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ASSESSMENT OF RADIOACTIVITY OF ^{226}Ra, ^{232}Th AND ^{40}K IN SOIL AND PLANTS FOR ESTIMATION OF TRANSFER FACTORS AND EFFECTIVE DOSE AROUND MKUJU RIVER PROJECT, TANZANIA

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ОЦІНКА РАДІОАКТИВНОСТІ ^{226}Ra, ^{232}Th ТА ^{40}K В ГРУНТІ ТА РОСЛИНАХ ДЛЯ ВИЗНАЧЕННЯ ФАКТОРІВ ПЕРЕНОСУ І ЕФЕКТИВНОЇ ДОЗИ НАВКОЛО УРАНОВОГО РОДОВИЩА "МКУЖУ-РІВЕР", ТАНЗАНІЯ

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ABSTRACT

Purpose. To establish pre-mining indicators to assess radiological impact as a result of release of radionuclides to environment during uranium mining at Mkuju River Project radioactivity of ^{226}Ra, ^{232}Th and ^{40}K in soil, plants, fruits and cereals.

Methods. The High Purity Germanium detector was used to determine the radioactivity and the data were subsequently used to establish soil to plant transfer factors and annual effective dose.

Findings. The results revealed a strong positive correlation (r) of 0.947 and 0.950 for ^{226}Ra and ^{232}Th, respectively, between values determined in soils and plants. Implicit in these finding is that the distribution of radionuclides in soils is directly proportional to the corresponding radionuclides in plants.

Originality. The roots of wild grass had the highest specific radioactivity (Bqkg^{-1}) for ^{226}Ra (2.15 ± 0.02), ^{232}Th (1.43 ± 0.02) and ^{40}K (198.16 ± 1.72) and the roots of cabbage had the highest values for ^{226}Ra (1.38 ± 0.04), ^{232}Th (1.34 ± 0.03) and ^{40}K (146.12 ± 1.02) among the food crops, an indication of a higher ability to uptake radionuclides from soil. Similarly, since the *TF*s were found higher in wild grass for ^{226}Ra (0.0533 ± 0.04), ^{232}Th (0.0374 ± 0.002) and ^{40}K (0.5297 ± 0.05) and cabbage for ^{226}Ra (0.0362 ± 0.03), ^{232}Th (0.0360 ± 0.001) and ^{40}K (0.4173 ± 0.05).

Practical implications. It is an evident that these plants can serve as good bio indicators to assess release of radionuclides from inside the mining site to the public domain. Moreover, the annual effective dose (mSvy^{-1}) for ^{40}K (0.23 ± 0.02), ^{226}Ra (0.046±0.004) and ^{232}Th (0.073 ± 0.006) in edible crops when consumed in the vicinity of the MRP before the mining operations were, as expected, insignificant.

Keywords: *radioactivity, transfer factors, effective dose, Mkuju River, Tanzania*

1. INTRODUCTION

Release of radioactive materials into the environment as a result of mining activity to a greater extent is responsible for enhanced effective dose to the population either through external gamma irradiation (due to a source outside the body) or internal exposure (due to a source within the body) by inhalation and ingestion of radionuclides or both (IAEA, 1994; UNSCEAR, 2000; IAEA, 2008; Bersimbaev & Bulgakova 2015). However, external exposure from the naturally occurring radionuclides does not contribute significantly to population exposure for various reasons. First, most of the gamma rays responsible for external exposure have average low intensity and their penetration into the body is limited. Second, the emission probability of gamma rays is relatively lower than that of beta and alpha particles. Third, the occupancy time of external exposure of approximately 20% is lower than occupancy time of 100% for internal exposure when radioactivity is inside the body. Therefore the external population exposure due to environmental radioactivity in this study has been neglected. Internal exposure which is more important than external is closely related to the concentration of radionuclides in food crop mainly through roots uptake from soil (Fernandes, Franklin, Veiga, Freitas, & Gomiero, 1996; Gaso, Segovia, Cervantes, Herrera, Perez-Silva, & Acosta, 2000; Santos, Lauria, Amaral, & Rochedo, 2002; Ababneh, Masa'deh, Ababneh, Awawdeh, & Alyassin, 2009). It is postulated that under equilibrium conditions the concentration of radionuclides in plants is proportional to concentration of radionuclides in soil (Eriksson, 1977; Whicker, Hinton, Orlandini, & Clark, 1999; Manigandan & Manikandan, 2008; Chakraborty, Azim, Rahman, & Sarker, 2013). Based on this concept, concentrations of radionuclide in plant can be inferred from concentrations of radionuclide in soil and vice versa. However, due to various factors influencing the availability of radionuclides by plants (Fig. 1), the linear relationship is not one to one.

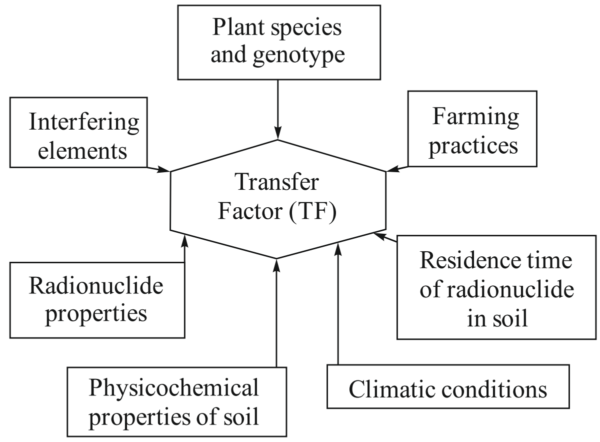

Figure 1. Shows factors influencing soil-to-plant transfer factor in the field conditions

For this reasona coefficient, which relates the specific activity concentration of a radionuclide in a dry mass of plant (A_{plant}) to the specific activity concentration of that radionuclide in a dry mass of soil (A_{soil}) known as Transfer factor (*TF*) has been introduced and is represented by Equation (1) (Linsalata et al., 1989; Mortvedt, 1994; Shaw & Bell, 1994; Chakraborty, Azim, Rahman, & Sarke, 2013):

$$TF = \frac{A_{plant}(dryweight)}{A_{soil}(dryweight)}. \quad (1)$$

Hence knowledge of the radionuclides concentration in soil is also important (Eriksson, 1977; Kabata-Pendias & Pendias, 1992; Kabata-Pendias, 2011). Since soil is inedible, in an effort to predict internal radiation exposure to humans associated with contamination of soil by anthropogenic activities including uranium mining, considerable reliance has been placed on soil-to-plant *TF*s of specific radionuclides (Ng, Colsher, & Thompson, 1979; UNSCEAR, 2013; Basu, Sarangapani, Sivasubramanian, & Venkatraman, 2015). In addition, the *TF* has been used widely to formulate radioecological models and to identify plants capable to be used for mapping and phytoremediation of sites contaminated with radionuclides (Mortvedt, 1994; Whicker, Hinton, Orlandini, & Clark, 1999; Adriano, Doswell, Ciravolo, Pinder, & McLeod, 2000; Baker, McGrath, Reeves, & Smith, 2000; IAEA, 2008; IAEA, 2010; Jagetiya, Sharma, Soni, & Khatik, 2014).

However, as shown in Figure 1, the *TF*s in the natural terrestrial environment, is influenced by a number of site specific factors (IAEA, 1994; IUR, 1994; IAEA, 2008). Assuming the factors in Figure 1 are constant, the *TF*s is also expected to be constant and therefore this factor can be used to estimate the concentrations of radionuclides in plants. Thus the aim of the present study was to establish site specific soil-to-plant *TF*s for ^{232}Th, ^{226}Ra and ^{40}K for terrestrial plants grown locally in the vicinity of the MRP to serve as bio-indicators for radionuclides contamination in the environment and subsequent estimation of exposure dose to population from consuming food crops grown in the vicinity of Mkuju river during and after uranium mining activities.

2. MATERIAL AND METHODS

2.1. Description of the study area

The Mkuju river project (MRP) is a large scale uranium development project located in Namtumbo district in Ruvuma region, Southern Tanzania between latitudes 9° 59′ 50″ to 10° 07′ 15″ S and longitudes 36° 30′ 00″ to 36° 37′ 55″ E. This area hosts a viable uranium deposit of sandstone type about 25200 tU, with an estimated production of 1600 tU in a year at its maximum capacity over a minimum of 12 years (MSL, 2010). Since the uranium ore occurs at shallow depths, conventional open-pit methods utilizing mid-size earth moving equipment will be used. With this method, it was estimated that about 2.2 million tons of waste rock per year could be excavated during open-pit mining. Using the site specific meteorological, topographical and physical chemical parameters available at site, an area of about 1300 km^2 around the MRP's boundary, which is potential to be polluted by the MRP activities was estimated using AERMOD dispersion model as described previously (Banzi et al., 2015). The demarcated area around the MRP is characterized by a hot summer and throughout the year the air temperature usually does not go below 0°C with markedly wet or dry seasons. The rain distribution is fairly regular throughout the year and the surface accumulation of soil organic matter is minimal.

2.2. Sample collection

A total of 75 samples comprising soil, species of plants, fruits and cereals have been collected in the study area and beyond in villages within a radius of about 50 kilometres from the perimeter of the MRP concession. The locally abundant and dominant crop coverage over large area were the main criteria used to select the samples to develop potential bio-indicators for pollution as well as for estimation population exposure due to consumption of food crops grown around the proposed uranium mine. The food samples include: tomato (lycopersiconesculentum), cabbage (brassica oleracea), cucumber (cucumissativus), papaya (carica papaya), maize (zea mays), beans, carrot, banana, and mango (mangiferaindica). For plants, the entire plant was harvested randomly from farms by hand using vinyl gloves. The soil samples were collected along with plants in a layer down to 30 cm where the roots of plants normally grow. The fruits and cereal samples were collected directly from the local market basket.

2.3. Sample preparation

In the laboratory, the fresh plants were washed using tap water and then rinsed with distilled water to get rid of dust before were dried under sun for more than one month. Since translocation of radionuclides in a plant system depend largely on plant compartments (root, stem and leaf) (Baeza, Barandica, Paniagua, Rufo, & Sterling, 1999), each dried plant was separated to form three parts of samples namely: root, stem and leaf samples. In order to reduce the moisture content so as to attain a constant weight, the samples were oven dried at 100°C for 24 hours (Ahmedali, 1989). After drying, each sample was ground into fine powder using an agate mortar and pestle then passed through a 2 mm stainless steel sieve to obtain uniform sample powder of similar matrix with the standard reference material. Between every sample preparation, pieces of equipment including pulverizer, mortar and paste were thoroughly cleaned with water followed by distilled water and acetone. This approach kept sample cross contamination below the minimum levels. The fine powdered dry-weight, which ranged from 250 to 400 g were sealed air tight with silicone and electrical tape into a stainless steel canister to prevent escape of radon gas and then stored for a period of one month to allow attainment of the radioactive equilibrium stage between ^{226}Ra, ^{232}Th and its short-lived decay products before radioactivity measurements.

2.4. Determination of radioactivity

The radioactivity in soil, plant, fruit and cereal samples were measured with a High Purity Germanium (HPGe) detector. Since the natural radioactivity levels of normal soils, plants, fruits and cereals are low; it was necessary to place a sample on top of the detector and collect a spectrum for more than 12 hours to increase the statistics of counting. In order to ensure that contribution of background count rates on the sample due to external gamma radiation was kept minimum, the detector was shielded by 100 mm thick of lead lined with concentric absorbers made of cadmium and copper metals each with 3 and 30 millimetres thick, respectively. Since the radioactivity of ^{226}Ra and ^{232}Th cannot be measured directly by a gamma spectrometer their activities were inferred using the gamma lines of their daughter decay products by assuming that there was a radioactive secular equilibrium between parents and daughters (Canet & Jacquemn, 1990; Bruzzi, Baroni, Mele, & Nanni, 1997).

The radioactivity of ^{226}Ra was obtained from an average of the gamma emitting lines (keV) of its two progenies: ^{214}Bi (609.3, 1120.3 and 1764.5) and ^{214}Pb (295.2 and 351.9). Similarly, the radioactivity of ^{232}Th was determined from an average of gamma line (keV) of its three progenies: ^{212}Pb (238.63), ^{208}Tl (583.2) and ^{228}Ac (338.4, 911 and 969). However, the radioactivity of ^{40}K was determined directly using its singlet gamma line of 1461 keV. On this basis the mean specific radioactivity (*SA*) of each radionuclide in a sample was derived using the net count rates of respective gamma photo peaks obtained by subtracting background contribution in the photo peaks denoted by R_b from total sample counts rates denoted by R_s. Equation (1) was used to convert the net sample counts rates into radioactivity for each radionuclide:

$$SA = \frac{R_s - R_b}{\eta \rho w}, \quad (2)$$

where:

η – the photo peak efficiency;

p – the emission probability of a gamma line;

w – the dry weight of the measured sample.

2.5. Quality control

Before measurement, the detector was calibrated using standard radiation point sources in the energy range between 60 keV and 2614 keV that made possible to establish energy channel linear relationship on the Multi-Channel Analyzer (MCA) for identification of radionuclides. The efficiency curve was developed using an In-Situ Object Counting-system (ISOCS) software a product of Genie 2000™. In order to determine level of accuracy on the values obtained by measurements, standard reference materials (SRM) obtained from the IAEA were prepared and analyzed in the same manners as unknown samples. The values of radionuclides in the SRMs obtained by the measurements were compared with the certified values of corresponding radionuclides indicated in the certificate. The results show that the measured values agreed with the certified values within ±8%. Implicit in this result is that variations of specific radioactivity were within the acceptable uncertainty. In addition, the detector used for this measurement indicated a capability to determine the minimum detection Limit ($Bqkg^{-1}$) of 0.12, 0.15 and 1.12 for ^{226}Ra, ^{232}Th and ^{40}K, respectively at 95% confidence level.

2.6. Quality control

For radiation protection purposes dose limits established by ICRP (1996) was considered as indices to assess whether the radiological safety requirement is satisfied or not. For the naturally occurring radioactive materials, the evaluation of effective dose is based on the three radionuclides (^{226}Ra, ^{232}Th and ^{40}K) those expected to be predominant contributors to radiation dose through ingestion of food crops. Therefore, the annual internal effective dose (E_D, μSvy^{-1}) of each radionuclide due to consumption of food crop grown in the vicinity of the MRP was estimated by Equation (3) using the specific radioactivity (*SA*, $Bqkg^{-1}$) which was determined in food, dose conversion factor (*DCF*, $SvBq^{-1}$) relevant to each radionuclide for an individual adult (> 17 years) and consumption rate (*CR*, kgy^{-1}) of relevant food:

$$E_D = SA \cdot CR \cdot DCF, \quad (3)$$

The *DCF* for ^{226}Ra ($2.25 \cdot 10^{-7}$), ^{232}Th ($3.69 \cdot 10^{-7}$) and ^{40}K ($5.90 \cdot 10^{-9}$) were adopted from the International Commission on Radiological Protection (ICRP, 2012).

3. RESULTS AND DISCUSSION

3.1. Radioactivity and soil-to-plant transfer factors

The mean radioactivity of ^{226}Ra, ^{232}Th and ^{40}K in soil, plant, fruit and cereals samples, and soil-to-plant transfer factors determined using Equations (1) and (2), respectively are presented in Table 1.

Table 1. Mean natural radioactivity (Bqkg-1 dry weight) of ^{226}Ra, ^{232}Th and ^{40}K in soils, plants, fruits and cereals, and soil-to-plant transfer factors in samples from MRP

Plant		Mean Radioactivity Concentration (Bqkg^{-1})						Soil-to-Plant Transfer Factor		
Cereal	Plant	Soils			Plants			(*TF*s)		
Species	Parts	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K
Wild Grass (Concession)	Root	3070.50	143.50	1307.88	12.55	10.56	214.15	0.0041	0.0736	0.1637
	Stem	—	—	—	12.34	9.83	184.36	0.0040	0.0685	0.1410
	Leaf	—	—	—	12.52	10.32	212.11	0.0041	0.0719	0.1622
Wild Grass (Vicinity)	Root	40.35	38.19	374.13	2.15	1.43	198.16	0.0533	0.0374	0.5297
	Stem	—	—	—	2.13	1.41	184.32	0.0528	0.0369	0.4927
	Leaf	—	—	—	2.11	1.42	192.14	0.0523	0.0372	0.5136
Cabbage	Root	38.13	37.23	350.16	1.38	1.34	146.12	0.0362	0.0360	0.4173
	Stem	—	—	—	1.38	1.26	135.18	0.0362	0.0338	0.3861
	Leaf	—	—	—	1.35	1.33	145.83	0.0354	0.0357	0.4165
Peas	Root	34.14	32.08	462.55	1.31	1.32	65.3	0.0384	0.0411	0.1412
	Stem	—	—	—	1.27	1.24	61.49	0.0372	0.0387	0.1329
	Leaf	—	—	—	1.29	1.29	63.85	0.0378	0.0402	0.1380
	Root	32.24	31.22	352.24	0.43	0.42	46.12	0.0133	0.0135	0.1309
Beans	Stem	—	—	—	0.41	0.41	45.04	0.0127	0.0131	0.1279
	Leaf	—	—	—	0.42	0.37	45.15	0.0130	0.0119	0.1282
Maize	Root	29.58	28.86	486.52	0.29	0.31	39.21	0.0098	0.0107	0.0806
	pod	—	—	—	0.25	0.28	37.27	0.0085	0.0097	0.0766
	Leaf	—	—	—	0.27	0.29	38.01	0.0091	0.0100	0.0781
Banana	Fruit	—	—	—	1.07	1.06	139.00	—	—	—
Carrot	Tuber	—	—	—	0.59	0.54	87.32	—	—	—
Onion	Tuber	—	—	—	0.46	0.44	65.22	—	—	—
Tomatoes	Fruit	—	—	—	0.35	0.31	66.22	—	—	—
Cucumber	Fruit	—	—	—	0.34	0.35	53.11	—	—	—
Papaya	Fruit	—	—	—	0.29	0.27	52.53	—	—	—
Rice	Grain	—	—	—	0.26	0.25	48.61	—	—	—
Maize	Grain	—	—	—	0.22	0.22	51.11	—	—	—
Beans	Grain	—	—	—	0.19	0.17	38.22	—	—	—

3.1.1. Radioactivity in soil

In Table 1 the spatial distribution of ^{40}K radionuclide in all of the soils analysed was considerably higher than that of ^{226}Ra and ^{232}Th. In the vicinity a maximum value for ^{40}K (486.52 ± 23.44 Bqkg^{-1}) was approximately 12 and 13 times higher than the maximum values for ^{226}Ra (40.35 ± 2.34 Bqkg^{-1}) and ^{232}Th (38.19 ± 2.18 Bqkg^{-1}), respectively. However, all values of radionuclides recorded in the vicinity were comparable with the typical ranges for ^{226}Ra (16 to 110), ^{232}Th (11 to 64) and ^{40}K (140 to 850) documented by UNSCEAR (2000) in normal soil. Moreover, these values agreed very well with the previous study (Mohammed & Mazunga, 2013).

According to the ICRP (2007) the radioactivity of each member of the naturally occurring radionuclides in the uranium and thorium decay series that exceeds 1 Bqg^{-1} and for ^{40}K exceeding 10 Bqg^{-1} requires a regulatory control to reduce the risk of radiation exposure of public. The overall means radioactivity (Bqkg^{-1}) for ^{226}Ra (34.89 ± 4.04), ^{232}Th (33.52 ± 3.72) and ^{40}K (405.12 ± 59.72) found in soilsin the vicinity of MRP were only up to 4 % of the upper limits that warrant a regulatory control and therefore is insignificant from a health point of view. In view of these findings, it was suffice to conclude that data obtained in the present study can serve as baseline reference to assess incremental radionuclides onto the environment during and after the mining operations.

3.1.2. Radioactivity in plants

It is apparently in Table 1 that all plants, fruits and cereal samples investigated contained traces of ^{226}Ra, ^{232}Th and ^{40}K above their minimum detectable radioactivity. However, values of ^{226}Ra, ^{232}Th and ^{40}K found in plants were significantly lower up to 35, 34 and 4 times that of the corresponding radionuclides concentrations found in soils collected along with plants, respectively. Partly this is attributable to many factors those influencing uptake of radionuclides by plants via roots such as physical, chemical and biological conditions of soil (Fig. 1). As such, plants pick only a tiny fraction of ^{226}Ra, ^{232}Th and ^{40}K that present on soil (Kabata-Pendias, 2011).

The wild grass growing in the concession with enriched natural radionuclides of ^{226}Ra and ^{232}Th exhibited higher levels of radioactivity about six and ten times than the same species of wild grass collected in the neighbourhood, respectively. The considerable difference between the same species of wild grass growing in the concession and in the vicinity in terms of radioactivity could be explained by the bioavailability of radioactivity on soil. Moreover, the values in Table 1 indicate significant differing radioactivity between species and also between plant parts. This suggest that different plants are not equally at absorbing radionuclides from soil. A comparative ranking of plant's genotype in terms of radioactivity was: wild grass > cabbage > peas > beans > maize. Thus, different values between plant's genotype were expected since the natural metabolic of plants species are different.

In Table 1 a pattern of radionuclides distribution between plants parts appear to be generally similar for all plants species. The roots had relatively the highest radioactivity than leaves and stems had the lowest radioactivity. The maximum values (Bqkg^{-1}) for ^{226}Ra (2.15 ± 0.02), ^{232}Th (1.43 ± 0.02) and ^{40}K (198.16 ± 1.72) were found in the roots of wild grass and the minimum values for^{226}Ra (0.25 ± 0.01), ^{232}Th (0.28 ± 0.03) and ^{40}K (37.27 ± 1.32) were recorded on the pod of maize. In general the comparative translocation of radionuclides in the different plant's parts was favoured towards the growing parts as already described elsewhere (Nielsen, 1981). The roots of wild grass tend to accumulate more of the radionuclides than other parts, thus the roots of wild grass could be potential bio-indicators for estimating pollution in the vicinity of the MRP during and after the mining operations.

Of the radionuclides analyzed, values of ^{40}K in all plants species were relatively higher than those of ^{226}Ra and ^{232}Th. This finding supported by two reasons: first potassium is naturally enriched in soils and mobile. Second potassium is an essential nutrient in plants. These reasons suggest that ^{40}K was preferentially picked up by plants via roots along with potassium and translocate in plant system to support the plant growth (Kabata-Pendias, 2011). It was also found that the radioactivity of ^{226}Ra in all samples were slightly higher in relation to those of ^{232}Th indicating that ^{226}Ra is relatively mobile and the two radionuclides originate from different natural decay series.

In order to assess a relation between values of radioactivity for ^{226}Ra, ^{232}Th and ^{40}K found in soils and plants data obtained in this study were tested using a Pearson's correlation coefficient (r) and coefficient of determination (R^2). The r has indicated a strong positive correlation ($r = 0.947$) between values of ^{226}Ra in soils and plants species as well as a strong positive correlation ($r = 0.950$) between values of ^{232}Th in soils and plant species. Implicit is that the dependence of radioactivity values in plants species on soil radioactivity. In addition, the coefficient of determination (R^2) for values of soil and plants indicated a regression line perfectly fits the data of soil and plants by 72.76 and 86.30% for ^{226}Ra and ^{232}Th, respectively suggesting a linear relation between radioactivity in soil and plant. However, the influence of other factors on the uptake of radionuclides by plants cannot be ruled out, since it is difficult to account exactly the effects caused by each factor shown in Figure 1. On this basis, it is recommended that future studies should use laboratory experiments under controlled field conditions to isolate the interfering effects and give good understanding of behavior of radionuclides in plants of this area.

3.1.3. Radioactivity in vegetable, fruit and cereal

Mean radioactivity for ^{226}Ra, ^{232}Th and ^{40}K in vegetable, fruit and cereal was determined using Equations (1) and presented in Table 1. Table 1 shows the values of ^{226}Ra in vegetable, fruit and cereal were relatively higher than those for ^{232}Th, and both radionuclides were substantially lower than the values of ^{40}K. In general, the values for ^{226}Ra, ^{232}Th and ^{40}K in vegetable, fruit and cereal samples varied consistently in the order: banana > carot > onion > tomatoes > cucumber > papaya > rice > maize > beans.

As expected the radioactivity of ^{40}K was found higher than those of ^{226}Ra and ^{232}Th due to its high mobility in soil and its subsequent uptake by plants. It is also appears that carrot has relatively the highest radioactivity (Bqkg^{-1}) for ^{226}Ra (0.59 ± 0.01), ^{232}Th (0.54 ± 0.01) and ^{40}K (87.32 ± 1.20) and mug beans has the lowest for ^{226}Ra (0.19 ± 0.02), ^{232}Th (0.17 ± 0.01) and ^{40}K (38.22 ± 0.68). In this case, carrot could serve as good bio-indicator and phytoremediation of soil contaminated with ^{226}Ra, ^{232}Th and ^{40}K, and to assess radioactivity exposure through ingestion.

3.1.4 Soil-to-plant transfer factors for ^{226}Ra, ^{232}Th and ^{40}K

Transfer factors (*TF*s) of^{40}K, ^{226}Ra and ^{232}Th for different plant species were calculated using Equation (1) and presented in Table 1.

Table 1 shows clearly that different species of plants and parts of plants are not equally at absorbing and translocations of radionuclides. The *TF*s vary widely, mainly as a result of different species, parts of plant and type of radionuclide. The highest *TF*s for ^{226}Ra (0.0533 ± 0.04), ^{232}Th (0.0374 ± 0.002) and ^{40}K (0.5297 ± 0.05) were found in the roots of wild grass and the lowest values of *TF*s for ^{226}Ra (0.0085 ± 0.0001), ^{232}Th (0.0097 ± 0.0001) and ^{40}K (0.0766 ± 0.02) were found on the pod of maize. Also the roots of cabbage presented the highest *TF*s for ^{226}Ra (0.0362 ± 0.03), ^{232}Th (0.0360 ± 0.001) and ^{40}K (0.4173 ± 0.05) among the vegetables, fruits and cereals investigated. High *TF* is associated with the potential ability of a plant to absorb radionuclides from soil and translocate in the plant system. Hence, roots exhibited generally the highest ability to accumulate radionuclides when compared to the leaves and stems analyzed. A ranking of *TF*s by different parts of plant investigated for each radionuclide was as follows: roots > leaves > stem, which also consistent with the results that translocations of radionuclides favoured towards the growing parts(IAEA, 1994; IUR, 1994).

The *TF*s for different species of plants varied in the order: wild grass > cabbage > beans > maize. The *TF*s values for ^{226}Ra, ^{232}Thand ^{40}K were maximum in the roots of wild grass and were minimum in the pod of maize. In general, the *TF*s across all plant species for the three radionuclides in the samples investigated varied as follows: ^{40}K > ^{226}Ra > ^{232}Th. The values of ^{40}K were significantly higher than the values of ^{226}Ra and ^{232}Th, which also implied higher levels of ^{40}K uptake by plants. In this case, the roots of wild grass and cabbage with relatively higher *TF*s were considered sensitive for absorbing the ^{226}Ra and ^{232}Th from soil and for the purposes of assessment of radioactive releases offsite the mining site, the *TF*s of wild grass and cabbage could serve as better indicators.

3.2. Annual effective dose

The potential effective dose (E_D) to population due to consumption of vegetables, fruits and cereals containing traces of naturally occurring radioactive materials was estimated using Equation (3) and presented in Table 2.

In general the annual effective dose for ^{40}K, ^{226}Ra and ^{228}Th ranged from $9.50 \cdot 10^{-3}$ to $8.64 \cdot 10^{-2}$ mSvy^{-1} with an average of $9.50 \cdot 10^{-3} \pm 2.86 \cdot 10^{-3}$ mSvy^{-1}.

*Table 2. Annual consumption of each food crop, radioactivity ($Bqkg^{-1}$ dry weight) for ^{226}Ra, ^{232}Th and ^{40}K in food crop, annual effective dose ($mSvy^{-1}$) for each radionuclides and total annual effective dose ($mSvy^{-1}$) for adult population**

Food crop	Annual	Radioactivity			Annual Effective Dose			Total Annual Effective
	Consumption	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K	Dose
	(Kgy^{-1})	($Bqkg^{-1}$)			($mSvy^{-1}$)			($mSvy^{-1}$)
Banana	30	1.07	1.06	139.00	7.22E-03	1.17E-02	2.46E-02	4.36E-02
Carrot	20	0.59	0.54	87.32	2.66E-03	3.99E-03	1.03E-02	1.69E-02
Mango	20	0.47	0.44	107.85	2.12E-03	3.25E-03	1.27E-02	1.81E-02
Onion	15	0.46	0.44	65.22	1.55E-03	2.44E-03	5.77E-03	9.76E-03
Tomatoes	20	0.35	0.31	66.22	1.58E-03	2.29E-03	7.81E-03	1.17E-02
Cucumber	35	0.34	0.35	53.11	2.68E-03	4.52E-03	1.10E-02	1.82E-02
Papaya	20	0.29	0.27	52.53	1.31E-03	1.99E-03	6.20E-03	9.50E-03
Rice	150	0.26	0.25	48.61	8.78E-03	1.38E-02	4.30E-02	6.56E-02
Maize	200	0.22	0.22	51.11	9.90E-03	1.62E-02	6.03E-02	8.64E-02
Beans	200	0.19	0.17	38.22	8.55E-03	1.25E-02	4.51E-02	6.62E-02
Total	—	—	—	—	3.46 E-01			

*consumption of each food crop for an individual adult was estimated based on average of the Tanzania population diet (TFCT, 2008; Cochrane & Anna, 2015)

The maximum dose was obtained from consumption of maize as staple food in the area and the minimum dose was obtained from consumption of papaya. According to the UNSCEAR (2000) upper bound of annual effective dose for an individual adult (> 17 years) due to consumption of food containing naturally occurring radioactive materials is 0.29 $mSvy^{-1}$, of which 0.17 $mSvy^{-1}$ is from ^{40}K and 0.12 $mSvy^{-1}$ is from ^{238}U and ^{232}Th series. The aforesaid upper bound, the annual effective dose obtained from this study of 0.35 $mSvy^{-1}$is relatively high (about 21%) largely due to the contribution from ^{40}K (0.23 ± 0.02 $mSvy^{-1}$) which is homeostatically controlled in the human body. The contribution of ^{226}Ra (0.046 ± 0.004 $mSvy^{-1}$) and ^{232}Th (0.073 ± 0.006 $mSvy^{-1}$) to the annual effective dose as expected were significantly low than the threshold dose.

4. CONCLUSIONS

The radioactivity of ^{226}Ra, ^{232}Th and ^{40}K were determined in species of plants, fruits, cereals and soils collected along with plants in the vicinity and the concession of the proposed MRP. Results reveal that the roots of wild grass had the highest specific radioactivity ($Bqkg^{-1}$) for ^{226}Ra (2.15 ± 0.02), ^{232}Th (1.43 ± 0.02) and ^{40}K (198.16 ± 1.72) and the roots of cabbage had the highest values for ^{226}Ra (1.38 ± 0.04), ^{232}Th (1.34 ± 0.03) and ^{40}K (146.12 ± 1.02) among vegetables, fruits and cereals. This information indication that wild grass and cabbage have more ability to uptake radionuclides from soil. On the other hand the pod of maize recorded the lowest values for ^{226}Ra (0.25 ± 0.01), ^{232}Th (0.28 ± 0.03) and ^{40}K (37.27 ± 1.32). In addition, the roots of wild grass were associated with the highest *TF*s for ^{226}Ra (0.0533 ± 0.04), ^{232}Th (0.0374 ± 0.002) and ^{40}K (0.5297 ± 0.05) and roots of cabbage had the highest *TF*s for ^{226}Ra (0.0362 ± 0.03), ^{232}Th (0.0360 ± 0.001) and ^{40}K (0.4173 ± 0.05) for the edible plants investigated. The lowest *TF*s for ^{226}Ra (0.0085 ± 0.0001), ^{232}Th (0.0097 ± 0.0001) and ^{40}K (0.0766 ± 0.02) were found on the pod of maize. It is clear from these results that wild grass and cabbage due to their higher abilities to absorb radionuclides from soil, can be used reliably as bio indicators to assess baseline radiation levels and provide a benchmark to predict release of any materials from inside the concession to the public domain. However, to obtain more reliable indicator for radionuclides pollution at MRP, the characteristics of local plants should be tested under laboratory conditions taking into account the site specific factors. In addition, estimation of annual effective dose ($mSvy^{-1}$) for ^{40}K (0.23 ± 0.02), ^{226}Ra (0.046 ± 0.004) and ^{232}Th (0.073 ± 0.006) in edible fruits when consumed in the vicinity of the MRP before the mining operations were, as expected, insignificant.

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ABSTRACT (IN UKRAINIAN)

Мета. Встановити показники радіологічного впливу викиду радіонуклідів на навколишнє середовище під час видобутку урану на родовищі “Мкужу-Рівер”, а саме ^{226}Ra, ^{232}Th та ^{40}K у ґрунті, рослинах, фруктах та злаках.

Методика. Для визначення радіоактивності використовувався детектор високочистого германію. Отримані дані були використані для визначення факторів переносу й ефективної дози для ґрунту і рослин.

Результати. Результати виявили сильну позитивну кореляцію (*r*) 0.947 і 0.950 ^{226}Ra та ^{232}Th, відповідно, між отриманими значеннями в ґрунтах та рослинах. Розподіл радіонуклідів у ґрунтах прямо пропорційний відповідним радіонуклідам рослин.

Наукова новизна. Найвища питома радіоактивність (Бк/кг$^{-1}$) зафіксована в коріннях трави – ^{226}Ra (2.15 ± 0.02), ^{232}Th (1.43 ± 0.02) та ^{40}K (198.16 ± 1.72), а корені капусти мають найвищі значення радіоактивності серед харчових культур – ^{226}Ra (1.38 ± 0.04), ^{232}Th (1.34 ± 0.03) та ^{40} K (146.12 ± 1.02), що свідчить про більш високу здатність поглинати радіонукліди з ґрунту. Аналогічно, найвищий фактор переносу зафіксований у коріннях трави – ^{226}Ra (0.0533 ± 0.04), ^{232}Th (0.0374 ± 0.002) та ^{40}K (0.5297 ± 0.05) та капусти – ^{226}Ra (0.0362 ± 0.03), ^{232}Th (0.0360 ± 0.001) та ^{40}K (0.4173 ± 0.05).

Практична значимість. Встановлено, що рослини можуть служити хорошими біоіндикаторами для загальнодоступної оцінки викиду радіонуклідів із гірничодобувної ділянки. Крім того, щорічна ефективна доза (мСв$^{-1}$) для ^{40}K (0.23 ± 0.02), ^{226}Ra (0.046 ± 0.004) та ^{232}Th (0.073 ± 0.006) в їстівних культурах, що споживаються в околицях уранового родовища “Мкужу-Рівер” до початку його розробки, як і очікувалося, є незначною.

Ключові слова: *радіоактивність, фактор переносу, ефективна доза, Мкужу-Рівер, Танзанія*

ABSTRACT (IN RUSSIAN)

Цель. Установить показатели радиационного воздействия выброса радионуклидов в окружающую среду при добыче урана на месторождении “Мкужу Ривер”, а именно ^{226}Ra, ^{232}Th та ^{40}K в почве, растениях, фруктах и злаках.

Методика. Для определения радиоактивности использовался детектор высокочистого германия. Полученные данные были использованы для определения факторов переноса и эффективной дозы для почвы и растений.

Результаты. Результаты выявили сильную положительную корреляцию (*r*) 0.947 и 0.950 ^{226}Ra и ^{232}Th, соответственно, между полученными значениями в почвах и растениях. Распределение радионуклидов в почвах прямо пропорционально соответствующим радионуклидам растений.

Научная новизна. Наивысшая удельная радиоактивность (Бк/кг$^{-1}$) зафиксирована в корнях травы – ^{226}Ra (2.15 ± 0.02), ^{232}Th (1.43 ± 0.02) и ^{40}K (198.16 ± 1.72), а корни капусты имеют наивысшие значения радиоактивности среди пищевых культур – ^{226}Ra (1.38 ± 0.04), ^{232}Th (1.34 ± 0.03) и ^{40} K (146.12 ± 1.02), что свидетельствует о более высокой способности поглощать радионуклиды из почвы. Аналогично, наивысший фактор переноса зафиксирован в корнях травы – ^{226}Ra (0.0533 ± 0.04), ^{232}Th (0.0374 ± 0.002) и ^{40}K (0.5297 ± 0.05) и капусты – ^{226}Ra (0.0362 ± 0.03), ^{232}Th (0.0360 ± 0.001) и ^{40}K (0.4173 ± 0.05).

Практическая значимость. Установлено, что растения могут служить хорошими биоиндикаторами для общедоступной оценки выброса радионуклидов с горнодобывающего участка. Кроме того, ежегодная эффективная доза (мСВ$^{-1}$) для для ^{40}K (0.23 ± 0.02), ^{226}Ra (0.046 ± 0.004) и ^{232}Th (0.073 ± 0.006) в съедобных культурах, потребляемых в окрестностях уранового месторождения “Мкужу-Ривер” до начала его разработки, как и ожидалось, является незначительной.

Ключевые слова: *радиоактивность, фактор переноса, эффективная доза, Мкужу-Ривер, Танзания*

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