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

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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 226Ra, 232Th and 40K 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 226Ra and 232Th, respectively, between values determined in soils and plants. Implicit in these findings 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 (Bq kg⁻¹) for 226Ra (2.15 ± 0.02), 232Th (1.43 ± 0.02) and 40K (198.16 ± 1.72) and the roots of cabbage had the highest values for 226Ra (1.38 ± 0.04), 232Th (1.34 ± 0.03) and 40K (146.12 ± 1.02) among the food crops, an indication of a higher ability to uptake radionuclides from soil. Similarly, since the TFs were found higher in wild grass for 226Ra (0.0533 ± 0.04), 232Th (0.0374 ± 0.002) and 40K (0.5297 ± 0.05) and cabbage for 226Ra (0.0362 ± 0.03), 232Th (0.0360 ± 0.001) and 40K (0.4173 ± 0.05).

**Practical implications.** It is evident that these plants can serve as good bio indicators to assess release of radio nuclides from inside the mining site to the public domain. Moreover, the annual effective dose (mSv y⁻¹) for 40K (0.23 ± 0.02), 226Ra (0.046 ± 0.004) and 232Th (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

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**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, Segu-
via, Cervantes, Herrera, Perez-Silva, & Acosta, 2000; Santos, Lauria, Amaral, & Rochedo, 2002; Ababneh, Masa‘deh, Ababneh, Awawdeh, & Alyassim, 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.

\[ TF = \frac{A_{\text{plant}}(\text{dryweight})}{A_{\text{soil}}(\text{dryweight})}. \]

(1)

However, as shown in Figure 1, the TFs 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 TFs 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 TFs for \(^{232}\text{Th}, {^{226}\text{Ra}}\) and \(^{40}\text{K}\) 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′ 60″ 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 km² 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 (cucumber sativus), papaya (carica papaya), maize (zea mays), beans, carrot, banana, and mango (mangifera indica). 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 being dried under sun for more than one month. Since the 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 pestle 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 in 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 226Ra, 232Th 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 226Ra and 232Th 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 & Jacquem, 1990; Bruzzi, Baroni, Mele, & Nanni, 1997).

The radioactivity of 226Ra was obtained from an average of the gamma emitting lines (keV) of its two progenies: 214Bi (609.3, 1120.3 and 1764.5) and 214Pb (295.2 and 351.9). Similarly, the radioactivity of 232Th was determined from an average of gamma line (keV) of its three progenies: 228Pb (238.63), 228Tl (583.2) and 228Ac (338.4, 911 and 969). However, the radioactivity of 40K 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:

\[
SA = \frac{R_s - R_b}{\eta \rho w},
\]

where:
- \( \eta \) – 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 226Ra, 232Th and 40K, 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 (226Ra, 232Th and 40K) those expected to be predominant contributors to radiation dose through ingestion of food crops. Therefore, the annual internal effective dose (\( E_D \), \( \mu Sv/\text{y} \)) 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 (\( SA \), \( \text{Bqkg}^{-1} \)) which was determined in food, dose conversion factor (\( DCF \), \( \text{SvBq}^{-1} \)) relevant to each radionuclide for an individual adult (>17 years) and consumption rate (\( CR \), \( \text{kgy}^{-1} \)) of relevant food:

\[
E_D = SA \cdot CR \cdot DCF, \quad \text{(3)}
\]

The \( DCF \) for 226Ra (2.25⋅10⁻³), 232Th (3.69⋅10⁻³) and 40K (5.90⋅10⁻⁴) 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 226Ra, 232Th and 40K 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 (Bq kg^-1 dry weight) of 226Ra, 232Th and 40K in soils, plants, fruits and cereals, and soil-to-plant transfer factors in samples from MRP

| Species          | Plant Parts | Soil 226Ra  | Soil 232Th  | Soil 40K  | Plant 226Ra | Plant 232Th | Plant 40K | TFs          |
|------------------|-------------|-------------|-------------|-----------|-------------|-------------|-----------|--------------|
| Wild Grass (Concession) | Root        | 3070.50     | 143.50      | 1307.88   | 12.55       | 10.56       | 214.15    | 0.0041       | 0.0736       | 0.1637       |
|                  | Stem        | —           | —           | —         | —           | 9.83        | 184.36    | 0.0040       | 0.0685       | 0.1410       |
|                  | Leaf        | —           | —           | —         | 12.34       | 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        | 1.26        | 135.18    | 0.0362       | 0.0338       | 0.3861       |
|                  | Stem        | —           | —           | —         | 1.27        | 1.24        | 135.18    | 0.0372       | 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    | 1.38        | 1.34        | 146.12    | 0.0362       | 0.0360       | 0.4173       |
|                  | Stem        | —           | —           | —         | 1.27        | 1.24        | 135.18    | 0.0372       | 0.0338       | 0.3861       |
|                  | Leaf        | —           | —           | —         | 1.35        | 1.33        | 145.83    | 0.0354       | 0.0357       | 0.4165       |
| Beans            | Root        | 34.14       | 32.08       | 462.55    | 1.38        | 1.34        | 146.12    | 0.0362       | 0.0360       | 0.4173       |
|                  | Stem        | —           | —           | —         | 1.27        | 1.24        | 135.18    | 0.0372       | 0.0338       | 0.3861       |
|                  | Leaf        | —           | —           | —         | 1.35        | 1.33        | 145.83    | 0.0354       | 0.0357       | 0.4165       |
| Maize            | Root        | 29.58       | 28.86       | 486.52    | 0.43        | 0.42        | 46.12     | 0.0133       | 0.0135       | 0.1309       |
|                  | 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       |
| 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 40K radionuclide in all of the soils analysed was considerably higher than that of 226Ra and 232Th. In the vicinity a maximum value for 40K (486.52 ± 23.44 Bq kg^-1) was approximately 12 and 13 times higher than the maximum values for 226Ra (40.35 ± 2.34 Bq kg^-1) and 232Th (38.19 ± 2.18 Bq kg^-1), respectively. However, all values of radionuclides recorded in the vicinity were comparable with the typical ranges for 226Ra (16 to 110), 232Th (11 to 64) and 40K (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 Bq g^-1 and for 40K exceeding 10 Bq g^-1 requires a regulatory control to reduce the risk of radiation exposure of public. However, values of 226Ra, 232Th and 40K found in soils 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 226Ra, 232Th and 40K that present on soil (Kabata-Pendias, 2011).

The wild grass growing in the concession with enriched natural radionuclides of 226Ra and 232Th 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.

3.1.2. Radioactivity in plants

It is apparently in Table 1 that all plants, fruits and cereal samples investigated contained traces of 226Ra, 232Th and 40K above their minimum detectable radioactivity. However, values of 226Ra, 232Th and 40K 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 226Ra, 232Th and 40K that present on soil (Kabata-Pendias, 2011).

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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 ²²⁶Ra (2.15 ± 0.02), ²³²Th (1.43 ± 0.02) and ⁴⁰K (198.16 ± 1.72) were found in the roots of wild grass and the minimum values for ²²⁶Ra (0.25 ± 0.01), ²³²Th (0.28 ± 0.03) and ⁴⁰K (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 ⁴⁰K in all plants species were relatively higher than those of ²²⁶Ra and ²³²Th. 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 ⁴⁰K 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 ²²⁶Ra in all samples were slightly higher in relation to those of ²³²Th indicating that ²²⁶Ra is relatively mobile and the two radionuclides originate from different natural decay series.

In order to assess a relation between values of radioactivity for ²²⁶Ra, ²³²Th and ⁴⁰K found in soils and plants data obtained in this study were tested using a Pearson’s correlation coefficient (r) and coefficient of determination (R²). The r has indicated a strong positive correlation (r = 0.947) between values of ²²⁶Ra in soils and plants species as well as a strong positive correlation (r = 0.950) between values of ²³²Th in soils and plant species. Implicit it is that the dependence of radioactivity values in plants species on soil radioactivity. In addition, the coefficient of determination (R²) 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 ²²⁶Ra and ²³²Th, 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 ²²⁶Ra, ²³²Th and ⁴⁰K in vegetable, fruit and cereal was determined using Equations (1) and presented in Table 1. Table 1 shows the values of ²²⁶Ra in vegetable, fruit and cereal were relatively higher than those for ²³²Th, and both radionuclides were substantially lower than the values of ⁴⁰K. In general, the values for ²²⁶Ra, ²³²Th and ⁴⁰K in vegetable, fruit and cereal samples varied consistently in the order: banana > carrot > onion > tomatoes > cucumber > papaya > rice > maize > beans. As expected the radioactivity of ⁴⁰K was found higher than those of ²²⁶Ra and ²³²Th 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 ²²⁶Ra (0.59 ± 0.01), ²³²Th (0.54 ± 0.01) and ⁴⁰K (87.32 ± 1.20) and mug beans has the lowest for ²²⁶Ra (0.19 ± 0.02), ²³²Th (0.17 ± 0.01) and ⁴⁰K (38.22 ± 0.68). In this case, carrot could serve as good bio-indicator and phytoremediation of soil contaminated with ²²⁶Ra, ²³²Th and ⁴⁰K, and to assess radioactivity exposure through ingestion.

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

Transfer factors (TFs) of ⁴⁰K, ²²⁶Ra and ²³²Th 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 TFs vary widely, mainly as a result of different species, parts of plant and type of radionuclide. The highest TFs for ²²⁶Ra (0.0533 ± 0.04), ²³²Th (0.0374 ± 0.002) and ⁴⁰K (0.5297 ± 0.05) were found in the roots of wild grass and the lowest values of TFs for ²²⁶Ra (0.0085 ± 0.0001), ²³²Th (0.0097 ± 0.0001) and ⁴⁰K (0.0766 ± 0.02) were found on the pod of maize. Also the roots of cabbage presented the highest TFs for ²²⁶Ra (0.0362 ± 0.03), ²³²Th (0.0360 ± 0.001) and ⁴⁰K (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 TFs 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 TFs for different species of plants varied in the order: wild grass > cabbage > beans > maize. The TFs values for ²²⁶Ra, ²³²Th and ⁴⁰K were maximum in the roots of wild grass and were minimum in the pod of maize. In general, the TFs across all plant species for the three radionuclides in the samples investigated varied as follows: ⁴⁰K > ²²⁶Ra > ²³²Th. The values of ⁴⁰K were significantly higher than the values of ²²⁶Ra and ²³²Th, which also implied higher levels of ⁴⁰K uptake by plants. In this case, the roots of wild grass and cabbage with relatively higher TFs were considered sensitive for absorbing the ²²⁶Ra and ²³²Th from soil and for the purposes of assessment of radioactive releases offsite the mining site, the TFs of wild grass and cabbage could serve as better indicators.

3.2. Annual effective dose

The potential effective dose (ED) 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 ⁴⁰K, ²²⁶Ra and ²³²Th ranged from 9.50·10⁻³ to 8.64·10⁻² mSv y⁻¹ with an average of 9.50·10⁻³ ± 2.86·10⁻³ mSv y⁻¹.
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 mSv\(^{-1}\), of which 0.17 mSv\(^{-1}\) is from \(^{40}\)K and 0.12 mSv\(^{-1}\) is from \(^{238}\)U and \(^{232}\)Th series. The aforesaid upper bound, the annual effective dose obtained from this study of 0.35 mSv\(^{-1}\) is relatively high (about 21\%) largely due to the contribution from \(^{40}\)K (0.23 ± 0.02 mSv\(^{-1}\)) which is homeostatically controlled in the human body. The contribution of \(^{226}\)Ra (0.046 ± 0.004 mSv\(^{-1}\)) and \(^{232}\)Th (0.073 ± 0.006 mSv\(^{-1}\)) 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 (Bq kg\(^{-1}\)) 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 indicates 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 \(T_{FS}\) for \(^{226}\)Ra (0.053 ± 0.04), \(^{232}\)Th (0.037 ± 0.002) and \(^{40}\)K (0.5297 ± 0.05) and roots of cabbage had the highest \(T_{FS}\) for \(^{226}\)Ra (0.0362 ± 0.03), \(^{232}\)Th (0.036 ± 0.001) and \(^{40}\)K (0.4173 ± 0.05) for the edible plants investigated. The lowest \(T_{FS}\) 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 (mSv\(^{-1}\)) 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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### REFERENCES

Ababneh, A.M., Masa’deh, M.S., Ababneh, Z.Q., Awawdeh, M.A., & Alyassim, A.M. (2009). Radioactivity Concentrations in Soil and Vegetables from the Northern Jordan Rift Valley and the Corresponding Dose Estimates. *Radiation Protection Dosimetry*, 134(1), 30-37.

Adriano, D.C., Boswell, A.C., Ciravolo, T.G., Pinder, III, J., & McLeod, K.W. (2000). Radionuclide Content of Selected Root Vegetables as Influenced by Culinary Preparation. *Journal of Environmental Radioactivity*, 49(3), 307-317. https://doi.org/10.1016/s0265-931x(99)00116-2

Ahmedali, S.T. (1989). X-ray Fluorescence Analysis in Geo- logical Sciences. *Advance Methodology. Geological Association of Canada Short Course*, (7).

Bacza, A., Barandica, J., Paniagua, J.M., Rufu, M., & Sterling, A. (1999). Using 226Ra/228Ra Disequilibrium to Determine

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| Food crop | Annual Radioactivity (Bq kg\(^{-1}\)) | Annual Effective Dose (mSv\(^{-1}\)) | Total Annual Effective Dose (mSv\(^{-1}\)) |
|-----------|----------------------------------|----------------------------------|----------------------------------|
|           | \(^{226}\)Ra | \(^{232}\)Th | \(^{40}\)K | \(^{226}\)Ra | \(^{232}\)Th | \(^{40}\)K | | |
| Banana    | 30 | 1.07 | 0.66 | 139.00 | 7.22E-03 | 1.17E-02 | 2.46E-02 | 4.36E-02 | 3.46 E-01 |
| Carrot    | 20 | 0.65 | 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 | 0.21 | 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 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 Residence Half-Lives of Radium in Vegetation Compartments. *Journal of Environmental Radioactivity*, 43(3), 291-304. https://doi.org/10.1016/s0265-931x(98)00047-2

Baker, A., McGrath, S., Reeves, R., & Smith, J. (1999). Metal Hyperaccumulator Plants. A Review of the Ecology and Physiology of a Biological Resource for Phytoremediation of Metal-Polluted Soil. *Phytoremediation of Contaminated Soil and Water*, 85-108. https://doi.org/10.2307/781439822654.ch5

Banzi, F.P., Msaki, P.K., & Mohammed, N.K. (2015). Distribution of Heavy Metals in Soils in the Vicinity of the Proposed Mkju Uranium Mine in Tanzania. *Environment and Pollution*, 4(3), 42-50. https://doi.org/10.5539/ep.v4n3p42

Basu, P., Sarangapani, R., Sivasubramanian, K., & Venkatraman, B. (2015). Estimation of Annual Effective Dose Rate due to the Ingestion of the Primordial Radionuclide $^{40}K$ for the Population around the Kalpakkam Nuclear Site, Tamil Nadu, India. *Radiation Protection and Environment*, 38(1), 14-22. https://doi.org/10.4103/0972-0464.162827

Bersimbaev, R.I., & Bulgakov, O. (2015). The Health Effects of Radon and Uranium on the Population of Kazakhstan. *Genes and Environment*, 37(1). https://doi.org/10.1080/14109851.2015.991937

Bruzzi, L., Baroni, M., Mele, R., & Nanni, E. (1997). Proposal for a Method of Certification of Natural Radioactivity in Building Materials. *Journal of Radiological Protection*, 17(2), 85-94. https://doi.org/10.1080/0952-4746.172.005

Canet, A., & Jacqueuen, R., (1990). Methods for Measuring Radium Isotopes. Gamma Spectrometry the Environmental Behavior of Radium. *IAEA Technical Report, (1), 189-204.

Chakraborty, S.R., Azim, R., Rahman, A.K.M.R., & Sarker, R. (2013). Radioactivity Concentrations in Soil and Transfer Factors of Radionuclides from Soil to Grass and Plants in the Chittagong City of Bangladesh. *Journal of Physical Science*, 24(1), 95-113.

Cochrane, N., & D’Souza, A. (2015). Measuring Access to Food in Tanzania: A Food Basket Approach. *Amber Waves*, 13-24.

Eriksson, A., (1977). Metal Hyperaccumulator Plants. A Review of the Ecology and Physiology of a Biological Resource for Phytoremediation of Metal-Polluted Soil. *Phytoremediation of Contaminated Soil and Water*, 85-108. https://doi.org/10.2307/781439822654.ch5

F. Banzi, P. Msaki, N. Mohammed. (2017). Mining of Mineral Deposits,11(3), 93-100

Gaso, M.I., Segovia, N., Cervantes, M.L., Herrera, T., Perez-Silva, E., & Acosta, E. (2000). Internal Radiation Dose from $^{137}Cs$ due to the Consumption of Mushrooms from a Mexican Temperate Mixed Forest. *Radiation Protection Dosimetry*, 87(3), 213-216. https://doi.org/10.1093/oxfordjournals.rpd.a033000

IAEA (International Atomic Energy Agency). (1994). *Handbook of Parameter Values for Predicting of Radionuclide Transfer in Terrestrial Environments*. Technical Report Series No. 364, Vienna.

IAEA (International Atomic Energy Agency). (2007). *Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments*. Technical Reports Series No. 472, Vienna.

ICRP (International Committee of Radiological Protection). (1996). *Age Dependent Doses to Members of Public from Intake of Radionuclides: Compilation of Ingestion and Inhalation Coefficients*. ICRP Publication, Elsevier Science.

ICRP (International Committee of Radiological Protection). (2012). *Compendium of Dose Coefficients Based on ICRP Publication*. ICRP Publication, Annals of the ICRP.

ICRP (International Committee of Radiological Protection). (2007). *The 2007 Recommendations of the International Commission on Radiological Protection*. ICRP Publication, Annals of the ICRP.

IUR (International Union of Radioecologists). (1994). *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial Environments*. Technical Reports Series No. 364, Vienna.

Jagetiya, B., Sharma, A., Sinha, A., & Khaitik, U.K. (2014). Phytoremediation of Radionuclides: A Report on the State of the Art. *Radionuclide Contamination and Remediation Through Plants*, 1-31. https://doi.org/10.1007/978-3-319-07665-2_1

Kabata-Pendias, A., & Pendias, H. (1992). *Trace Elements in Soil and Plants*. London: CRC Press, Taylor & Francis Group.

Kabata-Pendias, A. (2011). *Trace Elements in Soils and Plants*. London: CRC Press, Taylor & Francis Group.

Kabata-Pendias, A. (1977). *Factors of Radionuclides from Soil to Grass and Plants in the Vicinity of the Proposed Mkju Uranium Mine in Tanzania: A Food Basket Approach*. https://doi.org/10.1007/978-3-319-07665-2_1

Kabata-Pendias, A., & Pendias, H. (1992). *Trace Elements in Soil and Plants*. London: CRC Press, Taylor & Francis Group.

Kabata-Pendias, A. (2011). *Trace Elements in Soils and Plants*. London: CRC Press, Taylor & Francis Group.

Linsalata, P., Morse, R.S., Ford, H., Eisenbud, M., Franca, E.P., de Castro, M.B., & Carlos, M. (1989). An Assessment of Soil-to-plant Concentration Ratios for Some Natural Analogues of the Transuranic Elements. *Health Physics*, 56(1), 33-46. https://doi.org/10.1097/00004032-198901000-00003

Manigandgan, P.K., & Manikandan, N.M. (2008). Migration of Radionuclide in Soil and Plants in the Western Ghats Environment. *Iranian Journal of Radiation Research*, 6(1), 7-12.

Mohammed, N.K., & Mazunga, M.S. (2013). Natural Radioactivity in Soil and Water from Likuyu Village in the Neighborhood of Mkju Uranium Deposit. *International Journal of Analytical Chemistry*, 1-4. https://doi.org/10.1155/2013/501856

Mortvedt, J.J. (1994). Plant and Soil Relationships of Uranium and Thorium Decay Series Radionuclides a Review. *Journal of Environmental Quality*, 23(4), 643-650. https://doi.org/10.2134/jeq1994.00472425002300004004x

MSL (Mantra Resources Limited). (2010). NI 43 – 101 Technical Report on Resources Update of the Mkju River Project.

Ng, Y.C., Colshier, C.S., & Thompson, S.E. (1979). *Transfer Factors for Assessing the Dose from Radionuclides in Agricultural Products*. Livermore: Lawrence Livermore Laboratory.

Nielsen, O.J. (1981). *A Literature Review on Radioactivity Transfer to Plants and Soil*. Roskilde: Riso National Laboratory.

Santos, E.E., Lauria, D.C., Amaral, E.C.S., & Rochedo, E.R. (2002). *Estimation of Annual Effective Dose Rate due to the Ingestion of Radionuclides from Soil in Tanzania: A Food Basket Approach*. https://doi.org/10.2307/781439822654.ch5

Shaw, G., & Bell, J.N.B. (1994). *Plants and Radioelements*. In *Plants and the Chemical Elements*. Biochemistry, Uptake, Tolerance and Toxicity. Weinheim: VCH.

TFC (Tanzania Food Composition Tables). (2008). Compiled by Muhimbili University of Health and Allied Sciences (MUHAS), Dar es Salaam; Tanzania Food and Nutrition Centre (TFNC), Dar es Salaam; and the Harvard School of Public Health (HSPH), Boston, MA.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation Sources, Effects and Risks of Ionization Radiation). (2000). *Report to the General Assembly, with Scientific Annexes B: Exposures from Natural Radiation Sources*. New York.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation Sources, Effects and Risks of Ionization Radiation). (2013). *Attachment C-13. Methodology for the Assessment of Dose from Ingestion of Radionuclide Transfer in Terrestrial and Freshwater Environments*. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2013 Report, Annex A. Levels and Effects of Radiation Exposure due to the Nuclear Accident
ABSTRACT (IN UKRAINIAN)

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

Методика. Для визначення радіоактивності використовувався детектор високочистого германия. 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 226Ra та 232Th, відповідно, між отриманими значеннями в ґрунтах та рослинах. Розподіл радіонуклідів у ґрунтах прямо пропорційний відповідним радіонуклідам рослин.

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

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

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

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