essential nutrients required for the proper growth of the plants. This result was further corroborated by Aidara (2013) on the evaluation of mining and its impacts on land and agriculture in Ghana.

Bureau of Food and Agricultural Policy (BFAP, 2012) conducted a pilot survey on the impact of coal mining on agriculture in the major agriculture area in Mpumalanga area of South Africa with a specific focus on maize production. The area was reported to host about 46.4 % of the arable land in South Africa and were known for their grain production before the advent of coal mining. The work revealed a degradation in the agricultural land area due to land sterilization and acidification of the soil which leads to the loss of many tons of maize grain. The loss in maize production was expected to have a ripple effect of increasing the market price of maize by 15 %. The prospect of reclaiming the mined area could not be fully discussed as effect of such is expected after 5 to 15 years of rehabilitation of the mined land.

2.9.1 Soil-to-Plant Transfer Factor

Contaminants in the soil can enter and accumulate in different parts of a plant through the root uptake or aerial contamination. Assessment of the impact of contamination normally involves environmental assessment model, that treats the uptake of elements as a simple ratio defined as, concentration of plant tissue to total concentration in soil, this ratio is termed concentration ratio (CR) (Sheppard and Evenden 1988a, 1988b, 1990; Tome *et al.,* 2003; Sheppard *et al.,* 2005; ICRP 2009; Sheppard *et al.,* 2010) or transfer factor (TF) (Ehlken and Kirchner, 2002; Wasserman *et al.,*2002; Uchida *et*

*al.,*2007; Uchida *et al.,* 2005; Roivainen *et al.,*2011; Aswood *et al.,*2013; Okeme *et al.,*2016).

The uptake of radionuclides in soil solution is often facilitated by their similarities to the plants essential elements (Manigandan and Manikandan, 2008; Golmakani *et al.,* 2008). According to Golmakani *et al.*(2008), the radionuclides entering the plant system is not uniformly distributed, but are transported to a particular part of the plant based on the element's function in the plant metabolism. The root system of the plant also plays a major role in radionuclide uptake. Golmakani *et al.*(2008) also showed that deep root system can easily pick up radionuclides with high leach rate than shallow rooting system. Uptake of long-lived radionuclides by plants depends to a considerable extent on whether it remains within the root zone, and it is chemically available for transport to root endings and translocation to edible portions.

Shaw *et al.*(1992), conducted an experiment to verify the suppression in the uptake of radiocesium (^{137}Cs) by wheat plant as a result of competing ions from stable cesium(^{133}Cs), potassium (K), and ammonium(NH_4). The use of TF was criticised in this work because it assumed a direct proportionality between specific activity of the soil and that of the plant growing on it, and that TF values described equilibrium conditions which is unlikely. So, the use of mechanistic method to explain the uptake of radiocesium was suggested and used in the experiment. The results showed that the mean transfer factors of ^{137}Cs for the roots over the ion (K^+, Cs^+ and NH_4^+) concentrations ranges were almost one order of magnitude greater than those for shoots and the transfer functions in all cases were non-linear. For ^{133}Cs and NH_4, there was close adherence between the data obtained from the experiment and that of a theoretical model. Thus, an increase of either ^{133}Cs or NH_4 concentration in the rooting medium, would result in a non-linear decrease in the soil-to-shoot transfer factor. For K^+, the experimental data agreed with theoretical model up to 20 μM.

Sheppard and Evenden (1988a), compiled and reviewed the plant to soil concentration ratio (CR) of uranium, thorium and lead. The factors affecting the uptake of natural radionuclides were categorised into three scales viz. macro-scale, meso-scale and micro-scale. On a macro-scale, the plant was viewed as a hydraulic conduit for water stored in the soil to travel upward and be evaporated from the leave. A greater flow of water through the plant will tend to increase the uptake of radionuclides. The meso-

scale looked at the plant as an organism that regulates the intake and loss of materials from the environment. This process is largely controlled by the membranes enclosing the cells. The micro-scale focused on the plant roots which exude enzymes and chelates, metabolic byproducts and waste inorganic materials. Thus, the plant root creates a cylinder of soil with entirely different characteristics than the bulk soil. This can affect the uptake of radionuclides in a number of ways, e.g. by causing dissolution of radionuclides. Added to these factors affecting the CR are the climatic variations which invariably control the growth conditions of the plant and other soil properties. The complexities created by these varying factors introduced great variability in the values of the CR, spanning three to five orders of magnitude for each element. The CR model is however, accepted universally by regulatory agencies and mostly for radiological assessments.

A work on the examination of radioactive contamination in the soil-plant system and their transfer to selected animal tissues was done by Chibowski and Gladysz (1990), in Poland. Samples of soil, plant and animal tissues were collected from the same area and their activity concentrations were measured. The work showed that the main radioisotopes responsible for the radioactivity level in soil and plant samples are of the natural origin, mainly ^{40}K. A comparison of radioactivity of soil, plant and tissue samples of animal fed with these plants showed that despite some transfer effects of some radioisotopes to the animal organisms, isotope accumulation excluding ^{40}K is small. A high amount of accumulated potassium resulted from its high contents in green parts of the plants, grains and potato tubers. Other natural isotopes were not accumulated in selected animal tissue samples and the artificial isotope, ^{l37}Cs was detected in poultry bones and egg shells.

Wasserman *et al.* (2002), examined the cultural inputs of ^{226}Ra and ^{228}Ra in tropical agricultural environment of Brazil using samples of rice (*Oriza sativa*, L.), corn (*Zea mays*, L.), wheat (*Triticum vulgare*), beans (*Phuseolus vulgaris*, L.) and soybeans (*Glycifie max*). The results showed that legumes (beans and soybeans) presented a higher absorption of the radionuclides than cereals (rice, wheat and corn).Also, locations with low soil concentration of the radionuclides presented a higher availability to the plants while the reverse was observed in areas with higher concentrations.

Ehlken and Kirchner (2002), reviewed the environmental processes affecting the plant root uptake of radioactive trace elements and the variability of transfer factor data of radiocesium and strotium. They pointed out that the linear relationship between the plant/plant part and soil concentration, assumed in calculating transfer factor (TF) does not exist because of the extreme variability observed in the values of TF. This is because the macroscopic parameter(TF) integrated a number of soil chemical, soil biological, hydrological, physical and plant physiological processes, each of which shows its own variability and in addition may be influenced by external factors such as climate and human agricultural practices. The efforts made so far to evaluate the influence of these processes using statistical inference were highlighted but with moderate success. Other factors that were thoroughly reviewed were the effect of competing ions, bioavailability (rhizosphere effects), root uptake and translocation. They pointed out that present knowledge could not quantify the effects of some of these factors as it affects the TF values, and called for further researches to enhance the understanding and quantification of the factors so as to review the formular for TF. However, soil-to-plant transfer factor data available could be used to derive probability distributions from which representative values for use with screening models can be derived.

Tome *et al.* (2003), obtained the transfer factors for natural radionuclides (^{234}U, ^{238}U, ^{232}Th, ^{230}Th, ^{228}Th and ^{226}Ra) and stable elements in a Mediterranean area in grass pasture growing in granitic and alluvial soils around disused uranium mine. At a 95% confidence level, and considering all the sampling points, the TF values obtained for the two uranium isotopes were indistinguishable statistically, with mean values of 0.067 and 0.072 for ^{238}U and ^{234}U, respectively. Likewise, the TF values corresponding to ^{232}Th and ^{230}Th can be considered statistically indistinguishable with a mean value of 0.058 for ^{232}Th and 0.056 for ^{230}Th. In general, high variability in TF values were obtained for the thorium isotopes. ^{228}Th was considered at a 95% confidence level to be higher (by two orders of magnitude) than the other two thorium isotopes studied. The excess was attributed to the higher absorption of radium, in particular ^{228}Ra. Therefore, the excess of ^{228}Th arises from ^{228}Ra decay in the plant and the uptake of ^{228}Th. The uptake of radium isotopes recorded highest values than uranium and thorium isotopes. This is due to the preferential uptake of elements in oxidation state +II than elements with oxidation state of +IV.

Baeza and Guillen (2006), focused on the influence of the soil bioavailability of radionuclides on the transfer of uranium and thorium to mushrooms at two locations in Spain. The work detected that the classical definition of TF has the limitation that the radionuclides present in the soil are not 100% capable of being transferred to the fruiting bodies, but are associated in different degrees to the soil particles. This can be partially solved using a definition of transfer factor based on the percentage of radionuclides that may be accessible to exchange reactions instead of on the total fraction of the soil. To study this association, a sequential extraction procedure was applied to the surface soil samples from the two locations. This procedure considered separately the exchangeable, the dilute-acid soluble, the concentrated-acid soluble, and the residual fractions. The fraction of radionuclides capable of transfer to the fruiting bodies would be that which was not strongly bound to the soil particles, i.e., that in the exchangeable and dilute-acid soil fractions. Thus, the available fraction (AF) was defined as given in equation 2.28.

$$AF(\%) = 100 - \text{C}oncentrate\,d\ \text{acid fraction}(\%) - \text{Re si}dual\ \ fraction\,(\%) \quad (2.28)$$

This available fraction was found to be very small for both uranium and thorium, and of the same order of magnitude for uranium and thorium at the two selected locations. The available transfer factor (ATF) was then defined as the ratio between the fruiting bodies of the mushrooms and the AF. The ATF values were consequently higher than the TF values, the difference being one order of magnitude for $^{234,\,238}$U and 2–3 orders of magnitude for $^{228,\,230,\,232}$Th.

The activity concentrations of naturally occurring (^{226}Ra, ^{232}Th, ^{228}Th, and ^{40}K) and anthropogenic (^{137}Cs) radionuclides in soil, grass and plant and their respective transfer factors were determined in Chittagong city in Bangladesh by Chakraborty *et al.,* (2013). A total of 60 soil samples (15 from each of 4 different depths), 10 grasses (*Allium cepa, Amaranthus spinosis, Chenopodium album, Cynodon dactylon, Cyperus rotundas, Echinochloa crussgali, Eleusine indica, Mimosa pudica, Murdnnia nudiflora and Portulaca oleracea*) and 5 plant (*Acalypha indica, Bacopa monniera, Lantana camera, Solanum nigram and Syndrella nodiflora*) species were selected for the investigation. The average activity concentrations of ^{226}Ra, ^{232}Th, ^{228}Th, ^{40}K and ^{137}Cs in soil were found to be 22.13 ± 2.30, 38.47 ± 2.72, 50.47 ± 4.75, 451.90 ± 24.89 and 2.41 ± 0.18 Bq kg^{-1}, respectively while in grass, their values were 1.26 ± 0.11, 3.66 ±

0.31, 7.02 ± 0.49, 134.95 ± 3.68 and 0.17 ± 0.02 Bq kg^{-1}, respectively. In branches of the plant, the concentration values of these radionuclides were higher than those for leaves. For soil to grass, the transfer factor values were found to be 0.056, 0.089, 0.137, 0.275 and 0.054, respectively for ^{226}Ra, ^{232}Th, ^{228}Th, ^{40}K and ^{137}Cs. The soil to branch transfer factor values (0.062, 0.098, 0.136, 0.274 and 0.064 respectively for ^{226}Ra, ^{232}Th, ^{228}Th, ^{40}K and ^{137}Cs) were higher than those for soil to leaves (0.054, 0.088, 0.127, 0.266 and 0.061 respectively)

Aswood *et al.*(2013), measured the natural radionuclide of ^{238}U and ^{232}Th in some essential vegetables (Tomato, Eggplant, Lettuce, Pumpkin, Cucumber, Onion, Okra, and Chilli) and soil samples collected from farms in Cameron Highlands and Penang, Malaysia, using neutron activation analysis technique. In soil, the average concentrations of ^{238}U and ^{232}Th were 203.83 $\pm$ 2.05 Bq kg^{-1} and 186.17 $\pm$ 3.35 Bq kg^{-1}, respectively. The highest concentrations of uranium and thorium were 6.25 $\pm$ 1.58 Bq kg^{-1} and 2.5 $\pm$ 1.55 Bq kg^{-1} in cucumber and lettuce products, respectively. The transfer factors of these radionuclides from soil to vegetables were estimated, lettuce and cucumber had the highest values which were compared with the published data and were found to be within acceptable limits.

Tchokossa *et al.*(2013), assessed the radioactivity contents and transfer of ^{40}K,^{238}U, ^{232}Th and ^{137}Cs in food in the oil and gas producing area in Delta state, Nigeria. The following food samples were collected from different locations and analysed; water leaf (*Talinumtrangulare*), bitter leaf (*Vernoniaamygdalina*), ugu (*Telfairiaoccidental*), cassava leaf (*Manihotesculentum* linn), fresh maize leaf (*Zeamays*) and grass (*Penicunmaximum*, *Synedrellanodifloragaerin*, *Andropogontectorumschum* and *ttonn*). Similarly fruits such as oranges (*Citrussimansis*), pineapples (*Annanassativa*), bananas (*Musasapientum*) and platains (*Musaparadisaca*) were also collected from different locations. Sample collected for tubers were yams (*Dioscorea* spp.), cassava (*Manihotesculentum* linn) and coco-yams (*Xanthosonaesculentum*), fresh and dry maize (*Zeamays*). Meat samples of goats, chicken, sheep and grass cutters reared or found in the different oil and gas producing areas were collected. The range of the TF of ^{40}K from soil to plant was estimated to be between 0.1- 0.94 with the highest in dried maize (Zea mays) and the lowest in grass (*Panicunmaximum*). TF values ranged between 0.03 - 0.57 for ^{238}U with the highest in fresh red maize (*Zeamays*) and the lowest in banana (*Musasapientun*). Also, the TF values for ^{232}Th ranged between 0.01 –

0.80 with the highest in Plantain (*Musaparadisaca*) and lowest in Pineapple (*Annanassativa*). For ^{137}Cs, the TF ranged between 0.06 – 0.31 were detected with the highest in grass (*Panicunmaximum*) and lowest in Orange (*Citrussimansis*).

Chandrashekara and Somashekarappa (2015), estimated the transfer factors of ^{226}Ra, ^{210}Pb, ^{232}Th, ^{40}K and ^{137}Cs in the leaves and barks of *Fiscus racemosa (L.)* which is a medicinal plant used in India. They also estimated the average annual committed effective dose and threshold annual consumption rate of the plant. The activity concentrations of these radionuclides (^{226}Ra, ^{210}Pb, ^{232}Th, ^{40}K and ^{137}Cs) were found to be 31.16±1.30, 31.49±4.20, 51.34±2.24 and 225.00±12.91 respectively, in soil of the rooting area, and 3.65±0.60 Bq kg^{-1}, 1.28±0.17, 14.24±1.83, 1.34±0.27, 384.47±2.83 Bq kg^{-1}, and BDL in the bark of the plant respectively. The activity concentrations of these radionuclides in the leaves were BDL, 98.37±9.09, BDL, 1043.00±77.28 Bqkg^{-1}, and BDL, respectively. It was observed that the soil-to-plant transfer factor of ^{232}Th was lower than that of ^{226}Ra, in spite of the higher concentration of ^{232}Th in soil sample. This was attributed to the fact that radium dissolves more easily in water than thorium; consequently, it is transported to the plant through absorption of water through root. Also, radium exhibits similar chemical properties as that of calcium and magnesium, which are essential elements for the growth and nutrition of plants. Thus, in place of Ca and Mg, plants may take up ^{226}Ra depending on its availability in soil.

Al-Hamarneh *et al.*(2016), studied the soil-to-plant transfer factors (TFs) of ^{226}Ra, ^{234}U and ^{238}U for 13 types of vegetables and agricultural crops planted under semi-arid environment in the northwestern part of Saudi Arabia. In crop fruits, eggplant exhibited the highest uptake of ^{226}Ra (TF value of 0.11), while beans (0.16) have the highest TF for ^{234}U and ^{238}U. The geometric mean of the TF values indicated that the crop roots tend to accumulate Ra and U about four to six-folds higher than fruits. The relation between TF values and soil concentrations showed a weak correlation. Activity ratios between radionuclides in crop plants indicated the preferential translocation of U in fruits than Ra even though Ra is more available for root uptake. The fruit/root (F/R) ratios obtained for the investigated plants showed that pepper had the smallest F/R ratios (0.07 ± 0.01, 0.12 ± 0.02 and 0.11 ± 0.02 for ^{226}Ra, ^{234}U and ^{238}U, respectively), while the highest F/R ratios observed in potatoes were 0.71 ± 0.15, 0.44 ± 0.10 and 0.40 ± 0.08 for ^{226}Ra, ^{234}U and ^{238}U, respectively.

Okeme *etal.* (2016), computed the radioactivity concentration in soil and transfer factors of radionuclides (^{40}K, ^{226}Ra and ^{232}Th) from soil to rice from Lokoja and Ibaji areas of Kogi State, Nigeria. The mean activity concentrations in Lokoja soil samples were found to be 508.86 ± 54.02, 41.27 ± 9.31 and 18.90 ± 4.21 Bq kg^{-1} for ^{40}K, ^{226}Ra and ^{232}Th, respectively. The values for the rice samples from Lokoja were 41.15 ± 5.41, 12.73 ± 3.77 and 10.36 ± 1.72 Bq kg^{-1} for ^{40}K, ^{226}Ra and ^{232}Th, respectively. The concentrations of the three radionuclides for Lokoja market rice sample were 38.00 ± 10.23, 7.45 ± 2.37 and 9.08 ±3.04Bq kg^{-1}, respectively. Mean activity concentrations in Ibaji soil samples were 639.52 ± 64.97, 9.81 ± 3.13 and 11.95 ± 3.79 Bq kg^{-1}, respectively; those of Ibaji rice samples were 61.01 ± 18.05, 7.28 ± 0.83 and 9.89 ± 2.59 Bq kg^{-1},respectively. The concentrations for Ibaji market rice sample were 38.71 ± 10.25, 7.94 ± 2.27 and 8.65 ± 2.01 Bq kg^{-1}, respectively. The Mean transfer factors of the three radionuclides for Lokoja samples were 0.0808, 0.3090 and 0.5912, respectively and those of Ibaji soil samples were 0.0975, 0.8052, and 0.8710, respectively. Thorium had the highest value while potassium recorded the lowest value for transfer factor at the two locations.

2.10 Characteristics of the Crops used for the Research Work

2.10.1 Cowpea (*Vigna unguiculata* (L.) Walp.)

Cowpeas are herbaceous, warm region annual plants of thePhaseoleae tribe of the Leguminosaefamily (Ehlers and Hall, 1997; Timko *et al*., 2007). It is grown in the tropics and semi-tropics regions; Africa, Asia, Europe, United States and South America (Singh *et al*., 2003).Cowpea seeds are high in protein, several vitamins, minerals and have significant amounts of soluble fibreThe young leaves, immature pods and seed, and the mature dried grain areconsumed by human while the entire plant serve as forage for animal food.

Cowpea plants have high tolerance for drought and can grow in a wide variety of soils, the root noodles are capable of fixing atmospheric nitrogen, thereby increasing the soil fertility. These characteristics make cowpea plant an important economic plant especially for developing countries.Nigeria is the largest producer and consumer of cowpea (Ehlers and Hall, 1997; Langyintuo *et al*., 2003;IITA, 2017a). Over 5.4 million tons of dried cowpea are produced worldwide. Africa produces almost 5.2 million with Nigeria producing 61 % of the production from Africa and 58% of the worldwide

production (IITA, 2017a). The maturity period of cowpea range from 60 to 150 days depending on the genotype of the planted seed (Timko *et al*., 2007).

According to Wasserman *et* al. (2002), legumes (cowpea and soybeans) accumulated more radium than cereals (rice, wheat and corn). Laroche *et al.,* (2005), reported that uranium-phosphate complexes could be bioavailable to plant like common beans (*P. vulgaris)* with the root acting as strong ligand that would dissociate the uranium-phosphate complexes and only the dissociation of complex is relevant in uptake and not the entire complex. Roivainen *et al.* (2011), supported this observation with the report that dicotyledonous plant species tend to accumulate more uranium than monocotyledonous species.

2.10.2 Maize (*Zea mays* L.)

Maize also known as corn, is a large grain cereal crop which has become a major staple food and is grown in most parts of the world, ranking third in the world after wheat and rice (Onasanya *et al*., 2009; Ranum *et al*., 2014). Maize is an annual plant belonging to grass family. The major component of maize grain is starch and this forms the basis for most of the maize production. Maize grain ismade up of 72% starch, 10% protein and 4% fat, delivering a calorie of 365 Kcal/100 g with some vitamins, minerals and fibre.Some of the maize produced are used for corn ethanol, animal feed and other maize products, such as corn starch and corn syrup(Ranum *et al*., 2014). It has a maturity period of about one hundred and twenty (120) days.

About 785 million tons of maize is produced worldwide with Africa producing 6.5%. The world largest producer of maize is the United State at 42% of the world production while Nigeria is the Africa largest producer at 8 million tons (IITA, 2017b).

2.10.3 Cassava (*Manihot esculenta* L.)

Cassava is a drought tolerant perennial woody shrub with edible root, cultivated in the tropical and subtropical regions of the world.It serves as major source of carbohydrates and staple food in the developing world. It is the third largest source of carbohydrates in the tropics after maize and rice. Cassava roots are rich in starch and contain small amount of calcium, phosphorus and vitamin C (IITA, 2017c).

Over 228 million tons of cassava were produced worldwide in 2007, with Africa producing 52% of the world production. Nigeria produced 46 million tons, making it the world's largest producer (IITA, 2017c).

The cassava shrub may grow up to 2.75 m tall, with leaves deeply divided onto lobes. The shrub is often grow annually, and propagated from the stem after the root tubers have been removed. Its maturity requires between 10 – 14 months to grow to a harvestable size (Moorthy and Ramanujam, 1986; Pypers *et al*., 2011).

CHAPTER THREE
MATERIALS AND METHODS

3.1 Sample Collection

Tailings were collected from a tin mining site in Jos, Plateau State, Nigeria. Virgin soil from uncultivated area were also collected from the botanical garden of Redeemer's University temporary site, Mowe, Ogun State. Three soil groups for planting were prepared from the tailings and the virgin soil. Group A was made up of virgin soil from the uncultivated area, group B was made up of the tailings while group C was made of mixture of equal ratio by dry mass of the tailings and virgin soil. Ten aliquots were taken from each of the soilgroups and analysed for activity concentration of ^{40}K, ^{238}U and ^{232}Th before planting.

Seeds of maize (*Zea mays* L.; TZPB) and cowpea(*Vigna unguiculata* L.; Ife brown) were collected from Institute of Agricultural Research and Training (IARandT) Ibadan. Cassava (*Manihot escalenta* Crantz; TME 419) stems were collected from International Institute for Tropical Agriculture (IITA) Ibadan. These crops were chosen because of their high consumption rate across Nigeria. According to IITA (2004), the frequency of consumption of major staple food in Nigeria showed that maize had the highest percentage(20.1%), while cassava and cowpea followed closely with 16.5 and 11.5%,

respectively. They were also chosento represent the grains (maize), legumes (cowpea) and root crops(cassava).

3.2 Planting and Harvesting

Ten planting pots were prepared from eachsoil group for each of the plants. The seeds of maize and cowpea, and stems of cassava were separately planted in the pots. After planting the seeds and stems, the pots were kept in an open space where they were adequately exposed to sunlight. The plants were regularly watered daily until they attained maturity. The maize and the cowpea plants grew to maturity at four months (April 2013- August 2013) while the cassava grew to maturity at one year (April 2013 - March 2014).

Fertilizer was not applied during the planting process. So as not to introduce complexity that the application of fertilizer might introduce. It has been established that most fertilizer contain radionuclides in appreciable quantity (Ahmed and El-Arabi, 2005), so applying fertilizers would introduce radionuclides into the soil. It would therefore be difficult to account for the amount of the radionuclides in the fertilizer absorbed by the plant. The pictures of the pot experiments for the different plants are shown in appendix A.

At maturity, the crops and entire parts of the plants were harvested. The leaves, stems and roots were thoroughly washed with clean water, labeled and dried at room temperature.

3.3 Sample Preparation

The harvested crops, roots, stems and leaves of each plant from a particular pot were separately dried in an oven at a temperature of 80°C until a constant mass was attained. They were separately grinded, sieved, weighted and sealed in air-tight cylindrical plastic containers of height 8.0 cm and diameter 7.0 cm. A mass of 200 g each of soil samplesfrom each soil group were prepared for counting. The sealed samples were labeled and stored for more than four weeks in order to allow for the attainment of secular equilibrium of ^{238}U and ^{232}Th with their respective progenies (Jibiri et al., 2007; Al-Masri *et* al., 2008; Ademola and Okpalaonwuka, 2010). Each of the samples was counted for 36,000 s.A total of three hundred and thiry-nine samples were analysesd.

3.4 Counting Assembly

The counting system consists of a 7.6 cm × 7.6 cm NaI(Tl) scintillation detector by Bicron (Model No. 1002 series), sealed with a photo multiplier tube and connected through a preamplifier base to a Canberra series 10-plus multi-channel analyser (MCA). The detector is interfaced with the MCA through a 50 Ω coaxial cable and has a positive signal output. The MCA consists of an analogue-to-digital converter (ADC), control logic (CL) with an input and output devices, an internal spectroscopic amplifier (AMP), 4K memory, display and analysis logic (DAL) with screen display unit. It has an in-built high voltage power supply (HVPS) which supplies a stabilized extra high voltage.

Once all the cables are properly connected, the MCA is switched on through a rear knob that has the following points; RST (reset), STBY(standby), ON, and HV ON(high voltage on). The knob is turned to HV ON to turn the internal high voltage power supply. Through the SETUP menu, the HV is set to 1000 V. Other parameters that were set through the SETUP menu were viz. ADC GAIN at 1024, the amplifier was set at positive polarity, FAST shaping and gain of 3.5 and Preset time at 36,000 s.

3.4.1 Calibration of the Detector System

Two types of detector calibrations were carried out in this work. These are the energy and efficiency calibration of the detector. The energy calibration was carried out to enable the identification of the radionuclides present in the samples analysed. The detection efficiency was done toquantify the amount of radionuclide present in the samples analysed.

3.4.1.1 Energy Calibration

Single calibrated gamma sources (^{22}Na, ^{137}Cs, and ^{60}Co) from the Nucleus Inc., Oak Ridge, TN, USA and reference sources (RGK-1,RGU-1,RGTh-1) from the International Atomic Energy Agency (IAEA) were used for the energy calibration of the measuring system.Equation 3.1 gives the calibration equation obtained from the energy calibration. The true positions (channel numbers) of each full-energy peak for each nuclide was determined and reported in section 4.1.

$$E(MeV) = 1.888\times10^{-2}N + 0.32908758 \qquad (3.1)$$

where E is the gamma energy in MeV and N is the channel number. With this equation stored in the memory of the measuring system, it was possible to identify radionuclides in a mixed gamma field through the energies emitted.

3.4.1.2 Efficiency Calibration

In order to quantify the radionuclides present in the samples, efficiency calibration was carried out using standard sources; ENV 95050 for soil matrix, prepared from Rocketdyne laboratories, Canoga Park, California, USA and IAEA 152 for food matrix. The standard source for the soil matrix was certified to have activity concentration of 578.40 ± 27.30, 20.90 ± 0.92 and 10.47 ± 0.57 Bqkg^{-1} for ^{40}K, ^{238}U and ^{232}Th, respectively. The food matrixwas certified to have activity concentration ranges of 722 – 802, 2053 – 2209, 510 – 574 and 7.0 – 8.3 Bq kg^{-1} for ^{134}Cs, ^{137}Cs, ^{40}K and ^{90}Sr respectively, with the following recommended values at 95 % confidence level; 764 Bq kg^{-1} for ^{134}Cs, 2129 Bq kg^{-1} for ^{137}Cs, 539 Bq kg^{-1} for ^{40}K and 7.7 Bq kg^{-1} for ^{90}Sr. Due to the short half-lives of ^{134}Cs and ^{90}Sr, only activity concentrations of ^{137}Cs and ^{40}K were used for the efficiency calibration for the food matrix. The efficiencies for ^{238}U and ^{232}Th for the food matrix were then extrapolated from the curve obtained using the efficiencies of ^{137}Cs and ^{40}K.

The activity concentrations C of the radionuclides in the standard source was related to the area under each photopeak of the respective radionuclides above the background using equation 3.2 (Jibiri *et* al., 2007; Ademolaand Okpalaonwuka. 2010).

$$E_p = \frac{A}{tCYm} \tag{3.2}$$

where E_p is the detection efficiency, A is the area under the photopeak, t is counting time, Y is the gamma yield and m is the mass of the samples. The result obtained are reported in section 4.1.

3.5 Activity Concentration

The 1.460 MeV photopeak was used for the measurement of ^{40}K while the1.760 MeV photopeak from ^{214}Bi and the 2.614 MeV photopeak from ^{208}Tl were used for the measurement of ^{238}U and ^{232}Th, respectively. The activity concentration of ^{40}K, ^{238}U and ^{232}Th were calculated using equation 3.3;

$$C = \frac{A}{tE_p Ym} \tag{3.3}$$

where each of the parameters has the same definition as given by equation 3.2. The LLDof the measuring system calculated using equation 2.26 were converted to activity concentrations using equation 3.3. The values calculated for Below Dection limits are reported in section 4.1.

3.6 Transfer Factor

The transfer factor (TF) of ^{40}K, ^{238}U and ^{232}Th for all the samples were calculated using equation 3.4 (Tome *et al.,* 2003, Beresford *et al.,*2005).

$$TF = \frac{Activity\,\text{concentration of plant}(\text{Bqkg}^{-1}, \text{dry weigth})}{Activity\,\text{concentration of soil}(\text{Bqkg}^{-1}, \text{dry weigth})} \tag{3.4}$$

The geometric mean was used for the statistical analysis. A two-way analysis of variance (ANOVA) was used to test for the significance of the variations observed in the mean values of the transfer factor.

3.7 CommittedEffective Dose

Effective dose is a useful dosimetric quantitythat sumsup the radiation doses from different radionuclides, from different types and sources of radioactivity.It enables the estimation of the radiation induced health effects associated with intake of radionuclides into the body (Jibiri *et al*., 2007).The annualcommitted effective dose H (Sv y^{-1}), due to ingestion of ^{40}K, ^{238}U and $^{232}Th$of adult population in the food samples were calculated with equation 3.5

$$H = \sum \left(DC_r C_r^i\right) U^i \tag{3.5}$$

where DC_r is the dose conversion factor (Sv Bq^{-1}) of radionuclide r, C_r^i is the activity concentration (Bq kg^{-1}) of radionuclide r in i sample and U^i is the annual consumption rate (kg y^{-1}) of a food type. The conversion factors of ^{40}K, ^{238}U and ^{232}Th and the mean annual consumption values are given in tables 3.1 and 3.2, respectively.

Table 3.1: Dose coefficients for intake of Radionuclide by ingestion (ICRP, 2012)

Nuclide	DC_r (Sv Bq^{-1})
^{40}K	6.2×10^{-9}
^{238}U	4.5×10^{-8}
^{232}Th	2.3×10^{-7}

Table 3.2:Mean annual consumption (MAC) values (FOA, 2013)

Crop	MAC (kg y^{-1})
Cowpea	0.03
Maize	32.72
Cassava	118.46

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results from Energy and Detection Efficiency Calibration

The results obtained from the energy calibration is reported in table 4.1. A plot of the energies and the corresponding channel numbersfor energy calibration was obtained as shown in figure 4.1. The detection efficiencies of the radionuclides determined for the food and soil matrices are given in tables 4.2. The efficiency curves for the soil and food matrices are presented in figures 4.2 and 4.3, respectively.

The background count for each radionuclide was subtracted from the gross count for the respective radionuclide to obtain the net count in each of the sample. The net count with other parameters listed in table 4.2 were substituted into equation 3.3 to calculate the activity concentration of the radionuclides. The background counts are presented in table B.1 of appendix B. The activity concentrations calculated using the LLD (counts)were set as Below Detectable Limit (BDL) values. For soil samples, the BDLin Bq kg^{-1} for ^{40}K, ^{238}U and ^{232}Th are 74.84, 37.68 and 60.71, respectively while for food samples, the BDLin Bq kg^{-1} for ^{40}K, ^{238}U and ^{232}Th are 25.09, 9.78 and 21.18, respectively.

4.2 Activity Concentration of Radionuclides in the Samples

The activity concentrations of ^{40}K, ^{238}U and ^{232}Th inthe plant and soil samples are presented in tables C.1 to table C.45 of appendix C. The uncertainties in the activity concentrations for the samples were calculated using the error propagation formular given in equation 2.20. Tables 4-3 to 4.5 are the summaries of the activity concentrations of the radionuclides in the plants. The uncertainties stated with the mean values of thenatural radionuclides in tables 4.3 to 4.5 are the standard deviation of the replicates for the plant samples. The number of samples (column 3) reported in tables

4.3 to 4.5 are for the pots whose plants grew to maturity as some of the plants died in the course of the experiment.

Table 4.1: Energies of the calibrated gamma sources with their corresponding channel numbers

Nuclide	Energy (MeV)	Channel number
Na-22	0.511	11
Cs-137	0.662	18
Co-60	1.173	43
Na-22	1.275	48
Co-60	1.332	52
K-40	1.462	60
U-238	1.765	75
Th-232	2.615	123

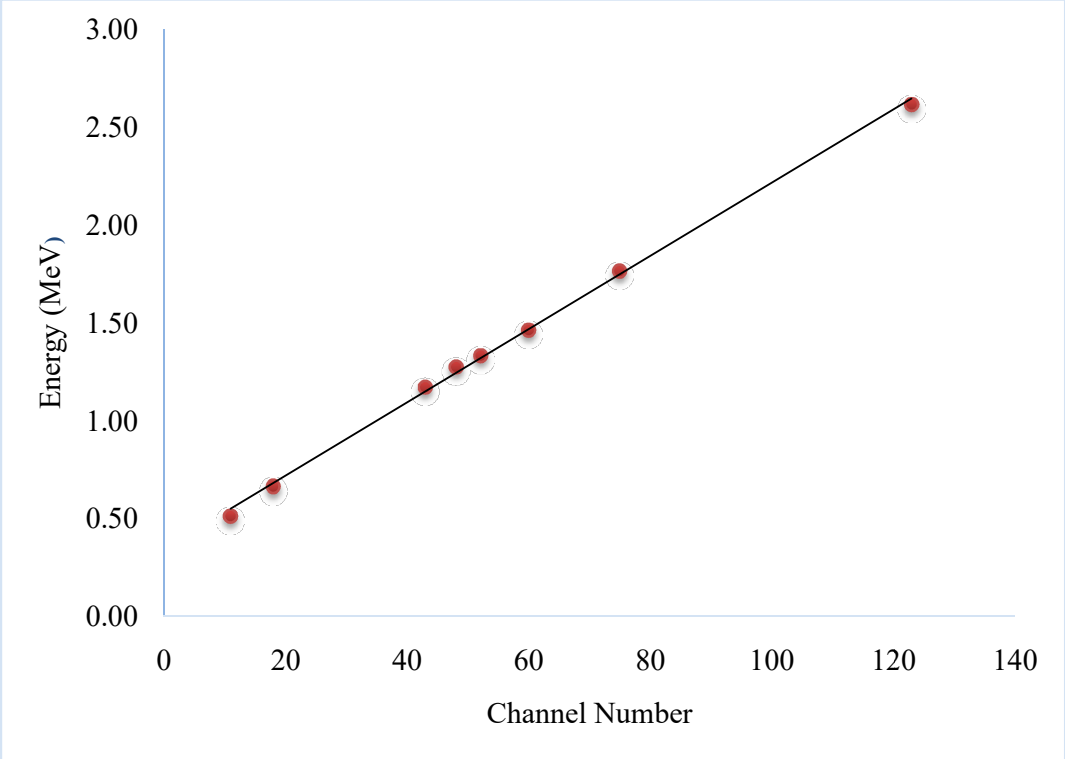

Figure 4.1 Energy (MeV) against the channel number

Table 4.2: Detection efficiencies at different gamma energies for soil and food matrix

Matrix	Radionuclide	Energy, E (MeV)	Log (E)	Yield	Efficiency (10^{-2}) (cs^{-1} Bq^{-1})
Food	^{137}Cs	0.662	-0.18	0.852	11.03
	^{40}K	1.462	0.16	0.107	7.01
	^{238}U	1.760	0.25	0.159	5.90
	^{232}Th	2.614	0.41	0.358	3.64
Soil	^{40}K	1.462	0.17	0.107	2.35
	^{238}U	1.760	0.25	0.159	1.53
	^{232}Th	2.614	0.42	0.358	1.27

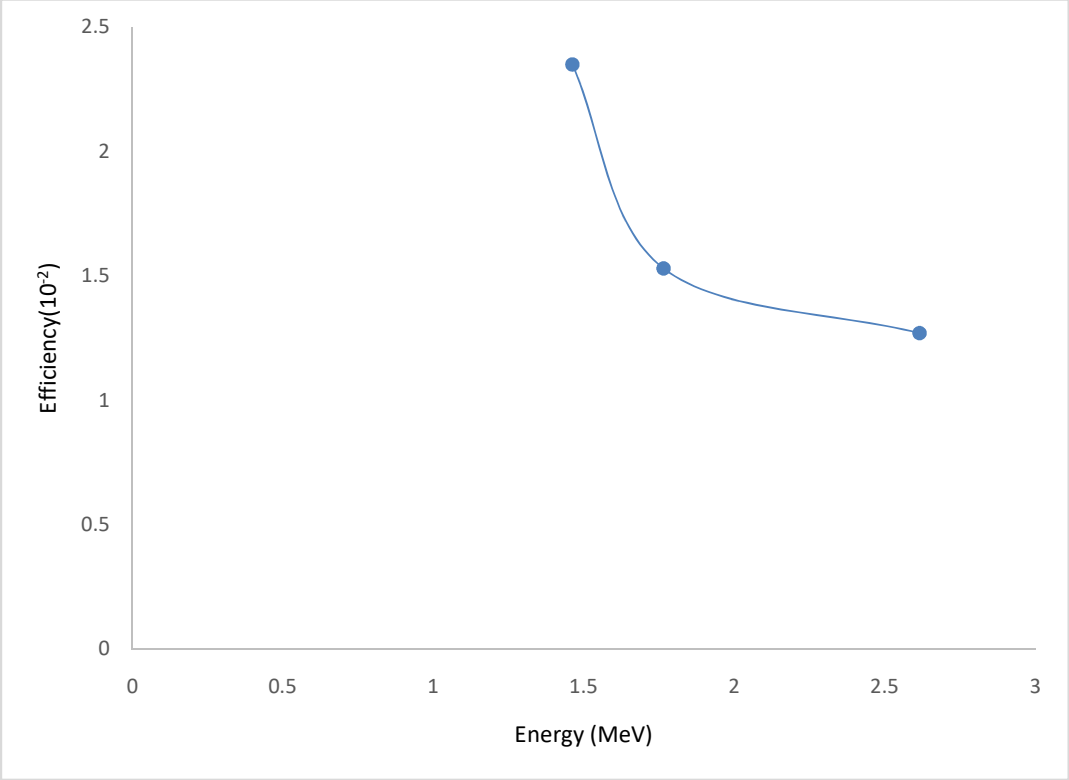

Figure 4.2a: Efficiency curve for the soil matrix.

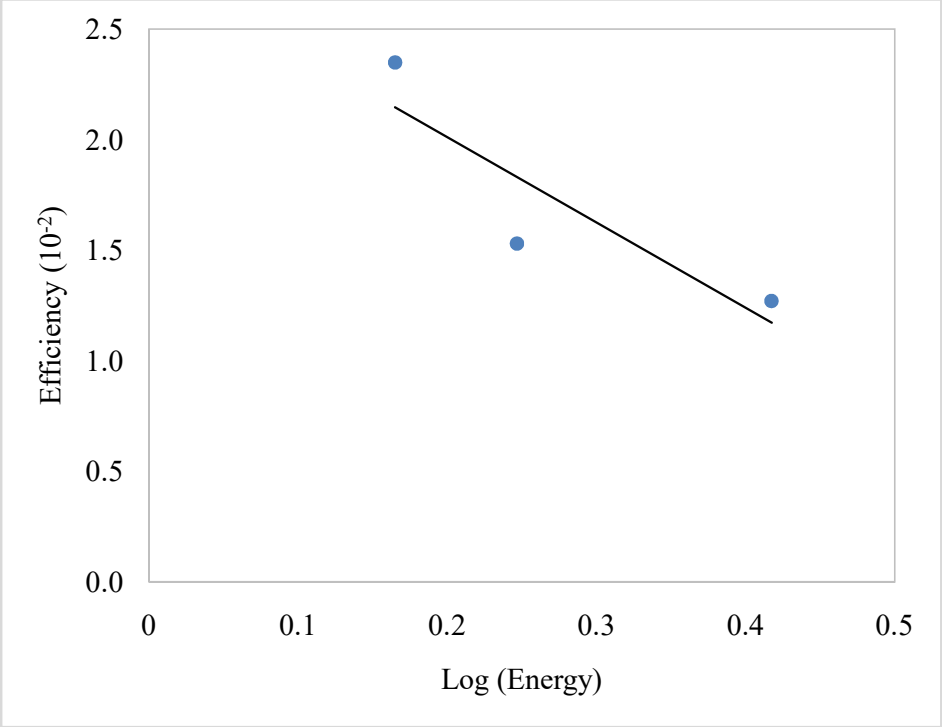

Figure 4.2b: Efficiency against Log (Energy) for soil matrix.

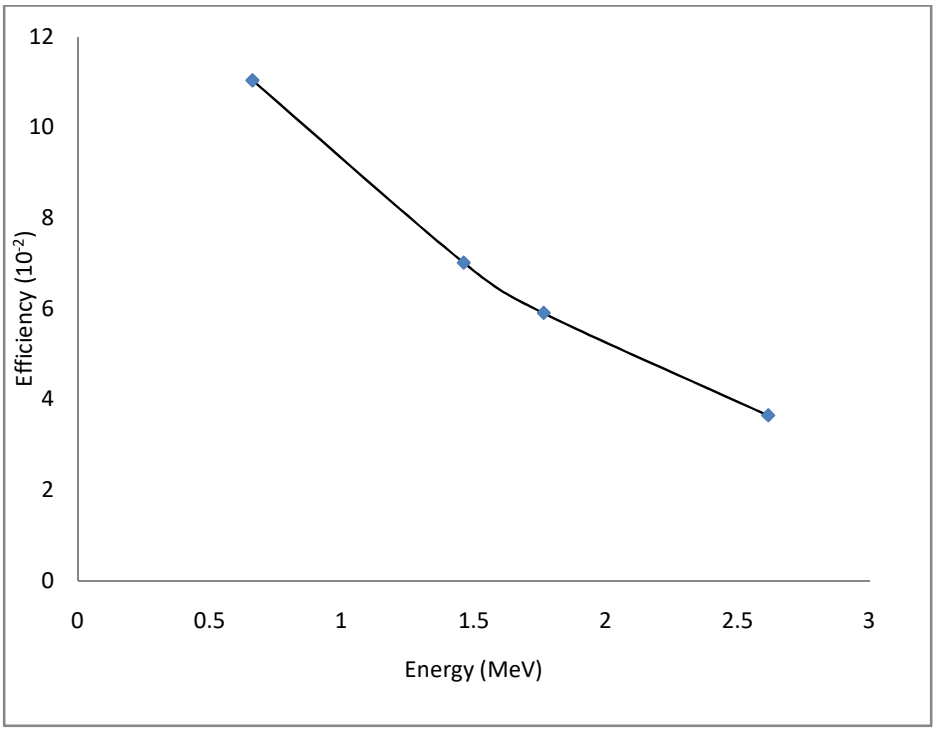

Figure 4.3a: Efficiency curve for the food matrix.

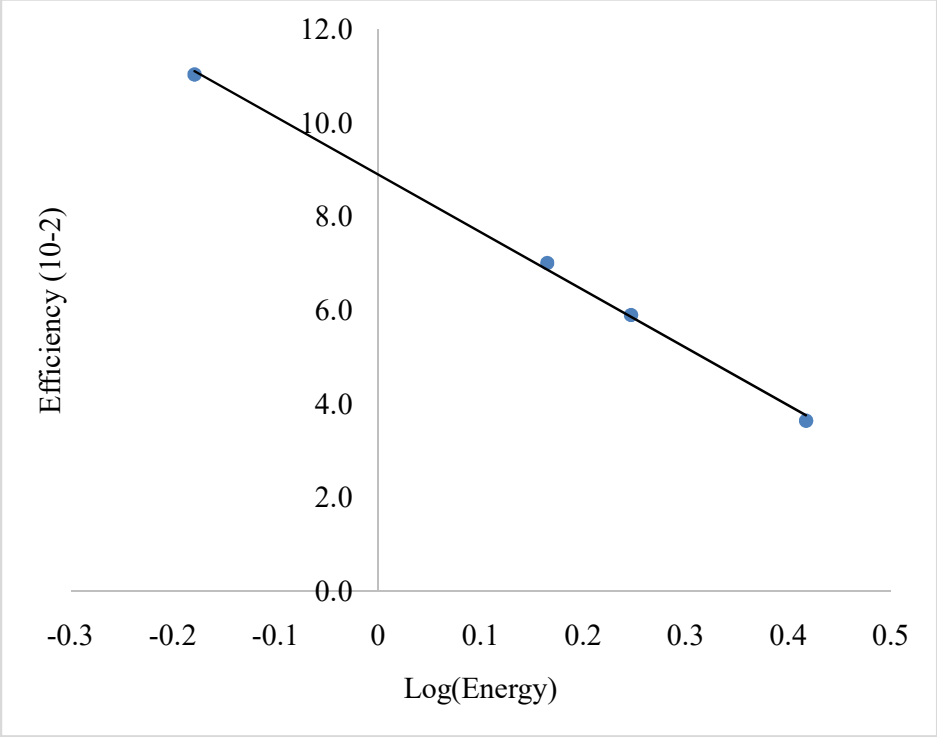

Figure 4.3b: Efficiency against Log(Energy) for food matrix

4.2.1. Activity Concentrations of Natural Radionuclides in Cowpea Plant

The activity concentrations of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1}in the differentcompartments of cowpea plantsare given in tables C.1 to C.12 of appendix C. The mean and standard deviation of the activity concentrationsof ^{40}K, ^{238}U and ^{232}Th in Bq $kg^{-1}$of cowpea plant compartments from the three soil groupsare summarised in table 4.3.

(i)Parts of Cowpea Plant harvested from Soil Group A

The activity concentrations of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} in cowpeacompartments harvested from soil group A are presented in tables C.1 to C.4 of appendix C.The average values of the activity concentrations in Bq kg^{-1} of ^{40}K, ^{238}U and ^{232}Th respectively in harvested seeds were 254.34 ± 46.52, 65.25 ± 61.73 and 334.02 ± 305.33; 876.15 ± 663.21, 36.14 ± 8.21 and 995.71 ± 519.46 for the stems; 2400.16 ± 1791.18, 88.82 ± 26.95 and 2848.75 ± 1210.85for the leaveswhile 1296.57 ± 874.73, 217.28 ± 62.29 and 1307.54 ± 697.84 are the average values of ^{40}K, ^{238}U and ^{232}Th, respectively for the roots in Bq kg^{-1}.

(ii) Parts of Cowpea Plant harvested from Soil Group B

The activity concentrations of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} in cowpeacompartments harvested from soil group B are presented from tables C.5- C.8 of appendix C.The average values for the activity concentrations in Bq kg^{-1} of ^{40}K, ^{238}U and ^{232}Th in the harvested the seeds were 228.88 ± 218.05, 150.87 ± 223.75 and 15972.92 ± 45359.97, respectively. For the stems, 533.49 ± 350.87, 121.28 ± 143.03 and 1426.92 ± 678.64, were respectively the average values of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1}. For the leaves, 913.79 ± 815.62, 717.90 ± 404.86 and 3255.28 ± 1702.68 were the average values of ^{40}K, ^{238}U and ^{232}Th, respectively while 736.76 ± 481.10, 176.66 ± 152.02 and 3327.41 ± 1510.92 were the average values of ^{40}K, ^{238}U and ^{232}Th, respectively for the roots in Bq kg^{-1}.

(iii) Parts of Cowpea Plant harvested from Soil Group C

The detailed activity concentrations of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} in cowpeacompartments harvested from soil group C are presented in tables C.9 to C.12 of appendix C. The average values for the activity concentrations in Bq kg^{-1} of ^{40}K, ^{238}U and ^{232}Th in harvested seeds were 152.88 ± 112.14, 85.42 ± 76.43 and 1338.89 ± 800.46, respectively.

Table 4.3:Summary of the activity concentrations (Mean ± STD) in Bqkg^{-1}of^{40}K, ^{238}U and ^{232}Th in cowpea plant compartments

Soil group	Plant part	Number of samples	Activity Concentration (Bqkg^{-1})		
			^{40}K	^{238}U	^{232}Th
Group A	Seed	5	254.34 ± 46.52	65.25 ± 61.73	334.02 ± 305.33
	Stem	5	876.15 ± 663.21	36.14 ± 8.21	995.71 ± 519.46
	Leaf	5	2400.17 ± 1791.18	88.82 ± 26.95	2848.75 ± 1210.85
	Root	5	1296.57 ± 874.73	217.28 ± 62.29	1307.54± 697.84
Group B	Seed	9	228.88 ± 218.05	150.87 ± 223.75	15972.92 ± 453.97
	Stem	9	533.49 ± 350.87	121.28 ± 143.03	1426.92 ± 678.64
	Leaf	9	913.79 ± 815.62	717.90 ± 404.86	3255.28 ± 1702.68
	Root	9	736.76 ± 481.10	176.66 ± 152.02	3327.41 ± 1510.92
Group C	Seed	8	152.88 ± 112.14	85.42 ± 76.43	1338.89 ± 800.46
	Stem	8	304.01 ± 189.75	BDL	700.30 ± 202.94
	Leaf	8	1302.55 ± 793.90	BDL	3658.87 ± 1745.86
	Root	8	1476.91 ± 613.64	BDL	2301.01 ± 1753.32

For the stems, 304.01 ± 189.75, BDL and 700.30 ± 202.94 were respectively, the average values of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1}. For the leaves, 1302.55 ± 793.90, BDL and 3658.87 ± 1745.86 were the average values of ^{40}K, ^{238}U and ^{232}Th, respectively in Bq kg^{-1} while 1476.91± 613.64, BDL and 2301.01 ± 1753.32 were the average values of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1}, respectively for the roots.

4.2.2 Activity Concentrations of Natural Radionuclides in Maize Plant

The mean and standard deviation in the activity concentrations for ^{40}K, ^{238}U and ^{232}Th in Bq $kg^{-1}$for all the compartments of maize plants are given in table 4.4.

(i) Parts of Maize Plant harvested from Soils Group A

Theactivity concentrations of^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} in maize compartments harvested from soil group A are presented from tables C.13 to C.16 of appendix C.The average values of activity concentrations of^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1}were respectively 105.43 ± 37.21, BDL and 318.46± 499.96, for the seeds; 685.08 ± 245.70, BDL and 828.87 ± 783.01 for maize stems;371.13 ± 137.34, 80.06 ± 5.60 and 304.31 ± 221.50 for the leaves and 472.95 ± 397.52, 245.47 ± 322.23 and 1065.80 ± 1035.16 for the roots.

(ii) Parts of Maize Plant harvested from Soils Group B

Theactivity concentrations of^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} in maize seeds, stems, leaves and roots harvested from soil group B are presented from tables C.17 to C.20.The average values of activity concentrations of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} were respectively 127.03 ± 115.46, 25.58 ± 23.08and 1098.08 ± 854.13 for the seeds; 299.90± 198.23, BDL and 485.51 ± 276.73for the stems; 190.83 ± 165.21,BDL and 826.37 ± 1182.03 forthe leaves and 243.77 ± 252.77, 567.19 ± 442.38 and 3831.23 ± 2282.00 for the root compartments.

(iii) Parts of Maize Plant harvested from Soils Group C

Theactivity concentrations of^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} in maizecompartments harvested from soil group C are presented in tables C.21 to C.24 of appendix C.The average values of activity concentrations of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} are respectively 283.50 ± 266.00, BDL and 433.72 ± 671.35 for maize seeds; 328.59 ±

Table 4.4: Summary of the activity concentrations (Mean ± STD) in $Bqkg^{-1}$ of ^{40}K, ^{238}U and ^{232}Th in maize plant compartments

Soil group	Plant part	Number of samples	Activity Concentration ($Bqkg^{-1}$)		
			^{40}K	^{238}U	^{232}Th
Group A	Seed	7	105.43 ± 37.21	BDL	318.46 ± 499.96
	Stem	7	685.08 ± 245.70	BDL	828.87 ± 783.01
	Leaf	7	371.13 ± 137.34	80.06 ± 5.60	304.31 ± 221.50
	Root	7	472.95 ± 397.52	245.47 ± 322.23	1065.80 ± 1035.16
Group B	Seed	8	127.03 ± 115.46	25.58 ± 23.08	1098.08 ± 854.13
	Stem	8	299.90 ± 198.23	BDL	485.51 ± 276.73
	Leaf	8	190.83 ± 165.21	BDL	826.37 ± 1182.03
	Root	8	243.77 ± 252.77	567.19 ± 442.38	3831.23 ± 2282.00
Group C	Seed	8	283.50 ± 266.00	BDL	433.72 ± 671.35
	Stem	8	328.59 ± 185.61	BDL	184.49 ± 81.32
	Leaf	8	349.48 ± 477.59	18.08 ± 9.54	238.05 ± 64.64
	Root	8	298.94 ± 504.20	185.36 ± 120.82	1648.80 ± 913.12

185.61, BDL and 184.49 ± 81.32 for maize stems; 349.48 ± 477.59, 18.08 ± 9.53 and 238.05 ± 64.64 for maize leaves and 298.94 ± 504.20, 185.36 ± 120.82 and 1648.80 ± 913.12 for maize roots.

4.2.3 Activity Concentrations of Natural Radionuclides in Cassava Plant

The mean and standard deviation in the activity concentrations for ^{40}K, ^{238}U and ^{232}Th in Bq $kg^{-1}$of all the compartments of cassava plants are given in table 4.5.

(i) Parts of Cassava Plant harvested from Soils Group A

The activity concentrations of^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} in cassava compartments harvested from soil group A are presented in tables C.25 to C.27 of appendix C. The tubers samples have average valuesof 163.94 ± 68.84, BDL and 158.16 ± 89.50; the stem samples have average values of 157.08 ± 98.50, 21.43 ± 6.23 and 183.22 ± 49.54 while the leaf samples have average values of 393.62 ± 334.75, 114.25 ± 117.20 and 1017.79 ± 1302.06 for^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1}, respectively.

(ii) Parts of Cassava Plant harvested from Soils Group B

The activity concentrations of^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} in cassava compartment from soil group B are presented in tables C.28 to C.30 of appendix C.The tubers samples have average values of 39.39 ± 26.67, BDL and 1569.11 ± 1487.87; the stem samples have average values of 47.28 ± 15.71, BDL and 689.35 ± 272.76 while the leaf samples have average values of 525.67 ± 345.00, BDL and 1410.52 ± 1128.36 for ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1}, respectively.

(iii) Parts of Cassava Plant harvested from Soils Group C

The activity concentrations of^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} in cassava compartments harvested from soil group C are presented in tables C.31- C.33 of appendix C.The tubers samples have average values of 62.19 ± 25.63, 14.26 ± 3.41 and 89.05 ± 110.86; the stem samples have average values of 183.65 ± 175.48, 18.84 ± 2.84 and 376.77 ± 243.09 while the leaf samples have average values of 1880.62 ± 1198.42, 120.58 ± 98.50 and 2613.92 ± 2010.38 for ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1}, respectively.

Table 4.5: Summary of the activity concentrations (Mean ± STD) in Bqkg^{-1}of ^{40}K, ^{238}U and ^{232}Th in cassava plant compartments

Soil group	Plant part	Number of samples	Activity Concentration (Bqkg^{-1})		
			^{40}K	^{238}U	^{232}Th
Group A	Tuber	5	163.94 ± 68.84	BDL	158.16 ± 89.50
	Stem	5	157.08 ± 98.50	21.43 ± 6.23	183.22 ± 49.54
	Leaf	5	393.62 ± 334.75	114.25 ± 117.20	1017.79 ± 1302.06
Group B	Tuber	7	39.39 ± 26.67	BDL	1569.11 ± 1487.87
	Stem	7	47.28 ± 15.71	BDL	689.35 ± 272.76
	Leaf	7	525.67 ± 345.00	BDL	1410.52 ± 1128.36
Group C	Tuber	9	62.19 ± 25.63	14.26 ± 3.41	89.05 ± 110.86
	Stem	9	183.65 ± 175.48	18.84 ± 2.84	376.77 ± 243.09
	Leaf	9	1880.62 ± 1198.42	120.58 ± 98.50	2613.92 ± 2010.38

4.2.4 Activity Concentrations of Natural Radionuclides in Soil Samples

The geometric mean (GM) and geometric standard deviation (GSD) of the activity concentrations of ^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1} of all the soil groups are presented in table 4.6.The respective GM (GSD) of^{40}K, ^{238}U and ^{232}Th in Bq kg^{-1}respectively, are 179.66 (2.88), 90.53 (3.37) and 273.06 (5.37) for soil A; 3421.52 (3.64), 1992.61 (1.85) and 25232.30 (1.33)Bq kg^{-1}, for soil B and 546.71(6.32), 1281.19 (6.42) and 10136.97 (4.18)Bq $kg^{-1}$for soil C.

4.3 Transfer Factors of Natural Radionuclides

The results of the transfer factors (TF) of ^{40}K, ^{238}U and ^{232}Th are presented on table D.1 to D.33 of appendix D. Table 4.7 to 4.9 show the range and GM (GSD)of the TF of the radionuclides for each of the plants for the soil groups. The GM and GSD for each table were calculated using equations 2.23 and 2.25,respectively.

4.3.1 Transfer Factors for Cowpea Plants

The TFs of ^{40}K, ^{238}U and ^{232}Th for cowpeacompartments harvested from the soil groups are shown in tables D.1 to D.12 of appendix D. The range, GM (GSD) of the TF of the radionuclides for the soil groups are summarised in table 4.7.

(i) Parts of Cowpea Plants Harvested from Soil Group A

The TFs of ^{40}K, ^{238}U and ^{232}Th for cowpeacompartments harvested from soil group A are shown in tables D.1 to D.4 of appendix D. The TFs of ^{40}K, ^{238}U and ^{232}Th respectively, varied between BDL – 1.71, BDL – 1.20 and 0.11 – 1.54with GM (GSD) of 1.40(1.15), 0.53(2.25) and 0.77(3.01) for the seeds; 2.66 – 11.01, BDL – 0.46 and 1.68 – 6.21 with GM (GSD) of 3.93(1.91), 0.39(1.18) and 3.32(1.65) for the stems; BDL – 22.45, BDL – 1.19 and 6.02 – 17.21 with GM (GSD) of 9.67(2.49), 0.96(1.24) and9.73(1.45) for the leaves andBDL – 11.47, BDL – 2.87 and 2.82 – 9.25 with GM (GSD) of 9.38(5.71), 2.34(1.23) and4.38(1.49) for the roots.

(ii) Parts of Cowpea Plants Harvested from Soil Group B

The TFs of ^{40}K, ^{238}U and ^{232}Th for cowpeacompartments harvested from soil group B are presented from tables D.5– D.8 of appendix D.The TFs of^{40}K, ^{238}U and ^{232}Th respectively, varied between BDL – 0.14, BDL - 0.21 and 0.03 – 5.43 with a GM

(GSD) of 0.05(1.88), 0.02(3.31), and 0.06(5.01) for the seeds; BDL – 0.33, BDL – 0.11 and

Table 4.6: Activity concentrations (GM(GSD)) in Bqkg^{-1} of ^{40}K, ^{238}U and ^{232}Th for the soil group

Soil group	Activity Concentration (Bqkg^{-1})		
	^{40}K	^{238}U	^{232}Th
Soil A	179.65 (2.88)	90.35 (3.37)	273.06 (5.37)
Soil B	3421.52 (3.64)	1992.61 (1.55)	25232.30 (1.33)
Soil C	546.71 (6.32)	1281.19 (6.42)	10136.97 (4.18)

Table 4.7: The range and GM (GSD) of the transfer factors of ^{40}K, ^{238}U and ^{232}Th in cowpea plant compartments for the soil groups

Soil group	Plant part	^{40}K		^{238}U		^{232}Th	
		Range	GM(GSD)	Range	GM(GSD)	Range	GM(GSD)
Group A	Seed	BDL-1.71	1.40(1.15)	BDL-1.20	0.53(2.25)	0.11-1.54	0.77(3.01)
	Stem	2.66-11.01	3.93(1.91)	BDL-0.46	0.39(1.18)	1.68-6.21	3.32(1.65)
	Leaf	BDL-22.45	9.67(2.49)	BDL-1.19	0.96(1.24)	6.02-17.21	9.73(1.45)
	Root	BDL-11.47	9.38(5.71)	BDL-2.87	2.34(1.23)	2.82-9.25	4.38(1.49)
Group B	Seed	BDL-0.14	0.05(1.88)	BDL-0.21	0.02(3.31)	0.03-5.43	0.06(5.01)
	Stem	BDL-0.33	0.12(2.08)	BDL-0.11	0.03(3.32)	0.02-0.09	0.05(1.70)
	Leaf	BDL-0.51	0.18(3.09)	BDL-0.50	0.33(1.53)	0.05-0.26	0.11(1.67)
	Root	BDL-0.42	0.17(2.07)	BDL-0.16	0.05(3.18)	0.06-0.24	0.12(1.53)
Group C	Seed	BDL-0.55	0.21(2.37)	BDL-0.11	0.05(2.12)	0.04-0.26	0.11(1.87)
	Stem	BDL-0.91	0.44(2.09)	BDL	BDL	BDL-0.09	0.07(1.37)
	Leaf	BDL-4.97	2.00(1.88)	BDL	BDL	0.11-0.62	0.31(1.78)
	Root	BDL-3.98	2.56(1.38)	BDL-0.25	0.21(1.18)	0.01-0.53	0.14(3.73)

0.02 – 0.09 with a GM (GSD) of 0.12(2.08),0.03(3.32) and0.05(1.70) for the stems; BDL – 0.51, BDL – 0.50 and 0.05 – 0.26 with a GM (GSD) of 0.18(3.09), 0.33(1.53) and0.11(1.67) for the leaves and BDL – 0.42, BDL – 0.16 and 0.06 – 0.24 with a GM (GSD) of 0.17(2.07), 0.05(3.18) and0.12 (1.53) for the roots.

(iii) Parts of Cowpea Plants Harvested from Soil Group C

For cowpea compartments harvested from soil C, the TFs of ^{40}K, ^{238}U and ^{232}Th are presented fromtables D.9 – D.12 of appendix D. The TFs of ^{40}K, ^{238}U and ^{232}Th respectively, varied between BDL – 0.55, BDL – 0.11 and 0.04 – 0.26 with GM (GSD) of 0.21(2.37),0.05(2.12) and 0.11(1.87) for the seeds;BDL – 0.91, BDL (for all the samples) and BDL – 0.09 with a GM (GSD) of 0.44(2.09), BDL and0.07(1.37) for the stems; BDL – 4.97, BDL (for all the samples) and 0.11 – 0.62 with a GM (GSD) of2.00(1.88), BDL and 0.31(1.78) for the leavesand BDL – 3.98, BDL – 0.25 and 0.01 – 0.53 with a GM (GSD) of 2.56(1.38), 0.21(1.18) and 0.14(3.73) for the roots.

4.3.2 Transfer Factors for Maize Plants

The TFs of ^{40}K, ^{238}U and ^{232}Th for maize compartments harvested from the soil groups are presented from tables D.13 – D.24 of appendix D. The range and GM (GSD) of the radionuclides for the soil groups are summarised in table 4.8.

(i) Parts of Maize Plants Harvested from Soil Group A

The TFs of ^{40}K, ^{238}U and ^{232}Th for maize compartments harvested from soil group A are presented in tables D.13 – D.16. The TFs varied between BDL – 0.83, BDL (for all the samples) and BDL – 4.88 with a GM(GSD) of 0.65(1.31), BDL (for all the samples), 0.58(2.79) for the seeds; 2.34 – 6.04, BDL (for all the samples) and from BDL – 8.22 with a GM (GSD) of 3.61(1.38), BDL and 1.89(3.01) for the stems; 1.09 – 3.18, BDL – 0.92and BDL – 2.40 with a GM (GSD) of 1.94(1.41),0.88(1.05) and 0.84(2.27) for the leaves and BDL – 6.57, BDL – 5.20 and 0.62 –11.87 with a GM (GSD) of 2.68(1.71), 1.00(5.18) and2.68(2.43) for the roots respectively, for ^{40}K, ^{238}U and ^{232}Th.

(ii) Parts of Maize plants harvested from Soil Group B

The TFs of ^{40}K, ^{238}U and ^{232}Th respectively for maize compartments harvested from soil group B are presented in tables D.17 – D.20 of appendix D. The TFsfor ^{40}K, ^{238}U and ^{232}Th respectively,varied between BDL – 0.06, BDL - 0.03 and 0.01 – 0.12with a GM(GSD) of 0.03(2.14), 0.01(2.00)0.03(2.04) for the seeds; BDL – 0.17, BDL (for all

Table 4.8: The range and GM (GSD) of the transfer factors of ^{40}K, ^{238}U and ^{232}Th in maize plant compartments for the soil groups

Soil group	Plant part	^{40}K		^{238}U		^{232}Th	
		Range	GM(GSD)	Range	GM(GSD)	Range	GM(GSD)
Group A	Seed	BDL-0.83	0.65(1.31)	BDL	BDL	BDL-4.88	0.58(2.79)
	Stem	2.34-6.04	3.61(1.38)	BDL	BDL	BDL-8.22	1.89(3.01)
	Leaf	1.09-3.18	1.94(1.41)	BDL-0.92	0.88(1.05)	BDL-2.40	0.84(2.27)
	Root	BDL-6.57	2.68(1.71)	BDL-5.20	1.00(5.18)	0.62-11.87	2.68(2.43)
Group B	Seed	BDL-0.06	0.03(2.14)	BDL-0.03	0.01(2.00)	0.01-0.12	0.03(2.04)
	Stem	BDL-0.17	0.07(1.88)	BDL	BDL	BDL-0.04	0.02(1.97)
	Leaf	BDL-0.09	0.04(2.04)	BDL	BDL	0.01-0.15	0.02(2.35)
	Root	BDL-0.22	0.05(2.41)	0.06-0.57	0.20(2.45)	0.06-0.33	0.13(1.72)
Group C	Seed	BDL-1.21	0.33(2.48)	BDL	BDL	0.003-0.174	0.015(4.00)
	Stem	BDL-0.92	0.43(2.88)	BDL	BDL	0.01-0.04	0.02(1.40)
	Leaf	0.09-2.77	0.38(2.61)	BDL-0.02	0.01(1.48)	BDL-0.22	0.02(1.27)
	Root	BDL-2.42	0.23(3.31)	BDL-0.25	0.11(2.37)	0.01-0.30	0.12(2.59)

the samples) and BDL – 0.04 with a GM(GSD) of 0.07(1.88), BDL, and 0.02(1.97) for the stems; BDL – 0.09, BDL (for all the samples) and 0.01 - 0.15 with a GM(GSD) of 0.04(2.04), BDL and0.02(2.35) for the leaves; and from BDL – 0.22, 0.06 – 0.57and 0.06– 0.33 with a GM(GSD) of 0.05(2.41), 0.20(2.45) and 0.13(1.72) for the roots.

(iii) Parts of Maize plants harvested from Soil Group C

The TFs of ^{40}K, ^{238}U and ^{232}Th for maize compartments harvested from soil group C are presented in tables D.21 – D.24 of appendix D. The TFsof^{40}K, ^{238}U and ^{232}Th respectively, varied between BDL – 1.21, BDL(for all the samples) and 0.003 – 0.174with a GM(GSD) of 0.33(2.48), BDL and 0.015(4.000) for the seeds; BDL – 0.92, BDL(for all the samples) and 0.01 – 0.04 with a GM(GSD) of 0.43(2.88), BDL and 0.02(1.40) for the stems; 0.09 – 2.77, BDL- 0.02 and BDL - 0.22 with a GM(GSD) of 0.38(2.61), 0.01(1.48) and 0.02(1.27) for the leaves; andBDL – 2.42, BDL – 0.25 and 0.01– 0.30with a GM(GSD) of 0.23(3.31),0.11(2.37) and0.12(2.59) for the roots.

4.3.3 Transfer Factors for Cassava Plants

The TFs of ^{40}K, ^{238}U and ^{232}Th for cassava compartments harvested from the soil groups are presented in tables D.25- D.33 of appendix D. The range and GM(GSD) of the TFs of ^{40}K, ^{238}U and ^{232}Th for cassava compartments are summarised in table 4.9.

(i) Parts of Cassava plants harvested from Soil Group A

The TFs of ^{40}K, ^{238}U and ^{232}Th for cassava compartments harvested from soil group A are presented in tables D,25 – D.27 of appendix D. The TFsof ^{40}K, ^{238}U and ^{232}Th respectively, varied between BDL – 1.18, BDL for all replicates, and BDL – 0.81with a GM(GSD) of0.87(1.36), BDL and 0.49(1.87) for the tubers; 0.45 – 1.51,BDL – 0.28 and BDL – 0.84 with a GM(GSD) of 0.74(1.75),0.23(1.23) and 0.65(1.30) for the stems; and BDL – 3.84, BDL – 2.74 and BDL – 10.52with a GM(GSD) of 1.46(2.64), 0.90(2.21) and 1.54(4.26) for the leaves.

(ii) Parts of Cassava plants harvested from Soil Group B

The TFs of ^{40}K, ^{238}U and ^{232}Th for cassava compartments harvested from soil group B are presented in tables D.28 – D.30 of appendix D. The TFs of ^{40}K, ^{238}U and ^{232}Th respectively, varied between BDL – 0.02, BDL for all the replicates, and BDL – 0.17with a GM(GSD) of 0.01(1.68), BDL and 0.04(2.32) for the tubers; BDL – 0.02,

BDL for all the replicates and 0.01 – 0.04with a GM(GSD) of 0.01(1.40), BDL and0.03(1.57)

Table 4.9: The range and GM (GSD) of the transfer factors of ^{40}K, ^{238}U and ^{232}Th in cassava plant compartments for the soil groups

Soil group	Plant part	^{40}K		^{238}U		^{232}Th	
		Range	GM(GSD)	Range	GM(GSD)	Range	GM(GSD)
Group A	Tuber	BDL-1.18	0.87(1.36)	BDL	BDL	BDL-0.81	0.49(1.87)
	Stem	0.45-1.51	0.74(1.75)	BDL-0.28	0.23(1.23)	BDL-0.84	0.65(1.30)
	Leaf	BDL-3.84	1.46(2.64)	BDL-2.74	0.90(2.21)	BDL-10.52	1.54(4.26)
Group B	Tuber	BDL-0.02	0.01(1.68)	BDL	BDL	BDL-0.17	0.04(2.32)
	Stem	BDL-0.02	0.01(1.40)	BDL	BDL	0.01-0.04	0.03(1.57)
	Leaf	BDL-0.28	0.12(2.04)	BDL	BDL	BDL-0.12	0.03(3.41)
Group C	Tuber	BDL- 0.17	0.11(1.50)	BDL-0.01	0.01(1.24)	BDL-0.04	0.006(2.51)
	Stem	BDL-1.00	0.23(2.53)	BDL-0.02	0.01(1.11)	0.01-0.07	0.03(2.15)
	Leaf	BDL-7.55	2.91(1.79)	BDL-0.22	0.07(2.04)	BDL-0.62	0.21(1.91)

for the stems; and BDL – 0.28,BDL and BDL – 0.12 with a GM(GSD) of 0.12(2.04), BDL and 0.03(3.41) for the leaves.

(iii) Parts of Cassava plants harvested from Soil Group C

The TFs of ^{40}K, ^{238}U and ^{232}Th for cassava compartments harvested from soil group C are presented in tables D.31 – D.33 of appendix D. The TFsof ^{40}K, ^{238}U and ^{232}Th respectively,varied between BDL – 0.17, BDL –0.01 and BDL – 0.04 with a GM(GSD) of 0.11(1.50), 0.011(1.24) and 0.006(2.51) for the tubers; BDL – 1.00, BDL – 0.02 and 0.01 – 0.07with a GM(GSD) of 0.23(2.53), 0.01 (1.11) and 0.03(2.15) for the stems; and BDL – 7.55, BDL – 0.22 and BDL – 0.62 with a GM(GSD) of 2.91(1.79), 0.07(2.04), 0.21(1.91) for the leaves.

4.4 Committed Effective Dose

The committed effective doses for each of the plants were calculated using equation 3.5. The range and mean values of the effective doses in μSvy^{-1} calculated for cowpea, maize and cassava are presented in table 4.10. The mean values of the effective doses ranged from 2.37 (soil A) to 110.30 (soil B) μSvy^{-1} for cowpea seeds, 2.41 (soil A) to 8.28 (soil B) $mSvy^{-1}$ for maize seeds and from 2.26 (soil C) to 36.78 (soil B) $mSvy^{-1}$ for cassava tubers.

4.5 Discussion

4.5.1 Activity Concentration of Natural Radionuclides in the Plant Samples

4.5.1.1 Cowpea Plants

The mean of the activity concentrations of the natural radionuclides in the compartments of the cowpea plants harvested from soil group Ahave the highest value for ^{232}Th,with ^{238}U having the least value for all the plant compartment (crop, stem, leave, root). The mean for^{40}K and ^{232}Th increased accordingly from seeds < stems < roots< leaves while ^{238}U followed the trend of stems < seeds < leaves < roots. It was also observed that for most samples from this soil group, ^{238}U recorded values that were BDL.Parts of cowpea plant harvested from soil group B maintained the trend of the average values for the activity concentration of ^{232}Th >^{40}K >^{238}U for all the plant compartments. Most of the samples from soil group B also recorded BDL for ^{238}U.

Table 4.10: The range and mean of the effective doses (μSv y^{-1}) from harvested crop

Soil group	Committed Effective Dose (μSv y^{-1})		
	Cowpea	Maize	Cassava
Soil A	0.21 -5.65 (2.37)	582 – 10,041 (2414)	85 – 6232 (2615)
Soil B	4.58 – 944.83 (110.30)	1712 – 22954 (8284)	15 – 115660 (36776)
Soil C	2.46 -15.18 (9.29)	249 – 13432 (3293)	306 -9895 (2257)

For soil group C, ^{232}Th still had the highest value for each plant compartment. No defined trend was observed in the average activity concentrations of ^{238}U and ^{232}Th for all the plant parts from all the soil groups. But for ^{40}K, it was observed that a regular trend seeds < stems < roots< leaves was maintained for soil groups A and B.

The high concentrations of ^{232}Th and low concentrations of ^{238}U could be as a result of the solubility of the radionuclides. Ahmed *et al.* (2012), reported that thorium is most soluble in acidic soil, its solubility being 5 -14 times greater than the solubility of uranium while Sheppard *et al. (*2005), stated that for uranium, there can be substantial mobility in neutral to basic soils as a result of complexation with soluble carbonates. From the soil elemental composition shown in table B.3of the appendix B, the pH values of the three soil groups used for this work were all slightly acidic, this could be the reason for the high values recorded for thorium for all the soil groups. The low values recorded for uranium could be as a result of the slightly acidic nature of the soil groups which could lead to the formation of some complexes that are not readily available for plant uptake like uranyl phosphates or hydroxides (Vandenhove *et al.,* 2007).

4.5.1.2 Maize Plants

All the compartments of maize plants harvested from soil group A had the highest average value for ^{232}Th with the exception of the stem. This is followed by ^{40}K, while^{238}U had the lowest value for all the compartments.The average values of the natural radionuclides for all the maize plant compartments for soil group B followed the trend ^{232}Th >^{40}K >^{238}U. For soil group C, the average activity concentrations of the natural radionuclides in the seed and root compartments followed the trend ^{232}Th >^{40}K >^{238}U but thestem and leaf compartments hadthe highest average value for^{40}K, followed by ^{232}Th with ^{238}U having the least values. The activity concentrations of ^{238}U of all the stem samples for all the soil groups, the seed samples from soil A and C, and leaf samples from soil Bwereall BDL while the root compartments had the highest values of^{238}U for all the soil groups. It was observed that ^{40}K maintained a regular trend of seeds < leaves < roots< stems for soil groups A and B.

The high values of thorium and low values of uranium could be as explained above for the cowpea plant, whilehigh values of uranium obtained for the roots samples could be

as a result of adsorption of uranium to the cell walls of the roots as reported by Sheppard and Evenden (1988a).

4.5.1.3 Cassava Plants

Cassava plant compartments harvested from soil group A had the average values of the activity concentrations of the natural radionuclides according to the trend, ^{232}Th >^{40}K >^{238}U for the stem and leaf compartments, while ^{40}K had the highest average value, followed by ^{232}Th, and ^{238}U had BDL in the tuber compartment. The trend ^{232}Th >^{40}K >^{238}U in the average activity concentrations was observed in thecassava compartments from soil groups B and C. The average values of all the natural radionuclidesfor all the soil groups followed the trend leaves>stems>tuber, except for soil B where ^{238}U had a BDL values for all the plant compartments and ^{232}Th had the trend stem>leaves>tuber.

The tuber compartments which was always in direct contact with soil had the least average values of the natural radionuclides. This observation contradicts Sheppard and Evenden (1988a), who reported that concentration of uranium and thorium are normally higher in tissues in the lower part of the plant. It was also observed that, the cassava plant compartments had the least values of the average activity concentration for all the radionuclides when compared correspondingly with the values obtained for the cowpea and maize plant compartments.The general low values of activity concentration recorded by the cassava plant could be linked to longer maturity period of the cassava plant. Sheppard and Evenden(1988a) reported that the accumulation of radionuclides in plant tissues slows down with time a result of translocation. There is also a possibility of the cassava roots exuding enzymes that could inhibit the absorption of the radionuclides into the plant (Sheppard and Evenden, 1988b).

4.5.2 Transfer Factors

According to Sheppard *et al.*(2010), discussion of the transfer factors (TF) are better grouped according to plant categories because of the discrete nature of the plant species. Therefore, the discussion below are grouped according to plant species viz. cowpea (legumes), maize (cereals) and cassava (root crops).

4.5.2.1 Cowpea Plants

The TFsof the natural radionuclides from soil A to different plant compartments ofcowpea plants showed that the highestmean values of the TFfor ^{40}K and ^{232}Th were

in leaf compartmentwhile ^{238}U had the highest mean value of the TF in the root compartment. The least mean values of the TFwere obtained in the seed compartment for ^{40}K and ^{232}Th while ^{238}U had its least mean value of the TF in the stem compartment.The following trends were observed in the mean values of the TFfor soil group A according to plant compartments; ^{40}K (leaf > root > stem > seed), ^{238}U (root > leaf > seed > stem) and ^{232}Th (leaf > root > stem > seed).

Cowpea plant compartments harvested from soil group B had the highest mean values of the TFin theroot compartment for ^{40}K and ^{232}Th, and in the leaf compartment for^{238}U. The least mean values of the TFs for ^{40}K,^{238}U and ^{232}Th were observed in the seed, seed and stem respectively. The following trends were observed in the mean values of the TFs of the radionuclides for soil group B; ^{40}K (root >leaf > stem > seed), ^{238}U (leaf > root > stem > seed) and ^{232}Th (root > leaf > seed > stem).

The root compartments had the highest mean values of the TFsfor^{40}K and^{238}U whilethe leaf compartments had the highest mean value of the TF for^{232}Th incowpea plant compartments harvested from soil group C. Theleastmean value of the TF for ^{40}K was in the seed compartment while ^{238}U and ^{232}Th had the least mean values of the TFs in thestem compartments. The following trends were observed in the mean values of the TFs of the natural radionuclides according to plant compartments; ^{40}K (root > leaf > stem > seed), ^{238}U (root > seed > leaf=stem) and ^{232}Th (leaf > seed > root> stem).

According to Sheppard and Evenden (1988a), plants conform to accumulator strategy. This implies that as the concentration of the radionuclide in the soil is increasing, the plants accumulate less of the radionuclide. The accumulator strategy of plants was observed inall the cowpeaplant compartments for ^{40}K and ^{232}Th for all the soil groups, because the mean values of the TFsof ^{40}K and ^{232}Th obtained decreased as their respective activity concentrations in the soil increased.Strict adherence in the accumulation of highest values of the radionuclides in the root parts of the cowpea plant was not observedfor the three soil groups as reported by Sheppard and Evenden (1988b). However, it was observed that the highest mean values of the TFs for the natural radionuclides of the three soil groups were either obtained for the root or leaf compartments only. The high values of the mean of the TFsfor the radionuclides observed for the root samples could be as a result of adsorption of these radionuclides on the cell walls of plant tissues found in the lower parts of the plant, because of their

direct contact with the radionuclides in the soil solutions. For the leaf samples, it could also be as a result of extraneous contamination of the leaves from dust and splash of soil particles especially during rainfall which adsorbs to the cells of the leaves and cannot be washed out with water as explained by Sheppard and Evenden (1988a).

The mean values of the TFs of ^{238}U were compared with those of other radionuclides.It was observed that ^{238}U had the least values of the TFs with most of the samples being BDL. This could be as a result of ^{238}U not being available in the form that could be easily taken up by plants. Vandenhove *et al.*(2007) reported a case of low uranium TF when it forms uranyl phosphate, uranyl sulphate or uranyl hydroxide complexes.Thus, there is need to identify the speciation of uranium in the soil and the complexes that it forms in the soil. It was also observed that ^{40}K had the highest mean values of the TFsfor the radionuclides for most of the cowpeacompartments. This could be attributed to the fact that potassium is one of the essential elements required for plant growth. So as the uptake elements by the plants are element specific (Tome *et al*., 2003), the radioactive potassium could have been taken up with the stable potassium.

A two-way ANOVA was used to test for significantdifferences in the means values of the TFs of the natural radionuclide for the soil groups.The mean activity concentrations of the soil groups followthe trend; soil A < soil C < soil B.

There was significant difference in the mean values of the TFs of ^{40}K in cowpea plantin the soil groups and in the different plant parts ($p < 0.05$). There was no significance difference in the mean values of the TFs of ^{40}K as a result of the interaction between the soil and plant parts (interaction effect). To elucidate the source of the difference, a post-hoc test was carried out for the different levels of the independent variables. The post-hoc test showed that the difference in the mean values of the TFs of ^{40}K in the cowpea plants observed between soil groups A and B as well as soil groups A and C were significant ($p < 0.05$), but there was no significant difference in the mean values of the TF of ^{40}K for soil groups B and C ($p = 0.387$).The post-hoc test also revealed a significant difference in the mean of the TFs of ^{40}K obtained for the seed and leafsamples ($p = 0.002$); seed and stem samples ($p = 0.047$) and leaf and root samples ($p = 0.004$) but no significant difference for the mean values of the TF of $^{40}K$was observed for seed and root sample ($p = 0.832$); stem and leaf samples ($p = 0.093$); stem and root samples ($p = 0.079$).

The two-way ANOVA for ^{238}U showed a significant difference in the mean of the TFs values for ^{238}U in the cowpea plantfor all the soil groups ($p = 0.001$), the plant parts ($p = 0.002$) and from the interaction effect ($p = 0.002$). The post-hoc test revealed that the difference observed in the mean values of the TFs of ^{238}U for soil groups A and B as well as soil groups A and C were significant ($p < 0.05$), but there was no significant difference in the TF values for soil groups B and C ($p = 0.501$). For the plant parts, significant difference in the mean values of the TF of ^{238}Uwere obtained for seed and root samples($p = 0.001$); stem and root samples ($p = 0.003$); stem and leaf samples ($p = 0.02$). No significant differences were found for the mean values of the TFs of ^{238}U in the remaining plant parts.

There was significant difference in the mean values of the TFs of ^{232}Th for cowpea plants for the soil groups ($p = 0.039$), but no significant difference for the plants parts ($p = 0.397$) and the interaction effect($p = 0.091$) were observed. The post-hoc test showed significant difference in the mean values of the TF of ^{232}Th for soil A and C ($p = 0.013$). But no significant difference was observed for the mean values of the TFs of ^{232}Th in the cowpea plant parts and for soil A and B ($p = 0.058$),and for soil B and C ($p = 0.425$).

The variability observed in the mean values of the TFs of ^{40}K, ^{238}U and ^{232}Th in the cowpea plant compartments ranged over 100-folds. These variability in the mean values of the TFs of radionuclides from the same plant species indicate that the radionuclides concentrations of the soil is not the only factor affecting the TFs as also observed by Ehlken and Kirchner (2002).

The comparison of the GM of theTFs of ^{40}K, ^{238}U and ^{232}Th for the present work and other TFs from literature for legumes are given in table 4.11. Data were not available for ^{40}K and ^{232}Th in legume seeds from the IAEA (2010) for the tropical region. The TF values for ^{238}U in legume seed for the present work is greater than the IAEA reported values by an order of magnitude for sandy and loamy soil. The TFs of ^{40}K and ^{238}U for cowpea seed from the sandy soil are of the same order of magnitude with the values reported by Elywa *et al*. (2016). The TF of ^{40}K for the leaf samples for sandy loam and loamy sand groups are of the same order of magnitude with values reported by Al-Masri *et al*., 2008.

4.5.2.2 Maize Plants

The mean values of the TFs of the natural radionuclides for the plant compartments of maize plants harvested from soil group A showed the highest mean values of the TFsfor

Table 4.11: A list of GM of the TFs of ^{40}K, ^{238}U and ^{232}Th in legume compartments from literature and the present study

S/N	Plant compartment	Soil group	^{40}K	^{238}U	^{232}Th	Region/Country	Reference
1	Seed	All	-	3.8×10^{-2}	-	Tropics	IAEA, 2010
2	Seed	Sand	-	3.4×10^{-3}	-	Tropics	IAEA, 2010
3	Seed	Loam	-	3.2×10^{-3}	-	Tropics	IAEA,2010
4	Pod	Not specified	2.0×10^{0}	0.5×10^{-2}	-	Syria	Al-Masri *et al*., 2008
5	Leaf	Not specified	2.6×10^{0}	2.1×10^{-2}	-	Syria	Al-Masri *et al*., 2008
6	White beans	Not specified	5.2×10^{-2}	9.8×10^{-2}	6.6×10^{-2}	Egypt	Elywa *et al*., 2016
7	Red beans	Not specified	4.0×10^{-2}	6.5×10^{-2}	8.9×10^{-2}	Egypt	Elywa *et al*., 2016
8	Seed	Sandy loam[a]	1.40×10^{0}	2.25×10^{0}	7.7×10^{-1}	Nigeria	Present work
9	Seed	Sand[b]	5.0×10^{-2}	2.0×10^{-2}	6.0×10^{-2}	Nigeria	Present work
10	Seed	Loamy sand[c]	2.1×10^{-1}	5.0×10^{-2}	1.1×10^{-1}	Nigeria	Present work
11	Leaf	Sandy loam[a]	9.67×10^{0}	9.6×10^{-1}	9.7×10^{0}	Nigeria	Present work
12	Leaf	Sand[b]	1.7×10^{-1}	3.3×10^{-1}	1.1×10^{-1}	Nigeria	Present work
13	Leaf	Loamy sand[c]	2.0×10^{0}	BDL	3.1×10^{-1}	Nigeria	Present work

Sandy loam[a] = soil group A, Sand[b] = soil group B, Loamy sand[c] = soil group C, nm = not measured

^{40}K in the stem compartment while^{238}U and ^{232}Th were in theroot compartments. The least mean values of the TFs for ^{40}Kand ^{232}Th were obtainedfrom the seed compartment while^{238}U had the least mean valuein the stem compartment. The following trends were observed in the mean values of the TFs of the radionuclides according to plant compartments; ^{40}K (stem > root > leaf > seed), ^{238}U (root > leaf > seed = stem) and ^{232}Th (root > stem > leaf > seed).

In soil group B, the root compartment had the highest mean values of the TFs of ^{238}U and ^{232}Th while ^{40}K had the highest mean value of the TFs in the stem compartment.The least mean values of the TF of ^{40}K was observed in the seed compartments, ^{238}U and ^{232}Th had the least mean values in the stem and leaf compartments, respectively.These trends were observed in the mean values of the TFs of the radionuclides according to plant compartments; ^{40}K (stem > root > leaf >seed), ^{238}U (root > seed > leaf = stem) and ^{232}Th (root > seed > leaf = stem).

For soil group C, the highest mean values of the TFs for^{238}U and ^{232}Th were obtained for theroot compartment while ^{40}K had the highest mean value of the TF in the stem compartment. The least mean valuesof the TF for ^{40}K, ^{238}U and ^{232}Th were respectively obtained from the root, stem and seed compartments. The following trends were observed in the mean values of the TFs of the natural radionuclides according to plant compartments; ^{40}K (stem > leaf > seed >root), ^{238}U (root > leaf > seed = stem) and ^{232}Th (root > leaf >stem> seed).

The accumulator strategy of plants were observed in the seed and root compartments for ^{40}K and in the leaf compartment for ^{232}Th.The highest mean values of the TFs of^{238}U and ^{232}Th were in the root compartments while the stem compartment had the highest mean value of the TFof^{40}K for all the soil groups. It was also observed that ^{40}K had most of the highest mean values of TF when compared to the mean values of the TFs of ^{238}U and ^{232}Th. The highest mean values of the TFs observed in the root compartment for ^{238}U and ^{232}Th were in agreement with the reports of Sheppard and Evenden (1988a) and Vandenhove *et al.*(2007) and this could be as a result of adsorption of these radionuclides in the soil solution to the cell walls of the roots. When compared with the other radionuclides, ^{40}K had the highest mean TFs. This could be as a result of the uptake of potassium as one of the essential nutrients required for plant growth.The mean values of the TFs of ^{40}K, ^{238}U and ^{232}Th were observed to be higher

in the cowpea plant compartments than in the maize plant compartments. This observation is in agreement with the report of Wasserman *et al*. (2002) that legumes accumulate more radionuclides than grains.

The analysis of variance in the mean values of the TFs of ^{40}K for maize plant showed a significant difference in the mean values of the TFs obtained for the soil groups ($p < 0.05$); plant compartments ($p = 0.047$) and interaction effect ($p = 0.013$). The post-hoc test showed that for the soil groups, soil groups A and B as well as soil groups A and C were significant ($p < 0.05$), but there was no significant difference in the mean values of the TF of ^{40}K for soil groups B and C ($p = 0.089$). For the plant compartments, the mean values of the TF of ^{40}K was significantly different for the seed and stem samples ($p = 0.005$) but no significant differences were observed between the remaining plant parts.

The mean values of the TFs of ^{238}U for maize plant showed significant difference for the soil groups ($p = 0.022$),but no significant difference was observed for the plant compartments ($p = 0.165$) and from the interaction effect between the plant compartments and soil groups ($p = 0.167$).The post hoc test showed that the difference observed for the soil groups were between soil A and soil C only.The mean values for the TF of^{232}Th for maize plants showed significant difference for the soil groups ($p < 0.05$) but no significant difference was observed for the mean values of the TF of ^{232}Th on the plant compartments ($p = 0.143$) and for the interaction effect (0.602). The post-hoc test revealed a significant difference between soil A and B ($p < 0.05$), and soil A and C ($p < 0.05$) but no significant difference was observed for the soil B and C ($p = 0.967$).

The variability observed in the mean values of the TFs of ^{40}K, ^{238}U and ^{232}Th in the samples from maize plant ranged over 100-fold for each of the radionuclide. The observed variabilities in the TFs of radionuclides buttressed the fact that other factors like plant physiology, climate, soil characteristic, soil concentration of the radionuclides, soil water etc. affect the accumulation of radionuclides in the plant.

The TFs of the natural radionuclides from literature were compared to the TFs of ^{40}K, ^{238}U and ^{232}Th obtained from the present work for cereals in table 4.12. There was no IAEA data for the tropical regions for ^{40}K and ^{232}Th for cereal seeds and stems. The TF value reported by Tchokossa *et al*. (2013) and Yadav *et al*. (2017) for ^{40}K are of the

same magnitude with the TFs of ^{40}K for the present work. For ^{238}U, the IAEA TF data and Tchokossa *et al*. (2013) for maize grain compared well withthe TF of the present work

Table 4.12: A list of GM of the TFs of ^{40}K, ^{238}U and ^{232}Th in cereals compartments from literature and the present study

S/N	Plant compartment	Soil group	^{40}K	^{238}U	^{232}Th	Region/Country	Reference
1	Maize grain	All	-	8.7×10^{-2}	-	Tropic	IAEA,2010
2	Maize grain	Loam	-	3.4×10^{-1}		Tropic	IAEA, 2010
3	Maize grain	Sand	-	1.5×10^{-3}	-	Tropic	IAEA,2010
4	Wheat grain	Not specified	0.16	-	-	Saudi Arabia	Alharbi and El-Taher,2013
5	Wheat straw	Not specified	2.0	1.2×10^{-2}	-	Syria	Al-Masiri *et al*., 2008
6	Wheat grain	Not specified	nm	5.0×10^{-2}	-	Syria	Al-Masiri *et al*., 2008
7	Wheat grain	Not specified	3.7×10^{-1}	-	1.0×10^{-3}	India	Yadav *et al*., 2017
8	Wheat fruit	Not specified	-	7.0×10^{-2}	-	Saudi Arabia	Al-Hamarneh *et al*., 2016
9	Wheat(green part)	Not specified	-	2.8×10^{-1}	-	Saudi Arabia	Al-Hamarneh *et al*., 2016
10	Maize grain (fresh)	Not specified	1.5×10^{-1}	5.7×10^{-1}	4.1×10^{-1}	Nigeria	Tchokossa *et al*., 2013
11	Maize grain (dried)	Not Specified	9.4×10^{-1}	4.7×10^{-1}	3.9×10^{-1}	Nigeria	Tchokossa *et al*., 2013
12	Maize grain	Sandy loam[a]	6.5×10^{-1}	BDL	5.8×10^{-1}	Nigeria	Present work
13	Maize grain	Sand[b]	3.0×10^{-2}	1.0×10^{-2}	3.0×10^{-2}	Nigeria	Present work
14	Maize grain	Loamy sand[c]	3.3×10^{-1}	BDL	1.5×10^{-2}	Nigeria	Present work

Sandy loam[a] = soil group A, Sand[b] = soil group B, Loamy sand[c] = soil group C, nm = not measured

with a variability of one order of magnitude.A variability of one order of magnitude was also observed in the TFs of ^{232}Th for the present work when compared with the values reported by Tchokossa *et al*. (2013) and Yadav *et al*. (2017) for the seed compartment.

4.5.2.3 Cassava Plants

The highest mean values of the TFs of ^{40}K, ^{238}U and ^{232}Th for soil group A were observed in the leaf compartment. The least mean values of the TFs of ^{40}K was from the stem compartment while^{238}U and ^{232}Th had the least mean values from the tuber compartment.The following trends were observed in the mean values of the TFsof the radionuclide according to plant compartments; ^{40}K (leaf > tuber > stem), ^{238}U (leaf > stem > tuber) and ^{232}Th (leaf > stem > tuber). In soil group B, the highest mean values of the TFs of^{40}K and ^{232}Th were from stem and tuber compartments, respectively while ^{238}U had BDL values from all the compartments.The least mean values of the TFs f0r^{40}Kand ^{232}Th were from the tuber and stem compartments, respectively. The following trends were observed in the mean values of the TFs of the radionuclides according to plant compartments; ^{40}K (stem > leaf > tuber), ^{238}U (leaf = stem = tuber) and ^{232}Th (tuber > leaf > stem).

For soil group C, the leaf compartment had the highest mean values of the TF for ^{40}K and^{238}U, while^{232}Th had the highest mean value from the stem compartments. The least mean values of the TFs of the radionuclides were from the tuber compartment for ^{40}K, stem compartment for ^{238}U and tuber compartment for ^{232}Th. The following trends were observed in the mean value of the TF values according to plant compartments; ^{40}K (leaf > stem > tuber), ^{238}U (leaf > tuber>stem) and ^{232}Th (leaf > stem > tuber).

The mean values of the TFs obtained from most of the cassava compartments from the all the soil groups did not strictly adhere to the accumulator strategy of Sheppard and Evenden (1988a). The leaf, rather than tuber compartmenthad most of the highest mean values of the TFs for the radionuclides. The tuber compartments when compared with the seed compartments of cowpea and maize for the corresponding soil group, had the least mean values of the TFs for most of the natural radionuclides despite being in theroot section of the plant. This observation contradicts the reports of Sheppard and Evenden (1988a) and Vandenhove e*t al.* (2007) that showed that root crops usually have higher TFs of the radionuclides. This contradiction could be from the plant

physiology and maturity period of cassava plants. Sheppard and Evenden (1988a) explained that at micro-scale level, the plant roots could exude enzymes, chelates, metabolic by product and waste inorganic materials that could alter the soil around the roots area, thereby affecting the uptake of radionuclide. So, there could bea possibility of cassava plants exuding material that could inhibit the accumulation of natural radionuclides in the plants.

The variations observed in the mean values of the TFs of ^{40}K for cassava plant were significant for the soil groups ($p = 0.018$) and plant parts ($p = 0.001$). There was no significant difference from the interaction effect ($p = 0.102$). The post-hoc test revealed the source of the variations in the soil groups to be significant between soil A and soil B ($p = 0.003$) and between soil B and soil C ($p = 0.012$). There was no significant difference between the mean values of the TF of ^{40}K measured between soil A and soil C ($p = 0.344$).For the variations in the plant compartments, there was significant difference in the mean values of the TFs of ^{40}K obtained for tubers and leaf compartment ($p < 0.05$), and for stem and leaf compartment ($p < 0.05$). There was no significant difference for the stem and tuber compartments ($p = 0.771$).

There wasno significant difference in themean values of the TF of ^{238}U from the soil groups. No significant difference was obtained for the mean values of the TFs of ^{238}U for plant compartments ($p = 0.227$) and from the interaction effect ($p = 0.182$). There was no post-hoc test for the soil groups because all the cassava compartments from soil group B had BDL values for the TFs of ^{238}U.

There was significant difference in the mean values of the TFs for^{232}Th in the soil groups ($p = 0.018$) and the plantcompartments ($p = 0.0053$). No significant difference was obtained from the interaction effect ($p = 0.075$).The post-hoc test showed that the significant difference obtained for the mean values of the TFs of ^{232}Th in the soil groupswere for soil A and soil B ($p = 0.004$), and for soil A and soil C ($p = 0.005$). No significant difference was observed for the mean values of the TFs for soil B and soil C ($p = 0.817$). For the plant compartments, there was significant difference in the mean values of the TFs of ^{232}Th for the tuber and leaf compartments ($p = 0.008$), and between the stem and leaf compartments ($p = 0.006$). There was no significant difference in the mean values of the TFs of ^{232}Th for the stem and tuber compartments ($p = 0.992$).

The variabilities observed in the mean values of the TFs of ^{40}K, ^{238}U and ^{232}Th in the cassava plant compartments ranged about 1000-fold for each of the radionuclide. Thus, other factor as mentioned for the case of maize, could contribute significantly to the variations obtained in the TFs.

Table 4.13 presents a list of TFs of the natural radionuclides obtained from literature and from the present work for root crops. The mean TFs of ^{40}K compared well with the values reported by Doyi *et al*.(2018). The TFs for ^{238}U for the present work is of the same order of magnitude with other TF values from literatures especially for countries in Africa, but greater than IAEA values by two to three orders of magnitude for the temperate regions. Most of the reported TFs of ^{232}Th are higher than the values reported for the present work. The comparison of the present work with values obtainable in literature shows that using the data from other region can over-estimate or under-estimate the TF values for the tropical region of Nigeria. Therefore, there is need to work more on the TF values so as to make more data available.

Generally, ^{40}K had the highest mean TFs in most of the cowpea, maize and cassava compartments for all the soil groups. The high uptake of ^{40}K could be as a result of the uptake of stable potassium as an essential plant nutrient, since the uptake of radionuclide and nutrients plants are element specific (Tome *et al*., 2003). The TFs of ^{232}Th were consistently higher than the TFs of ^{238}U. This observation could be facilitated by the slightly acidic pH of the soil groups in accordance with the report of Ahmed *et al*. (2012). The higher TF values of ^{232}Th could also be as a result of the uptake of radium ($^{228}Ra$and ^{224}Ra) which is one of the daughters of ^{232}Th. According to Chandrashekara and Somashekarappa (2015), radium exhibit similar chemical properties as calcium and magnesium which are both plant essential elements. Since uptake of radionuclide could be aided if the radionuclide showed similarities with the plant essential element (Manigandan and Manikanda, 2008; Golmakani *et al*., 2008), the higher TFs of ^{232}Th could be from the uptake of ^{232}Th and radium, and the subsequent decay of radium in the plant. The TFs of ^{238}U general had the least values but in most cases were BDL. This could be as a result of insoluble complexes formed by the radionuclides in the soil (Vandenhove *et al*., 2007).

Table 4.13: A list of GM of the TFs of ^{40}K, ^{238}U and ^{232}Th in cassava compartments from literature and the present study

S/N	Plant compartment	Soil group	^{40}K	^{238}U	^{232}Th	Region/Country	Reference
1	Potato tubers	Unspecified	-	6.0×10^{-4}	4×10^{-4}	United Kingdom	Ewers *et al*., 2003
2	Tubers	All	-	5.0×10^{-3}	2×10^{-4}	Temperate	IAEA, 2010; Vandehove *et al*., 2009
3	Tubers	Sand	-	1.9×10^{-2}	-	Temperate	IAEA, 2010; Vandehove *et al*., 2009
4	Tubers	Loam	-	2.8×10^{-2}	2.5×10^{-4}	Temperate	IAEA, 2010; Vandehove *et al*., 2009
5	Tubers	Clay	-	9.2×10^{-4}	9.6×10^{-5}	Temperate	IAEA, 2010; Vandehove *et al*., 2009
6	Tubers	Unspecified	-	2.0×10^{-2}	-	Tropic	IAEA, 2010
7	Tubers	Loam	-	-	8.9×10^{-6}	Tropic	IAEA, 2010
8	Potato	Unspecified	-	6.9×10^{-4}	7.2×10^{-4}	Japan	Uchida and Tagami, 2007.
9	Potato root	Unspecified	-	2.0×10^{-1}	-	Saudi Arabia	Al-Hamarneh *et al*., 2016
10	Cassava tubers	Unspecified	-	12.2×10^{-1}	4.1×10^{-1}	Cameroon	Ben-Bolie *et al*., 2013
11	Cassava tubers	Unspecified	1.2×10^{-1}	1.0×10^{-1}	4.0×10^{-2}	Ghana	Doyi *et al*., 2018
12	Cassava tubers	Unspecified	4.6×10^{-1}	3.4×10^{-1}	2.5×10^{-1}	Nigeria	Tchokossa *et al*., 2013
13	Cassava tubers	Sandy loam[a]	8.7×10^{-1}	BDL	4.9×10^{-1}	Nigeria	Present study
14	Cassava tubers	Sand[b]	1.0×10^{-2}	BDL	4.4×10^{-2}	Nigeria	Present study
15	Cassava tubers	Loamy sand[c]	1.1×10^{-1}	1.1×10^{-2}	6.0×10^{-3}	Nigeria	Present study
16	Cassava leaves	Unspecified	-	7.3×10^{-1}	9.7×10^{-1}	Cameroon	Ben-Bolie *et al*., 2013
17	Cassava leaves	Sandy loam[a]	1.46×10^{0}	9.0×10^{-1}	1.54×10^{0}	Nigeria	Present study
18	Cassava leaves	Sand[b]	1.2×10^{-1}	BDL	3.0×10^{-2}	Nigeria	Present study
19	Cassava leaves	Loamy sand[c]	2.91×10^{0}	7.0×10^{-2}	2.1×10^{-1}	Nigeria	Present study

Sandy loam[a] = soil group A, Sand[b] = soil group B, Loamy sand[c] = soil group C

4.6Committed Effective Dose

The committed annual effective (CED) dose from the ingestion of ^{40}K, ^{238}U and ^{232}Th were higher in the cassava tubers and maize seeds, and least in the cowpea seeds. The high doses from the cassava tubers and maize seedscould be attributed to the high mean annual consumption values of these crops. The effective doses of the cassava tubers from all the soil groups were of the same order of magnitude with the effective dose reported by Jibiri *et al*.(2007a) for yam tuber(2164.1 μSvy^{-1}).Also, Jibiri *et al*. (2007b) reported an effective dose of 0.74, 0.67 and 0.18 $mSvy^{-1}$ for cereals, potatoes and legumes, respectively. The legume in Jibiri *et al*.(2007b), had the least effective dose in line with the observation of the present work. The committed effective doses from the maize seeds and cassava tuber exceed the annual average doses of 0.29 mSv y^{-1} recommended for the public by UNSCEAR (2008).

CHAPTER FIVE
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The activity concentrations of ^{40}K, ^{238}U and ^{232}Th have been determined for the different compartments of cowpea, maize and cassava plants harvested from virgin soil (soil A), tailings from abandoned mining site in Jos (soil B), and contaminated soil (soil C). The transfer factors of ^{40}K, ^{238}U and ^{232}Th were computed using the activity concentration of each radionuclide in the soil and plant compartments. The committed effective doses that would accrued through the ingestion of cowpea seeds, maize seeds and cassava tubers were estimated.

The geometric mean of the activity concentrations ($Bqkg^{-1}$) of ^{40}K, ^{238}U and ^{232}Th ranged from 179.65(2.88) to 3421.52(3.64), 90.35(3.37) to 1992.61(1.85) and 273.06(5.37) to 25232.30 (1.33) in the soil samples, while in the harvested plant compartments they ranged from 39.39 ± 26.67 (tuber group-B) to 2400.17 ± 1791.18 (cowpea-leaf group-A), BDL(maize-stems groups-A-B-C) to 717.90 ± 404.86 (cowpea-leaf group-B) and 89.05 ± 110.86 (tuber group-C) to 15972.92 ± 45359.97 (cowpea-seed group-B) $Bqkg^{-1}$, respectively. The geometric mean of the TFs of ^{40}K, ^{238}U and ^{232}Th ranged from 0.01(tuber group-B) to 9.67(cowpea-leaf group-A), BDL(maize-stem groups-A-B-C) to 2.34(cowpea-root group-A) and 0.006(tuber group-C) to 9.73(cowpea-leaf group-A) respectively.

High variabilities in the TFs of the radionuclides showed that the activity concentration of the radionuclides in the soil was not the only factor affecting the TFs of the radionuclides. The high TF values of the radionuclides in the leaf and root compartments suggests adsorption of the radionuclides from the dust and soil particles to the cell walls of the leaves and roots.The TFs of ^{40}K were found to be consistently higher in most of the plant compartments while ^{238}U was not readily available for plant uptake. The accumulation of the radionuclides were found to be minimal in cassava

plant compartments and maximal in the cowpeaplant compartments. The committed effective dose due to ingestion of the radionuclides in the cassava tuber and maize seeds exceeded the annual average dose for the public.

5.2Recommendation

There is need to educate the farmers on the possible route of soil contaminants like radionuclides into food crops and the danger of internal exposure when contaminated cropsare consumed. This would keep the internal radiation exposure as low as possible.

The present research was potted because it was carried out at a time when there was frequent communal clashes in the Jos area. There is need to carry out field work on the farm lands that are at close proximity to the mining sites and on abandoned mining sites that had been converted to farm lands. Determination of the speciation of the radionuclides in the soil sample could also reduce or explain the variability observed in the transfer factors.

Since concentration of radionuclides in soil are location dependant, determination of transfer factor of both natural and artificial radionuclide could be extended to other parts of the country. So as to establish the location based effects of transfer factors for the commonly consumed crops.

5.3 Contribution to Knowledge

- The research provided data on the soil-to-plant transfer factors of radionuclides for three major food crops that are grown and consumed in Nigeria. These data will be useful for the prediction of the accumulation of radionuclides in the different compartments of similar plants in the tropical African region. It also expanded the body of available data in the tropics that could be used in the validation of developed transfer models for the studied radionuclides.

- The research also established that cowpea absorbed and accumulated more radionuclides in its different compartments, hence demonstrating its potential for phytoremediation application.It also provided farmers that are constrained to cultivate on tin mining impacted soil, with the information of the crop that could be better managed on such contaminated soil.

- Also, cassava had the least accumulation of radionuclides in its compartments. However, the high consumption rate can lead to high ingestion dose which could be of radiological concern.

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Appendix A
Appendix A.1: Photographs of cowpea plants

Appendix A.2: Photographs of maize plant

Appendix A.3: Photographsof cassava plants

Appendix B

Table B.1: Background count and lower limit of detection

	^{40}K	^{238}U	^{232}Th
Background count	1283 ± 36	294 ± 17	2789 ± 53
BDL for soil samples ($Bqkg^{-1}$)	74.84	37.68	60.71
BDL for food samples ($Bqkg^{-1}$)	25.09	9.77	21.18

Table B.2: Soil texture properties of the soil samples

S/N	Soil ID	Clay (g/kg)	Silt (g/kg)	Fine sand (g/kg)	Soil Type
1	Group A	134	114	752	Sandy loam
2	Group B	34	14	952	Sand
3	Group C	74	74	852	Loamy sand

Table B.3: Soil elemental composition

S/N	Soil ID	pH	O.C g/kg	N (g/kg)	P (mg/kg)	Exch. Acidity	Na (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)	K (cmol/kg)	Mn mg/kg	Fe mg/kg	Cu mg/l	Zn mg/l
1	Group A	6.63	22.42	2.32	11.50	0.2	0.75	2.50	0.66	0.16	93.3	168.00	1.05	2.71
2	Group B	6.83	6.84	0.70	6.33	0.2	0.78	0.10	0.17	0.39	12.9	68.2	0.77	39.00
3	Group C	6.86	12.92	1.34	11.10	0.2	0.43	2.28	0.47	0.09	61.5	115.0	0.81	15.83

Table B.4: Heavy chemical composition of the soil samples

S/N	Soil ID	Co (mg/kg)	Cr (mg/kg)	Cd (mg/kg)	Pb (mg/kg)	Ni (mg/kg)
1	Group A	0.000	11.30	0.000	0.000	0.000
2	Group B	0.000	20.90	0.000	291.9	0.000
3	Group C	0.000	16.85	0.000	82.1	0.000

Appendix C

Table C.1: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea seeds harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A1C	226.14 ± 39.19	108.90 ± 19.47	166.41 ± 33.06
A2C	308.04 ± 48.37	21.60 ± 6.49	234.32 ± 43.89
A3C	228.85 ± 36.38	BDL	419.14 ± 76.64
A4C	BDL	BDL	819.47 ± 152.86
A5C	BDL	BDL	30.75 ± 10.69
Mean	254.34	65.25	334.02
STD	46.52	61.73	305.33

Table C.2: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea stems harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A1S	926.06 ± 152.43	41.95 ± 13.12	535.16 ± 105.02
A2S	707.52 ± 131.48	BDL	459.54 ± 98.05
A3S	1981.91 ± 582.30	BDL	1294.86 ± 403.95
A4S	286.08 ± 58.68	BDL	993.12 ± 197.43
A5S	479.17 ± 125.50	30.35 ± 25.31	1695.89 ± 417.36
Mean	876.15	36.14	995.71
STD	663.21	8.21	519.46

Table C.3: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea leaves harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A1L	489.51 ± 127.47	70.47 ± 29.81	2592.50 ± 635.61
A2L	BDL	BDL	1643.60 ± 883.01
A3L	2669.67 ± 1405.28	BDL	4698.88 ± 2499.34
A4L	4041.32 ± 2114.33	BDL	3305.57 ± 1760.93
A5L	BDL	108.08 ±	2003.20 ± 619.84
Mean	2400.16	88.82	2848.75
STD	1791.18	26.95	1210.85

Table C.4: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea roots harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A1R	1681.62 ± 497.14	BDL	1024.54 ± 322.16
A2R	52.30 ± 97.05	173.23 ± 64.15	1191.41 ± 372.58
A3R	BDL	BDL	1026.21 ± 322.66
A4R	1387.15 ± 414.18	BDL	2526.31 ± 779.89
A5R	2065.22 ± 605.99	261.32 ± 86.90	769.24 ± 245.68
Mean	1296.57	217.28	1307.54
STD	874.73	62.29	697.84

Table C.5: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea seeds harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B1C	BDL	46.55 ±8.43	654.42 ± 118.22
B3C	94.61 ± 61	16.51 ± 4.18	761.52 ± 137.14
B4C	BDL	BDL	1216.75 ± 219.41
B5C	BDL	BDL	854. ± 153.99
B6C	BDL	BDL	979.97 ± 176.79
B7C	480.46 ± 76.59	27.31 ± 8.85	789.26 ± 147.28
B8C	111.56 ± 18.49	16.15 ± 4.14	902.45 ± 162.45
B9C	BDL	BDL	136931 ± 25002
B10C	BDL	409.16 ± 64.65	665.87 ± 120.41
Mean	228.88	150.87	15972.92
STD	218.05	223.75	45359.97

Table C.6: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea stems harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B1S	443.01 ± 118.71	BDL	2027.95 ± 498.12
B3S	143.36 ± 46.83	BDL	1375.29 ± 283.29
B4S	266.19 ± 45.81	BDL	503.93 ± 94.68
B5S	666.45 ± 162.35	BDL	1762.08 ± 433.45
B6S	1120.76 ± 220.85	222.42 ± 49.35	1250.64 ± 275.25
B7S	873.36 ± 159.43	BDL	2110.16 ± 433.27
B8S	150.34 ± 47.56	19.97 ± 15.10	620.40 ± 130.15
B9S	BDL	BDL	837.32 ± 173.92
B10S	604.45 ± 149.90	BDL	2354.45 ± 577.61
Mean	533.49	121.28	1426.92
STD	350.87	143.03	678.64

Table C.7: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea leaves harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B1L	122.05 ± 161.16	BDL	1249.39 ± 274.98
B3L	1751.37 ± 4387.03	BDL	3625.95 ± 1116.92
B4L	BDL	BDL	1768.75 ± 363.55
B5L	BDL	BDL	3647.64 ± 1942.12
B6L	867.93 ± 2175.87	BDL	1665.30 ± 516.68
B7L	BDL	431.62 ±239.51	4647.15 ± 2471.91
B8L	BDL	BDL	3719.39 ± 1980.14
B9L	BDL	1004.18 ± 533.12	6602.79 ± 3509.24
B10L	BDL	BDL	2371.13 ± 1266.56
Mean	913.79	717.90	3255.28
STD	815.62	404.86	1702.68

Table C.8: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea roots harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B1R	251.86 ± 121.84	22.02 ± 36.63	1425.85 ± 443.75
B3R	440.43 ± 118.24	BDL	2746.02 ± 673.02
B4R	906.68 ±512.12	BDL	6070.50 ± 3226.84
B5R	162.74 ± 74.36	BDL	2323.85 ± 570.16
B6R	1433.64 ± 773.27	BDL	2180.91 ± 1166.10
B7R	BDL	182.04 ± 121.17	3227.14 ± 1719.40
B8R	1394.89 ± 416.35	325.92 ± 104.52	3717.72 ± 1145.07
B9R	705.20 ± 416.68	BDL	5356.32 ± 2848.00
B10R	598.64 ± 200.01	BDL	2898.42 ± 893.87
Mean	736.76	176.66	3327.41
STD	481.10	152.02	1510.92

Table C.9: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea seeds harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C1C	BDL	139.47 ± 23.84	2172.29 ± 398.68
C3C	204.27 ± 31.04	BDL	1034.75 ± 186.11
C4C	302.23 ± 50.84	BDL	701.49 ± 131.08
C5C	BDL	BDL	2644.18 ± 487.58
C6C	31.86± 11.86	BDL	1240.07 ± 224.37
C7C	174.36± 26.23	31.38 ± 5.62	731.44 ± 131.26
C9C	51.66± 23.11	BDL	355.61 ± 68.39
C10C	BDL	BDL	1831.25 ± 337.90
Mean	152.88	85.42	1338,89
STD	112.14	76.43	800.46

Table C.10: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea stems harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C1S	BDL	BDL	BDL
C3S	496.74 ± 96.81	BDL	889.38 ± 324.38
C4S	125.93± 103.20	BDL	759.23 ± 408.64
C5S	BDL	BDL	673.80 ± 246.40
C6S	79.82± 41.36	BDL	892.05 ± 325.34
C7S	447.14 ± 88.91	BDL	819.30 ± 299.01
C9S	BDL	BDL	348.75 ± 129.52
C10S	370.42 ± 77.01	BDL	519.61 ± 190.78
Mean	304.01	BDL	700.30
STD	189.75		202.94

Table C.11: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea leaves harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C1L	BDL	BDL	4315.09 ± 2295.86
C3L	1236.03 ± 674.14	BDL	1410.00 ± 760.43
C4L	BDL	BDL	4315.09 ± 2295.86
C5L	1336.77 ± 400.07	BDL	2979.35 ± 918.67
C6L	33.22 ± 99.17	BDL	1118.54 ± 277.42
C7L	1344.52 ± 728.44	BDL	3946.32 ± 2100.39
C9L	2716.17 ± 484.20	BDL	6277.41 ± 3336.61
C10L	848.56 ± 484.20	BDL	4909.13 ± 2610.83
Mean	1302.55	BDL	3658.87
STD	793.90		1745.86

Table C.12: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cowpea roots harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C1R	BDL	BDL	1539.59 ± 379.40
C3R	BDL	BDL	1425.57 ± 351.74
C4R	BDL	BDL	5369.67 ± 2855.08
C5R	1017.11 ± 311.38	BDL	3056.94 ± 942.45
C6R	BDL	BDL	2314.40 ± 715.02
C7R	1239.91 ± 243.02	BDL	62.57 ± 34.39
C9R	2173.71 ± 1150.24	BDL	3927.97 ± 2090.67
C10R	BDL	BDL	711.40 ± 179.73
Mean	1476.91		2301.01
STD	613.64		1753.32

Table C.13: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize seeds harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A21C	123.51 ± 31.63	BDL	1330.95 ± 252.74
A22C	74.02± 11.34	BDL	92.98± 16.83
A23C	BDL	BDL	86.50 ± 15.67
A25C	BDL	BDL	84.32 ± 15.67
A26C	BDL	BDL	BDL
A29C	149.18 ± 26.68	BDL	240.76 ± 45.04
A30C	75.00± 11.52	BDL	75.27 ± 13.72
Mean	105.43	BDL	318.46
STD	37.21		499.95

Table C.14: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize stems harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A21S	1086.86 ± 330.57	BDL	2245.15 ± 693.83
A22S	563.77 ± 88.89	BDL	BDL
A23S	747.04 ± 138.10	BDL	1106.97 ± 228.66
A25S	606.88 ± 99.31	BDL	743.79 ± 142.07
A26S	915.59 ± 141.51	BDL	70.08 ± 18.32
A29S	420.53 ± 64.01	BDL	266.43 ± 49.39
A30S	454.89 ± 72.84	BDL	540.80 ± 101.46
Mean	685.08		828.87
STD	245.70		783.01

Table C.15: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize leaves harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A21L	572.68 ± 109.13	BDL	301.69 ± 67.32
A22L	277.43 ± 43.58	BDL	104.35 ± 20.97
A23L	470.00 ± 75.05	BDL	656.77 ± 122.83
A25L	337.40 ± 53.12	84.02 ± 15.11	60.58 ± 14.90
A26L	265.42 ± 45.70	BDL	258.30 ± 49.91
A29L	197.09 ± 32.45	BDL	444.19 ± 81.39
A30L	477.88 ± 74.11	76.10 ± 14.22	BDL
Mean	371.13	80.06	304.31
STD	137.34	5.60	221.50

Table C.16: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize roots harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A21R	448.82 ± 82.67	BDL	319.27 ± 66.90
A22R	607.04 ± 97.02	17.61 ± 8.76	169.83 ± 35.09
A23R	281.56 ± 90.74	BDL	1189.18 ± 294.49
A25R	BDL	BDL	1188.90 ± 371.82
A26R	BDL	473.31 ± 89.87	3241.49 ± 664.49
A29R	1183.34 ± 212.42	BDL	701.16 ± 146.41
A30R	285.95 ± 64.60	BDL	650.77 ± 136.26
Mean	472.95	245.47	1065.80
STD	397.52	322.23	1035.16

Table C.17: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize seeds harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B21C	BDL	BDL	3050.08 ± 570.85
B22C	45.39 ± 8.21	BDL	226.26 ± 40.69
B23C	BDL	BDL	424.58 ± 77.26
B25C	BDL	13.86 ±3.80	983.76 ± 176.95
B26C	208.68 ± 44.43	BDL	1046.95 ± 202.68
B27C	BDL	BDL	1175.95 ± 212.51
B28C	BDL	52.17 ± 8.75	867.19 ± 155.67
B30C	BDL	10.72 ± 3.70	1009.89 ± 181.87
Mean	127.03	25.58	1098.08
STD	115.46	23.07	854.13

Table C.18: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize stems harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B21S	152.28 ± 30.93	BDL	657.94 ± 123.04
B22S	567.26 ± 89.41	BDL	BDL
B23S	429.32 ± 69.10	BDL	291.68 ± 55.92
B25S	125.54 ± 23.13	BDL	539.19 ± 98.56
B26S	133.68 ± 32.70	BDL	887.51 ± 169.12
B27S	523.86 ± 82.99	BDL	108.96 ± 24.11
B28S	167.39 ± 28.48	BDL	661.89 ± 120.78
B30S	BDL	BDL	251.41 ± 46.70
Mean	299.90	BDL	485.51
STD	198.23		276.73

Table C.19: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize leaves harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B21L	BDL	BDL	632.58 ± 118.36
B22L	BDL	BDL	306.03 ± 58.52
B23L	307.65 ± 89.49	BDL	292.43 ± 53.30
B25L	BDL	BDL	343.96 ± 63.31
B26L	74.01 ± 43.29	BDL	703.84 ± 131.51
B27L	BDL	BDL	426.34 ± 77.32
B28L	BDL	BDL	3719.39 ± 1980.14
B30L	BDL	BDL	186.39 ± 34.39
Mean	190.83	BDL	826.37
STD	165.21		1182.02

Table C.20: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize roots harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B21R	220.08 ± 39.55	363.79 ± 60.44	2614.08 ± 485.17
B22R	BDL	529.30 ± 84.47	3000.54 ± 545.21
B23R	BDL	1011.22 ± 188.33	5623.97 ± 1151.74
B25R	70.91 ± 22.51	116.27 ± 21.02	1503.27 ± 279.38
B26R	164.89 ± 34.09	1144.13 ± 189.14	4233.70 ± 792.07
B27R	737.74 ± 136.54	1067.01 ± 198.58	8408.26 ± 1721.31
B28R	220.86 ± 55.82	134.48 ± 29.92	3545.52 ± 726.65
B30R	48.16 ± 15.79	171.34 ± 28.31	1720.48 ± 313.64
Mean	243.77	567.19	3831.23
STD	252.77	442.38	2282.00

Table C.21: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize seeds harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C21C	BDL	BDL	71.37 ± 13.85
C22C	97.31 ± 15.39	BDL	78.80 ± 14.68
C23C	93.53 ± 14.81	BDL	177.43 ± 32.08
C24C	BDL	BDL	55.12 ± 10.14
C25C	BDL	BDL	33.10 ± 6.17
C26C	BDL	BDL	67.94 ± 13.13
C27C	659.67 ± 136.55	BDL	1767.09 ± 387.28
C29C	BDL	BDL	1218.94 ± 224.04
Mean	283.50	BDL	433.72
STD	266.00		671.35

Table C.22: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize stems harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C21S	BDL	BDL	374.61 ± 108.19
C22S	BDL	BDL	160.77 ± 39.01
C23S	BDL	BDL	201.10 ± 46.21
C24S	29.31± 9.58	BDL	166.14 ± 39.00
C25S	449.85 ± 72.10	BDL	113.47 ± 35.05
C26S	288.67 ± 52.39	BDL	168.95 ± 54.51
C27S	501.58 ± 78.61	BDL	127.67 ± 37.65
C29S	373.52 ± 57.25	BDL	163.19 ± 42.70
Mean	328.59	BDL	184.49
STD	185.61		81.32

Table C.23: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize leaves harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C21L	1511.14 ± 812.39	BDL	BDL
C22L	72.49 ± 12.59	BDL	234.27 ± 42.35
C23L	248.25 ± 37.47	BDL	227.83 ± 41.52
C24L	245.60 ± 36.76	BDL	BDL
C25L	49.73 ± 9.91	BDL	BDL
C26L	307.30 ± 45.68	11.34 ± 3.59	231.98 ± 42.17
C27L	160.69 ± 28.41	24.83 ± 6.95	338.51 ± 62.70
C29L	200.64 ± 30.27	BDL	157.64 ± 28.81
Mean	349.48	18.08	238.05
STD	477.59	9.54	64.64

Table C.24: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from maize roots harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C21R	BDL	129.40 ± 21.30	1202.58 ± 217.87
C22R	186.54 ± 41.68	326.34 ± 57.70	1213.81 ± 234.66
C23R	62.64± 62.64	173.72±34.01	3054.71 ± 602.81
C24R	115.03 ± 115.03	28.44 ± 5.79	2290.50 ± 412.27
C25R	1322.24 ± 258.39	275.27 ± 59.28	1695.33 ± 371.70
C26R	28.66 ± 4.53	BDL	118.23 ± 21.18
C27R	BDL	56.21 ± 11.51	1231.22 ± 226.62
C29R	78.53 ± 17.75	308.10 ± 49.58	2384.04 ± 433.28
Mean	298.94	185.36	1648.80
STD	504.20	120.82	913.12

Table C.25: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cassava tubers harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A31C	212.63 ± 34.14	BDL	222.24 ± 41.30
A33C	BDL	BDL	55.90 ± 10.42
A34C	BDL	BDL	BDL
A36C	BDL	BDL	196.34 ± 64.30
A38C	115.27 ± 18.04	BDL	BDL
Mean	163.94		158.16
STD	68.84		89.50

Table C.26: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cassava stem harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A31S	82.92 ± 18.22	BDL	208.91 ± 39.13
A33S	271.62 ± 41.28	BDL	230.52 ±42.24
A34S	257.86 ± 39.34	25.84 ± 5.73	176.71 ± 32.68
A36S	80.79 ± 15.64	BDL	116.72 ± 22.16
A38S	92.20 ± 14.45	17.01 ± 3.40	BDL
Mean	157.08	21.43	183.22
STD	98.50	6.23	49.54

Table C.27: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cassava leaves harvested from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A31L	79.24 ± 15.46	BDL	147.34 ± 27.50
A33L	BDL	249.57 ± 83.76	2872.56 ± 885.95
A34L	691.64 ± 107.93	BDL	BDL
A36L	674.20 ± 101.41	46.77 ± 9.53	76.28 ± 16.77
A38L	129.42 ± 28.28	46.39 ± 11.01	974.98 ± 181.61
Mean	393.62	114.25	1017.79
STD	334.75	117.20	1302.06

Table C.28: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cassava tubers harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B31C	20.54 ± 4.98	BDL	BDL
B32C	BDL	BDL	523.58 ± 93.85
B33C	BDL	BDL	993.72 ± 180.18
B35C	BDL	BDL	909.23 ± 164.42
B37C	BDL	BDL	2391.53 ± 447.78
B39C	58.24 ±	BDL	365.77 ± 65.45
B40C	BDL	BDL	4230.82 ± 834.39
Mean	39.39	BDL	1569.11
STD	26.66		1487.87

Table C.29: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cassava stems harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B31S	54.25 ± 10.73	BDL	613.22 ± 110.26
B32S	BDL	BDL	239.95 ± 43.92
B33S	BDL	BDL	1117.53 ± 201.37
B35S	25.80 ± 6.15	BDL	712.14 ± 127.56
B37S	37.20 ± 11.29	BDL	900.98 ± 162.74
B39S	65.68 ± 13.96	BDL	638.00 ± 115.39
B40S	53.47 ± 11.24	BDL	603.65 ± 108.72
Mean	47.27	BDL	689.35
STD	15.71		272.75

Table C.30: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cassava leaves harvested from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B31L	141.30 ± 53.16	BDL	349.52 ± 64.31
B32L	635.45 ± 643.46	BDL	BDL
B33L	380.50 ± 386.65	BDL	1822.48 ± 374.52
B35L	BDL	BDL	2999.16 ± 567.97
B37L	BDL	BDL	2203.71 ± 540.90
B39L	945.43 ± 1583.19	BDL	1000.35 ± 248.92
B40L	BDL	BDL	87.88 ± 16.16
Mean	525.67	BDL	1410.52
STD	345.00		1128.36

Table C.31: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cassava tubers harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C31C	92.34 ± 13.85	14.04 ± 2.61	95.50 ± 17.27
C32C	BDL	14.33 ± 2.79	51.26 ± 9.59
C33C	BDL	18.50 ± 3.24	358.34 ± 64.14
C35C	BDL	BDL	BDL
C36C	BDL	BDL	24.33 ± 4.94
C37C	43.01 ± 7.14	BDL	31.37 ± 6.05
C38C	82.00 ± 12.63	BDL	46.72 ± 8.81
C39C	31.22 ± 5.40	10.15 ± 1.98	57.28 ± 10.45
C40C	62.38 ± 9.71	BDL	47.58 ± 8.83
Mean	62.19	14.26	89.05
STD	25.63	3.41	110.86

Table C.32: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cassava stems harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C31S	547.50 ± 86.48	BDL	589.53 ± 169.42
C32S	197.87 ± 32.56	BDL	517.61 ± 132.64
C33S	BDL	20.85 ±	630.62 ± 133.44
C35S	224.73 ± 36.23	BDL	428.39 ± 109.91
C36S	89.12 ± 18.88	BDL	691.59 ± 177.00
C37S	BDL	BDL	168.28 ± 35.81
C38S	34.98 ± 7.45	BDL	161.00 ± 34.57
C39S	140.20 ± 21.62	16.83 ± 3.76	88.44 ± 20.04
C40S	51.15 ± 9.04	BDL	115.52 ± 24.63
Mean	183.65	18.84	376.77
STD	175.48	2.84	243.09

Table C.33: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from cassava leaves harvested from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C31L	BDL	33.28 ± 25.55	1101.86 ± 273.39
C32L	1100.42 ± 334.31	120.38 ± 51.93	2180.07 ± 673.92
C33L	1208.91 ± 364.39	BDL	BDL
C34L	2609.62 ± 761.31	286.28 ± 93.64	2322.74 ± 717.57
C35L	1290.28 ± 387.07	BDL	6247.37 ± 1921.44
C36L	BDL	BDL	1591.04 ± 494.04
C38L	4122.69 ± 2156.48	BDL	5249.53 ± 2791.36
C39L	635.45 ± 156.10	99.83 ± 34.29	1039.00 ± 258.23
C40L	2196.96 ± 643.51	63.13 ± 41.28	1179.73 ± 369.04
Mean	1880.62	120.58	2613.92
STD	1198.42	98.50	2010.38

Table C.34: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from soil group A

Sample	^{40}K	^{238}U	^{232}Th
A1	BDL	61.26 ± 6.45	124.12 ± 28.50
A2	BDL	55.49 ± 5.90	1530.23 ± 396.26
A3	1429.21 ± 67.63	1009.57 ± 99.44	12010.01 ± 3476.43
A4	79.70 ± 5.07	BDL	BDL
A5	94.07 ± 5.66	44.59 ± 4.86	95.58 ± 33.63
A6	114.45 ± 6.52	39.74 ±4.41	BDL
A7	BDL	BDL	150.26 ± 61.94
A8	BDL	BDL	78.51 ± 34.83
A9	152.61 ± 8.18	BDL	118.77 ± 56.23
A10	BDL	BDL	101.17 ± 51.00
Mean	374.01	242.13	1776.08
STD	828.72	429.10	4164.89

Table C.35: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from soil group B

Sample	^{40}K	^{238}U	^{232}Th
B1	BDL	3261.01 ± 13.95	14367.27 ± 13.95
B2	6111.66 ± 18.59	810.03 ± 7.39	22653.56 ± 7.39
B3	3558.86 ± 14.30	816.25 ± 7.41	28444.33 ± 7.41
B4	4611.31 ± 16.20	4181.57 ± 15.72	30325.81 ± 15.72
B5	BDL	2652.35 ± 12.64	16587.03 ± 12.64
B6	4611.31 ± 16.20	2878.77 ± 13.14	26039.53 ± 13.14
B7	5996.06 ± 18.41	2969.72 ± 13.34	28661.51 ± 13.34
B8	119.42 ± 3.80	1205.39 ± 8.79	24341.97 ± 8.79
B9	7535.07 ± 20.58	3375.88 ± 14.18	33207.60 ± 14.18
B10	7526.79 ± 20.58	834.18 ± 7.48	3759.77 ± 7.48
Mean	5008.81	2298.51	22838.84
STD	24.27	1260.39	8921.21

Table C.36: Activity concentration (Bq kg^{-1}) of ^{40}K, ^{238}U and ^{232}Th from soil group C

Sample	^{40}K	^{238}U	^{232}Th
C1	101.91 ± 3.67	1823.59 ± 10.61	19120.03 ± 24.22
C2	7372.30 ± 20.37	159.69 ± 4.18	23574.97 ± 26.88
C3	171.62 ± 4.16	BDL	233.94 ± 3.09
C4	BDL	1985.96 ± 11.03	16052.53 ± 22.20
C5	243.75 ± 4.61	3909.52 ± 15.22	14359.26 ± 21.00
C6	BDL	2612.78 ± 12.55	21206.92 ± 25.50
C7	1553.99 ± 9.68	3075.17 ± 13.56	107.04 ± 2.38
C8	BDL	2511.96 ± 12.32	18582.08 ± 23.88
C9	58.88 ± 3.33	8376.72 ± 22.06	14748.77 ±21.28
C10	BDL	2066.01 ± 11.24	10188.47 ± 17.71
Mean	1583.74	1449.10	13817.40
STD	2892.02	2276.41	8113.40

Appendix D

Table D.1: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to cowpea seeds

Sample	^{40}K	^{238}U	^{232}Th
A1C	1.26	1.20	0.61
A2C	1.71	0.24	0.86
A3C	1.27	BDL	1.54
A4C	BDL	BDL	3.00
A5C	BDL	BDL	0.11
Geometric Mean	1.40	0.53	0.77
Geometric STD	1.15	2.25	3.01

Table D.2: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to cowpea stems

Sample	^{40}K	^{238}U	^{232}Th
A1S	5.14	0.46	1.96
A2S	3.93	BDL	1.68
A3S	11.01	BDL	4.74
A4S	1.59	BDL	3.64
A5S	2.66	0.33	6.21
Geometric Mean	3.93	0.39	3.23
Geometric STD	1.91	1.18	1.65

Table D.3: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to cowpea leaves

Sample	^{40}K	^{238}U	^{232}Th
A1L	2.72	0.77	9.50
A2L	BDL	BDL	6.02
A3L	14.83	BDL	17.21
A4L	22.45	BDL	12.11
A5L	BDL	1.19	7.34
Geometric Mean	9.67	0.96	9.73
Geometric STD	2.49	1.24	1.45

Table D.4: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to cowpea roots

Sample	^{40}K	^{238}U	^{232}Th
A1R	9.34	BDL	3.75
A2R	0.29	1.90	4.36
A3R	BDL	BDL	3.76
A4R	7.71	BDL	9.25
A5R	11.47	2.87	2.82
Geometric Mean	9.38	2.34	4.38
Geometric STD	5.71	1.23	1.49

Table D.5: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to cowpea seeds

Sample	^{40}K	^{238}U	^{232}Th
B1C	BDL	0.02	0.03
B3C	0.03	0.01	0.03
B4C	BDL	BDL	0.05
B5C	BDL	BDL	0.03
B6C	BDL	BDL	0.04
B7C	0.14	0.01	0.03
B8C	0.03	0.01	0.04
B9C	BDL	BDL	5.43
B10C	BDL	0.21	0.03
Geometric Mean	0.05	0.02	0.06
Geometric STD	1.88	3.31	5.01

Table D.6: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to cowpea stems

Sample	^{40}K	^{238}U	^{232}Th
B1S	0.13	BDL	0.08
B3S	0.04	BDL	0.05
B4S	0.08	BDL	0.02
B5S	0.19	BDL	0.07
B6S	0.33	0.11	0.05
B7S	0.26	BDL	0.08
B8S	0.04	0.01	0.02
B9S	BDL	BDL	0.03
B10S	0.18	BDL	0.09
Geometric Mean	0.12	0.03	0.05
Geometric STD	2.08	3.32	1.70

Table D.7: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to cowpea leaves

Sample	^{40}K	^{238}U	^{232}Th
B1L	0.04	BDL	0.05
B3L	0.51	BDL	0.14
B4L	BDL	BDL	0.07
B5L	BDL	BDL	0.14
B6L	0.25	BDL	0.06
B7L	BDL	0.22	0.18
B8L	BDL	BDL	0.15
B9L	BDL	0.50	0.26
B10L	BDL	BDL	0.09
Geometric Mean	0.18	0.33	0.11
Geometric STD	3.09	1.53	1.67

Table D.8: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to cowpea roots

Sample	^{40}K	^{238}U	^{232}Th
B1R	0.07	0.01	0.06
B3R	0.13	BDL	0.11
B4R	0.26	BDL	0.24
B5R	0.05	BDL	0.09
B6R	0.42	BDL	0.09
B7R	BDL	0.09	0.13
B8R	0.41	0.16	0.15
B9R	0.21	BDL	0.21
B10R	0.17	BDL	0.11
Geometric Mean	0.17	0.05	0.12
Geometric STD	2.07	3.18	1.53

Table D.9: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to cowpea seeds

Sample	^{40}K	^{238}U	^{232}Th
C1C	BDL	0.11	0.21
C3C	0.37	BDL	0.10
C4C	0.55	BDL	0.07
C5C	BDL	BDL	0.26
C6C	0.06	BDL	0.12
C7C	0.32	0.03	0.07
C9C	0.09	BDL	0.04
C10C	BDL	BDL	0.18
Geometric Mean	0.21	0.05	0.11
Geometric STD	2.37	2.12	1.87

Table D.10: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to cowpea stems

Sample	^{40}K	^{238}U	^{232}Th
C1S	BDL	BDL	BDL
C3S	0.91	BDL	0.09
C4S	0.23	BDL	0.07
C5S	BDL	BDL	0.07
C6S	0.15	BDL	0.09
C7S	0.82	BDL	0.08
C9S	BDL	BDL	0.03
C10S	0.68	BDL	0.05
Geometric Mean	0.44	BDL	0.07
Geometric STD	2.09		1.37

Table D.11: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to cowpea leaves

Sample	^{40}K	^{238}U	^{232}Th
C1L	BDL	BDL	0.43
C3L	2.26	BDL	0.14
C4L	BDL	BDL	0.43
C5L	2.45	BDL	0.29
C6L	0.61	BDL	0.11
C7L	2.46	BDL	0.39
C9L	4.97	BDL	0.62
C10L	1.55	BDL	0.48
Geometric Mean	2.00		0.31
Geometric STD	1.88		1.78

Table D.12: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to cowpea roots

Sample	^{40}K	^{238}U	^{232}Th
C1R	BDL	BDL	0.15
C3R	BDL	0.25	0.14
C4R	BDL	BDL	0.53
C5R	1.86	BDL	0.31
C6R	BDL	BDL	0.23
C7R	2.27	0.18	0.01
C9R	3.98	BDL	0.39
C10R	BDL	BDL	0.07
Geometric Mean	2.56	0.21	0.14
Geometric STD	1.38	1.18	3.73

Table D.13: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to maize seeds

Sample	^{40}K	^{238}U	^{232}Th
A21C	0.69	BDL	4.88
A22C	0.41	BDL	0.34
A23C	BDL	BDL	0.32
A25C	BDL	BDL	0.31
A26C	BDL	BDL	BDL
A29C	0.83	BDL	0.88
A30C	0.75	BDL	0.28
Geometric Mean	0.65	BDL	0.58
Geometric STD	1.31		2.79

Table D.14: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to maize stems

Sample	^{40}K	^{238}U	^{232}Th
A21S	6.04	BDL	8.22
A22S	3.13	BDL	BDL
A23S	4.15	BDL	4.05
A25S	3.37	BDL	2.72
A26S	5.09	BDL	0.26
A29S	2.34	BDL	0.98
A30S	2.53	BDL	1.98
Geometric Mean	3.61	BDL	1.89
Geometric STD	1.38		3.01

Table D.15: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to maize leaves

Sample	^{40}K	^{238}U	^{232}Th
A21L	3.18	BDL	1.11
A22L	1.54	BDL	0.38
A23L	2.61	BDL	2.40
A25L	1.87	0.92	0.22
A26L	1.47	BDL	0.95
A29L	1.09	BDL	1.63
A30L	2.65	0.84	BDL
Geometric Mean	1.94	0.88	0.84
Geometric STD	1.14	1.05	2.27

Table D.16: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to maize roots

Sample	^{40}K	^{238}U	^{232}Th
A21R	2.49	BDL	1.17
A22R	3.37	0.19	0.62
A23R	1.56	BDL	4.36
A25R	BDL	BDL	4.35
A26R	BDL	5.20	11.87
A29R	6.57	BDL	2.57
A30R	1.59	BDL	2.38
Geometric Mean	2.68	1.00	2.68
Geometric STD	1.71	5.18	2.43

Table D.17: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to maize seeds

Sample	^{40}K	^{238}U	^{232}Th
B21C	BDL	BDL	0.12
B22C	0.01	BDL	0.01
B23C	BDL	BDL	0.02
B25C	BDL	0.01	0.04
B26C	0.06	BDL	0.04
B27C	BDL	BDL	0.05
B28C	BDL	0.03	0.03
B30C	BDL	0.01	0.04
Geometric Mean	0.03	0.01	0.03
Geometric STD	2.14	2.00	2.04

Table D.18: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to maize stems

Sample	^{40}K	^{238}U	^{232}Th
B21S	0.04	BDL	0.030
B22S	0.17	BDL	BDL
B23S	0.13	BDL	0.010
B25S	0.04	BDL	0.020
B26S	0.04	BDL	0.040
B27S	0.15	BDL	0.004
B28S	0.05	BDL	0.030
B30S	BDL	BDL	0.010
Geometric Mean	0.07	BDL	0.020
Geometric STD	1.88		1.970

Table D.19: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to maize leaves

Sample	^{40}K	^{238}U	^{232}Th
B21L	BDL	BDL	0.03
B22L	BDL	BDL	0.01
B23L	0.09	BDL	0.01
B25L	BDL	BDL	0.01
B26L	0.02	BDL	0.03
B27L	BDL	BDL	0.02
B28L	BDL	BDL	0.15
B30L	BDL	BDL	0.01
Geometric Mean	0.04	BDL	0.02
Geometric STD	2.04		2.35

Table D.20: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to maize root

Sample	^{40}K	^{238}U	^{232}Th
B21R	0.06	0.18	0.10
B22R	BDL	0.27	0.12
B23R	BDL	0.51	0.22
B25R	0.02	0.06	0.06
B26R	0.05	0.57	0.17
B27R	0.22	0.54	0.33
B28R	0.06	0.07	0.14
B30R	0.01	0.09	0.07
Geometric Mean	0.05	0.20	0.13
Geometric STD	2.41	2.45	1.72

Table D.21: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to maize seeds

Sample	^{40}K	^{238}U	^{232}Th
C21C	BDL	BDL	0.007
C22C	0.18	BDL	0.008
C23C	0.17	BDL	0.018
C24C	BDL	BDL	0.005
C25C	BDL	BDL	0.003
C26C	BDL	BDL	0.007
C27C	1.21	BDL	0.174
C29C	BDL	BDL	0.120
Geometric Mean	0.33	BDL	0.015
Geometric STD	2.48		4.000

Table D.22: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to maize stems

Sample	^{40}K	^{238}U	^{232}Th
C21S	BDL	BDL	0.04
C22S	BDL	BDL	0.02
C23S	BDL	BDL	0.02
C24S	0.05	BDL	0.02
C25S	0.82	BDL	0.01
C26S	0.53	BDL	0.02
C27S	0.92	BDL	0.01
C29S	0.68	BDL	0.02
Geometric Mean	0.43	BDL	0.02
Geometric STD	2.88		1.40

Table D.23: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to maize leaves

Sample	^{40}K	^{238}U	^{232}Th
C21L	2.768	BDL	BDL
C22L	0.133	BDL	0.023
C23L	0.455	BDL	0.224
C24L	0.450	BDL	BDL
C25L	0.091	BDL	BDL
C26L	0.563	0.009	0.023
C27L	0.294	0.019	0.033
C29L	0.367	BDL	0.016
Geometric Mean	0.378	0.013	0.023
Geometric STD	2.611	1.480	1.274

Table D.24: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to maize roots

Sample	^{40}K	^{238}U	^{232}Th
C21R	BDL	0.10	0.12
C22R	0.34	0.25	0.12
C23R	0.11	0.14	0.30
C24R	0.21	0.02	0.23
C25R	2.42	0.21	0.17
C26R	0.05	BDL	0.01
C27R	BDL	0.04	0.12
C29R	0.14	0.24	0.24
Geometric Mean	0.23	0.11	0.12
Geometric STD	3.31	2.37	2.59

Table D.25: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to cassava tuber

Sample	^{40}K	^{238}U	^{232}Th
A31C	1.18	BDL	0.81
A33C	BDL	BDL	0.21
A34C	BDL	BDL	BDL
A36C	BDL	BDL	0.71
A38C	0.64	BDL	BDL
Geometric Mean	0.87	BDL	0.49
Geometric STD	1.36		1.87

Table D.26: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to cassava stems

Sample	^{40}K	^{238}U	^{232}Th
A31S	0.46	BDL	0.77
A33S	1.51	BDL	0.84
A34S	1.43	0.28	0.65
A36S	0.45	BDL	0.43
A38S	0.51	0.19	BDL
Geometric Mean	0.74	0.23	0.65
Geometric STD	1.75	1.23	1.30

Table D.27: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group A to cassava leaves

Sample	^{40}K	^{238}U	^{232}Th
A31L	0.44	BDL	0.54
A33L	BDL	2.74	10.52
A34L	3.84	BDL	BDL
A36L	3.75	0.51	0.28
A38L	0.72	0.51	3.57
Geometric Mean	1.46	0.90	1.54
Geometric STD	2.64	2.21	4.26

Table D.28: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to cassava tubers

Sample	^{40}K	^{238}U	^{232}Th
B31C	0.006	BDL	BDL
B32C	BDL	BDL	0.021
B33C	BDL	BDL	0.039
B35C	BDL	BDL	0.036
B37C	BDL	BDL	0.095
B39C	0.017	BDL	0.014
B40C	BDL	BDL	0.168
Geometric Mean	0.010	BDL	0.044
Geometric STD	1.684		2.315

Table D.29: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to cassava stem

Sample	^{40}K	^{238}U	^{232}Th
B31S	0.015	BDL	0.024
B32S	BDL	BDL	0.010
B33S	BDL	BDL	0.044
B35S	0.008	BDL	0.028
B37S	0.011	BDL	0.036
B39S	0.019	BDL	0.025
B40S	0.016	BDL	0.024
Geometric Mean	0.013	BDL	0.025
Geometric STD	1.395		1.565

Table D.30: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group B to cassava leaves

Sample	^{40}K	^{238}U	^{232}Th
B31L	0.04	BDL	0.010
B32L	0.19	BDL	BDL
B33L	0.11	BDL	0.070
B35L	BDL	BDL	0.120
B37L	BDL	BDL	0.090
B39L	0.28	BDL	0.040
B40L	BDL	BDL	0.003
Geometric Mean	0.12	BDL	0.030
Geometric STD	2.04		3.410

Table D.31: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to cassava tubers

Sample	^{40}K	^{238}U	^{232}Th
C31C	0.169	0.011	0.009
C32C	BDL	0.011	0.005
C33C	BDL	0.014	0.035
C35C	BDL	BDL	BDL
C36C	BDL	BDL	0.002
C37C	0.079	BDL	0.003
C38C	0.150	BDL	0.005
C39C	0.057	0.008	0.006
C40C	0.114	BDL	0.005
Geometric Mean	0.106	0.011	0.006
Geometric STD	1.497	1.237	2.509

Table D.32: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to cassava stems

Sample	^{40}K	^{238}U	^{232}Th
C31S	1.00	BDL	0.06
C32S	0.36	BDL	0.05
C33S	BDL	0.02	0.06
C35S	0.41	BDL	0.04
C36S	0.16	BDL	0.07
C37S	BDL	BDL	0.02
C38S	0.06	BDL	0.02
C39S	0.26	0.01	0.01
C40S	0.09	BDL	0.01
Geometric Mean	0.23	0.01	0.03
Geometric STD	2.53	1.11	2.15

Table D.33: The transfer factors of ^{40}K, ^{238}U and ^{232}Th from soil group C to cassava leaves

Sample	^{40}K	^{238}U	^{232}Th
C31L	BDL	0.02	0.11
C32L	2.02	0.09	0.21
C33L	2.21	BDL	BDL
C35L	4.78	0.22	0.23
C36L	2.36	BDL	0.62
C37L	BDL	BDL	0.16
C38L	7.55	BDL	0.52
C39L	1.16	0.08	0.10
C40L	4.02	0.05	0.12
Geometric Mean	2.91	0.07	0.21
Geometric STD	1.79	2.04	1.91