Measurement and spatial distribution pattern of natural radioactivity in a uranium tailings pond in Northwest China

Jinlong Yong\textsuperscript{a}, Qian Liu\textsuperscript{b}, Baoshan Wu\textsuperscript{a}, Henglei Chen\textsuperscript{a}, Guangwen Feng\textsuperscript{a}\textsuperscript{b} and Youhua Hu\textsuperscript{c}

\textsuperscript{a}Research Center of Radiation Ecology and Ion Beam Biotechnology, College of Physics Science and Technology, Xinjiang University, Urumqi, Xinjiang, PR China; \textsuperscript{b}School of Statistics and Data Science, Xinjiang University of Finance & Economics, Urumqi, Xinjiang, PR China; \textsuperscript{c}Radiation Environment Supervision Station of Xinjiang, Urumqi, Xinjiang, PR China

ABSTRACT
Numbers of radioactive tailings were produced in the process of uranium mining and milling. In this study, radiation environment monitoring was carried out on a decommissioned uranium mining and milling tailings pond in northwest China, and the governance effect and operation status of the tailings pond was investigated. The soil radionuclide activity concentration and ambient dose equivalent rate (H(10)) were measured, and soil surface radon exhalation rate was calculated. The results shown that in the tailings pond and its surrounding area, the average soil radionuclide activity concentration was respectively 238U: 42.64±11.17 Bq·kg\textsuperscript{-1}, 226Ra: 45.47±13.56 Bq·kg\textsuperscript{-1}, 232Th: 33.30±7.33 Bq·kg\textsuperscript{-1}, 40K: 631.33±72.05 Bq·kg\textsuperscript{-1}, the average H(10) was 63.32±6.46 nSv·h\textsuperscript{-1}, and the average radon exhalation rate was 40.46±11.29 mBq·m\textsuperscript{-2}·s\textsuperscript{-1}. Radionuclide activity concentration, H(10) and radon exhalation rate were within the range of world natural background. Spatial distribution of radioactivity was analyzed by OK interpolation based on the investigated data. According to the measured results and spatial interpolation analysis, the decommissioning governance effect of the uranium tailings reservoir is good, the operation is normal, and there is no migration or diffusion situation of radionuclides in the pond has been found.

1. Introduction
The continuous development and extensive utilization of nuclear energy have led to the increasing demand for uranium smelting products. However, a large number of radioactive contaminations will inevitably be produced in the process of uranium mining and milling (Craft et al., 2004; Jagetiya & Purohit, 2006; Portnov et al., 2017; Qin et al., 2020). The fine mineral slag produced in the process of uranium mining and milling is called uranium tailings which contain natural long-life radionuclides such as 238U, 226Ra, 232Th, 40K and some heavy metals associated with uranium mines (Dinis de & Fiúza, 2013; Landa, 2004; Laxman Singh et al., 2015; Momčilović et al., 2013; Zong et al., 2017). It is often hard to completely separate the long-life radionuclides and heavy metals in uranium tailings account for technical reasons and economic factors. Thus, most of the slag will be centrally managed through storage in the tailings pond, and the effect of the uranium tailings on the surrounding ecological environment safety and public health will be reduced through decommissioning governance of the tailings pond (Liu et al., 2020; Ouyang et al., 2020; Portnov et al., 2017). However, with the increase of decommissioning years, the tailings pond may be disturbed by natural or anthropogenic factors, resulting in the migration and diffusion of radionuclides in the uranium tailings pond, affecting the stability of the tailings pond and its surrounding soil quality, and having a persistent potential effect on the regional ecological environment and public health (Liu et al., 2020; Lou et al., 2018; Zong et al., 2017).

Due to the particularity, uranium tailings pond has been widely concerned and investigated all over the world (Carvalho et al., 2007; Momčilović et al., 2010). In this study, the investigation of the natural radioactivity levels in vertical profiles of the uranium tailings pond was conducted firstly, and then the spatial distribution pattern of the radionuclide, the ambient dose equivalent rate H(10) and the soil radon exhalation rate were analyzed. So, this work is of eminent importance to identify the decommissioning governance effect and operation status of the uranium tailings pond, and prevent environmental radioactive contamination.

2. Materials and methods
2.1. Overview of the study area
A uranium mining and milling tailings pond which is located in the northwest of China was taken as the object of investigation in this research. The tailings pond is...
2.2. Sampling

A storage pond of solid uranium tailings, the decommissioning governance work has been completed through surface soil covering, slope protection, and other projects more than a decade ago, as shown in Figure 1. The area where the tailings pond is located belongs to arid and semi-arid climate, with less surface soil and vegetation coverage, abundant sunshine, and less rain all year round, and far away from the surface water source. The average altitude of the tailings pond is 926 m, the terrain in the north is higher than in the south, and the terrain in the west is higher than in the east. The concrete slope protection is located in the northeast of the tailings pond, and the hills are in the southeast.

2.2. Sampling and sample pretreatment

Soil samples were collected at different depths of 0–5 cm, 5–15 cm, and 15–30 cm. Three equal amounts of soil were randomly collected near each sampling point and mixed evenly as soil samples at this point and put into a sampling bag marked in advance. The soil sampling points were calibrated by coordinate information, including 4 sampling points in the tailings pond (points 01–04) and 4 sampling points around the tailings pond (points 05–08), with a total of 24 (8 × 3) soil samples. The ambient dose equivalent rate H*(10) was measured in the field, according to the grid of 36 m × 56 m, a total of 24 measurement points (points 01–24) were set (points 01, 03, 04 to 08, 17, 21, 22, 24 are located in the surrounding area of the tailings pond, and points 02, 09 to 16, 18 to 20, 23 are located in the tailings pond). Soil sampling points and the ambient dose equivalent rate measurement points were shown in Figure 2.

The sample pretreatment was carried out according to the specifications. The soil samples after weed and gravel removal were placed in the blast drying oven, dried to constant weight at 105°C, then ground and sieved until the particle size was less than 80 mesh. After weighing with an electronic analysis balance, the pretreated samples were put into the cylindrical polyethylene sample container and sealed for 4 weeks to

Figure 1. Simplified map of uranium tailings ponds.

Figure 2. (a) is the sampling point of the soil sample, and (b) is the measurement point of the ambient dose equivalent rate.
ensure the radioactive nuclides uranium, radium, and their progenies reached the decay equilibrium (Ndontchueng et al., 2014).

2.3. Radioactivity measurements and calculation

2.3.1. Measurement of radionuclide activity concentration

In this research, the N-type high purity germanium (HPGe) γ spectrometer produced by ORTEC Company (model GMX40P4) was used to measure the activity concentration of natural radionuclides in samples. The crystal size of the detector is 42.4 mm × 73.2 mm, and the energy resolution at the peak of 1.33 MeV (60Co reference source) is 1.92 keV. Before the sample measurement, the soil mixing reference source (226Ra-60Co, 238U, 232Th, 40K) produced by Shanghai Institute of Measurement and Testing Technology was used to calibrate the energy and efficiency of the spectrometer. The measurement time of each sample is no less than 21600s, and the quality control is carried out by repeated measurement. Take average value of measurement was taken as the final measurement result.

The energy of the characteristic peaks selected by the radionuclides are respectively, 238U (63.29 keV and 92.6 keV), 226Ra (351.92 keV, 609.31 keV, and 1120.29 keV), 232Th (583.19 keV and 911.21 keV), and 40K (1460.22 keV), and the calculation formula of radionuclide activity concentration mentioned above was quoted from reference (Turhan & Varinlioğlu, 2012). The formula is as follows:

\[ A = \frac{N}{\varepsilon(E_p) \cdot P_y \cdot t \cdot M} \]  

(1)

Where \( A \) is the activity concentration of the radionuclide; \( N \) is the net count of the characteristic energy peak with energy \( E_p \); \( \varepsilon(E_p) \) is the detection efficiency of the characteristic energy peak with energy \( E_p \); \( P_y \) is the probability of the selected characteristic γ rays emitted by each decay of the radionuclide; \( t \) is the measurement time; \( M \) is the net weight of the sample.

2.3.2. Field measurement of ambient dose equivalent rate H\(^*(10)\)

The ambient dose equivalent rate H\(^*(10)\) (with the unit nSv·h\(^{-1}\)) was measured using the FH40G+FHZ672E-10 gamma dose rate detector, and the detection limit is 1 nSv·h\(^{-1}\) (UNSCEAR, 2013). The detector was preheated for 10 min before measurement, then it was moved to the measuring point and placed the sensitive area center of the detector probe at 1 m above ground. And it was read once every 10 s after the measured data stabilized, and the average value as the measurement result at the measuring point (Jónás et al., 2017).

The ambient dose equivalent rate H\(^*(10)\) (nSv·h\(^{-1}\)) was reported by Sanada et al. to be equivalent to the absorbed dose rate in air (nGy·h\(^{-1}\)) (Sanada et al., 2020). In this research, H\(^*(10)\) after deducting the contribution of cosmic rays is considered as the absorbed dose rate in air caused by terrestrial components, while the contribution of other gamma radiation sources in the air is considered negligible (Jónás et al., 2018; UNSCEAR, 2000). The theoretical formula for calculating the absorbed dose rate in air caused by the component of the cosmic rays is as follows:

\[ D_C = D_C(0) \cdot \left[ 0.21 e^{-1.649h} + 0.79 e^{0.4528h} \right] \]  

(2)

\[ D_C(0) = \begin{cases} 32, \lambda_m \leq 30^\circ N & 30, \lambda_m > 30^\circ N \end{cases} \]  

(3)

Where \( D_C(0) \) is the absorbed dose rate in air caused by cosmic rays’ ionization component at sea level; \( h \) is the altitude of the measuring point with the unit of km; \( \lambda_m \) is the geomagnetic latitude of the measuring point with the unit of N; \( \lambda \) and \( \varphi \) are the latitude and longitude of the measuring point respectively (UNSCEAR, 2000).

2.3.3. Calculation of radon exhalation rate

The radon exhalation rate of the tailings pond is calculated by a theoretical model, and its formula is as follows:

\[ F = R \cdot p \cdot \varepsilon \cdot \left( \frac{T}{273} \right)^{0.75} \cdot \sqrt{\lambda \cdot D_0 \cdot \rho \cdot \exp\left(-65p - 6514\varphi\right)} \]  

(4)

Where \( F \) is the radon exhalation rate in Bq·m\(^{-2}\)·s\(^{-1}\); \( R \) is the activity of 226Ra in soil, the unit is Bq·kg\(^{-1}\); \( p \) is the bulk density of soil, the unit is kg·m\(^{-3}\); \( \varepsilon \) is the emanation coefficient of radon in the soil; \( T \) is soil temperature in K; \( \lambda \) is the decay constant of radon, with the value of 2.6 × 10\(^{-6}\) s\(^{-1}\); \( D_0 \) is the diffusion coefficient of radon in free air, with the value of 1.1 × 10\(^{-5}\) m\(^2\)·s\(^{-1}\); \( \rho \) is the soil porosity; \( S \) is the water saturation of soil (IAEA, 2013; Zhuo et al., 2006).

\[ \varepsilon = \varepsilon_0 [1 + a(1 - \exp(-bS))] [1 + c(T - 298)] \]  

(5)

Where \( \varepsilon_0 \) is the emanation coefficient of radon at 298 K, \( a, b, \) and \( c \) are constants. For clay, \( \varepsilon_0, a, b, \) and \( c \) are 0.10, 1.85, 18.8, and 0.012 respectively (Zhuo et al., 2008).

3. Result and discussions

3.1. Soil radionuclide activity concentration

Table 1 summarizes the soil radionuclide activity concentration at different depths vertical profile of uranium tailings pond and its surrounding areas. In the tailings pond, the activity concentration range of radionuclide 238U, 226Ra, 232Th and 40K at the depth of 0–5 cm profile is 35.27–50.06 Bq·kg\(^{-1}\), 36.24–50.78 Bq·kg\(^{-1}\), 34.06–42.98 Bq·kg\(^{-1}\) and 534.10–720.24 Bq·kg\(^{-1}\) respectively. At the depth of 5–15 cm,
Table 1. Soil radionuclide activity concentration of the uranium tailings pond and its surrounding area.

| Radionuclide (Bq·kg⁻¹) | Inside the uranium tailings pond (n = 12) | Vertical profile depth (cm) | The area around the uranium tailings pond (n = 12) |
|-------------------------|------------------------------------------|-----------------------------|-----------------------------------------------|
|                         | 0–5                                      | 5–15                        | 15–30                                        |
| 238U                    | Range 35.27–50.06                        | 30.22–55.82                 | 34.10–61.39                                   |
|                         | Mean±SD 40.30 ± 6.62                    | 43.11 ± 10.52               | 43.24 ± 9.79                                  |
| 226Ra                   | Range 36.24–50.78                       | 33.00–74.72                 | 37.58–59.37                                   |
|                         | Mean±SD 40.79 ± 7.71                    | 44.78 ± 20.08               | 45.92 ± 10.27                                 |
| 212Th                   | Range 34.06–42.98                       | 29.09–36.65                 | 33.95–35.60                                   |
|                         | Mean±SD 37.40 ± 4.15                    | 33.69 ± 3.35                | 34.65 ± 1.07                                  |
| 40K                     | Range 534.10–720.24                     | 533.38–668.26               | 525.65–698.22                                 |
|                         | Mean±SD 637.91 ± 84.69                  | 605.89 ± 64.75              | 613.70 ± 87.94                                |

* n Number of soil samples.

238U is 30.22–55.82 Bq·kg⁻¹, 226Ra is 33.00–74.72 Bq·kg⁻¹, 232Th is 29.09–36.65 Bq·kg⁻¹ and 40K is 533.38–668.26 Bq·kg⁻¹. At the depth of 15–30 cm, 238U is 34.10–61.39 Bq·kg⁻¹, 226Ra is 37.58–59.37 Bq·kg⁻¹, 232Th is 33.95–35.60 Bq·kg⁻¹ and 40K is 525.65–698.22 Bq·kg⁻¹. In the area around the tailings pond, the activity concentration range of radionuclide 238U, 226Ra, 232Th and 40K at the depth of 0–5 cm profile is 38.56–77.01 Bq·kg⁻¹, 39.42–73.34 Bq·kg⁻¹, 20.38–40.33 Bq·kg⁻¹ and 548.45–771.68 Bq·kg⁻¹ respectively. At the depth of 5–15 cm, 238U is 29.10–48.14 Bq·kg⁻¹, 226Ra is 28.81–57.44 Bq·kg⁻¹, 232Th is 19.31–43.70 Bq·kg⁻¹ and 40K is 520.61–728.59 Bq·kg⁻¹. At the depth of 15–30 cm, 238U is 32.82–55.56 Bq·kg⁻¹, 226Ra is 27.94–63.56 Bq·kg⁻¹, 232Th is 21.04–48.77 Bq·kg⁻¹ and 40K is 573.81–682.52 Bq·kg⁻¹. The soil radionuclides in uranium tailings pond and surrounding areas are all within the range of Chinese soil natural radionuclides activity concentration in the UNSCEAR (2000) report (238U: 2–690 Bq·kg⁻¹, 226Ra: 2–440 Bq·kg⁻¹, 232Th: 1–360 Bq·kg⁻¹, 40K: 9–1800 Bq·kg⁻¹) (UNSCEAR, 2000).

The boxplot of soil radionuclide activity concentration inside and around the uranium tailings pond is shown in Figure 3. Although there are differences in the concentrations of radionuclide 238U, 226Ra, 232Th, and 40K inside and surrounding areas of the tailings pond, the results of one-way ANOVA show that the differences are not significant (p < 0.05).

The correlation between different radionuclides is present in Figure 4(a). Among the four radionuclides, only 238U and 226Ra show a strong positive correlation. It conforms to the theory that 226Ra is the decay progeny of 238U and is in the same decay series. Statistical tests prove that there is no significant difference between the activity concentration of 238U and 226Ra in the soil of the study area (p < 0.05). The results indicate that uranium and radium in the tailings pond and its surrounding area are in a state of decay equilibrium.

Table 2 shows soil radionuclide activity concentrations from some countries or regions in the references. In contrast, the radionuclide activity of uranium tailings pond is in the natural soil radionuclide activity concentration in these countries and regions (238U: 0.58–88.1, 226Ra:6.81–265.58 Bq·kg⁻¹, 232Th: 7–404 Bq·kg⁻¹, 40K: 3.35–30.031 Bq·kg⁻¹, 137Cs: 0.05–8.62 Bq·kg⁻¹) (JOURNAL OF RADIATION RESEARCH AND APPLIED SCIENCES 2003, 2008, 2009).
3.2. Ambient dose equivalent rate $H^{*}(10)$

The average values of $H^{*}(10)$ in the study area after deducting the absorbed dose rate in air caused by the component of cosmic rays are presented in Table 3. The maximum and minimum values appear at point 07 and point 24 respectively, and the range of $H^{*}(10)$ is from 53.34 to 81.40 nSv·h$^{-1}$. The average value is 64.12 ± 7.45 nSv·h$^{-1}$, slightly lower than the average absorbed dose rate in air caused by outdoor terrestrial radiation in China (69.9 nGy·h$^{-1}$), and within the range of the absorbed dose rate in air caused by outdoor terrestrial radiation (12.7–1300 nGy·h$^{-1}$) (UNSCEAR, 2008). The average $H^{*}(10)$ inside the uranium tailings pond is 63.32 ± 6.46 nSv·h$^{-1}$, and the average $H^{*}(10)$ around the uranium tailings pond is 65.07 ± 8.46 nSv·h$^{-1}$, without significant difference (p < 0.05).

Table 3. $H^{*}(10)$ of the uranium tailings pond and its surrounding area.

| Measurement point | $H^{*}(10)$ (the contribution of cosmic rays has been deducted) (nSv·h$^{-1}$) | Measurement point | $H^{*}(10)$ (the contribution of cosmic rays has been deducted) (nSv·h$^{-1}$) |
|-------------------|----------------------------------|-------------------|----------------------------------|
| 01                | 72.83 ± 1.52                     | 13                | 60.83 ± 0.57                     |
| 02                | 69.83 ± 1.15                     | 14                | 61.49 ± 1.52                     |
| 03                | 68.49 ± 1.52                     | 15                | 68.49 ± 2.08                     |
| 04                | 66.16 ± 3.60                     | 16                | 55.03 ± 0.55                     |
| 05                | 65.49 ± 3.05                     | 17                | 56.06 ± 1.47                     |
| 06                | 63.16 ± 1.00                     | 18                | 56.93 ± 0.40                     |
| 07                | 54.89 ± 1.55                     | 19                | 58.79 ± 0.66                     |
| 08                | 56.79 ± 0.11                     | 20                | 57.23 ± 0.40                     |
| 09                | 57.19 ± 0.21                     | 21                | 56.56 ± 0.78                     |
| 10                | 65.16 ± 1.00                     | 22                | 74.49 ± 1.52                     |
| 11                | 64.83 ± 0.57                     | 23                | 78.16 ± 1.00                     |
| 12                | 67.16 ± 1.00                     | 24                | 80.83 ± 0.57                     |
| Range             |                                  |                   | 53.34–81.40                      |
| Mean±SD           |                                  |                   | 64.12 ± 7.45                     |
3.3. Soil radon exhalation rate

The calculated radon exhalation rate on the soil surface at each point in the study area is summarized in Table 5. The average radon exhalation rate is 40.46 ± 11.29 mBq·m⁻²·s⁻¹. The highest and lowest radon exhalation rates are 65.02 and 28.41 mBq·m⁻²·s⁻¹, corresponding to point 07 and point 03, respectively. The calculated soil radon exhalation rates are within the world average range of soil radon exhalation rate as reported in the UNSCEAR (1982) report, 0.2–70 mBq·m⁻²·s⁻¹ (UNSCEAR, 1982).

| Sampling point | Radon exhalation rate (mBq·m⁻²·s⁻¹) |
|----------------|-------------------------------------|
| 01             | 31.20 ± 2.03                        |
| 02             | 43.73 ± 2.15                        |
| 03             | 28.78 ± 0.44                        |
| 04             | 36.79 ± 0.36                        |
| 05             | 51.72 ± 1.18                        |
| 06             | 33.94 ± 1.28                        |
| 07             | 63.16 ± 1.86                        |
| 08             | 34.36 ± 0.03                        |
| Range          | 28.41–65.02                          |
| Mean±SD       | 40.46 ± 11.29                       |

Table 5. Radon exhalation rate on the soil surface of the uranium tailings pond and its surrounding area.

In Table 6, the estimated soil radon exhalation rate of uranium tailings pond is compared with the measured results of some countries or regions. The range of radon exhalation rates in these countries or regions is from 3.2 to 2100 mBq·m⁻²·s⁻¹, and the soil radon exhalation rate in tailings pond and its surrounding areas is within this range (Jasaitis & Girgiždys, 2007; Shweikani & Hushari, 2005; Vasidov, 2014; Zhang et al., 2015).

3.4. Spatial distribution of radiation in the study area

To further analyze the radiation distribution pattern of the environment and soil in the tailings pond and its surrounding area, the spatial distribution of radionuclides, H*(10), and radon exhalation rate in the uranium tailings pond and its surrounding area were predicted by the Ordinary Kriging (OK) spatial interpolation method in the study.

The distribution characteristics of soil radionuclides in the vertical profile of the study area are shown in Figure 5, the spatial distribution pattern between ²³⁵U and ²²⁶Ra is roughly similar, other radionuclides do not show relatively similar distribution pattern. ²³⁸U has the highest activity concentration in the northwest of the study area, ²²⁶Ra has higher activity concentration in the west and east of the study area, ²³²Th and ⁴⁰K has higher activity concentrations in the northeast and southeast of the study area, respectively. In the vertical profile within 0 to 30 cm, the activity concentration of radionuclides ²³⁸U, ²²⁶Ra, and ⁴⁰K decreased with the increase of soil depth, in contrast, the activity concentration of ²³²Th in the northeast direction of the study area increased with the increase of soil depth.

Figure 6 shows the spatial distribution of H*(10) (the contribution of cosmic rays has been deducted) and soil radon exhalation rate in the study area. The ambient equivalent dose rate is higher in the northeast and south of the study area, and the soil radon exhalation rate is higher in the east of the study area but lower in the tailings pond.

Table 4. Comparison of H*(10) or absorbed dose rate in air from some countries or regions in the world.

| Countries/regions | H*(10) (nSv h⁻¹) | Absorbed dose rate in air (nGy h⁻¹)¹ | References               |
|-------------------|------------------|--------------------------------------|--------------------------|
| Ondo, Nigeria     | -                | 56.82–140.17                        | Aladeniyi et al., 2019   |
| Mojokvar, Montenegro | -              | 57.00–74.67                          | Antović et al., 2012     |
| Rize, Turkey      | -                | 10.7–156.4                           | Durusoy & Yildirim, 2017 |
| Pahang, Malaysia  | -                | 26–750                               | Gabdo et al., 2015       |
| Cameroon          | -                | 81.92–112.96                         | Ndotchuen et al., 2014   |
| Qingdao, China    | -                | 13.4–433.2                           | Qu et al., 2008          |
| Mamuju, Indonesia | 51–176           | -                                    | Shilfa et al., 2020      |
| Xinjiang, China   | 53.34–81.40      | -                                    | Present study            |
|                   | 93.18–121.24     | -                                    |                          |

Table 6. Comparison of radon exhalation rate from some countries or regions in the world.

| Countries/regions | Radon exhalation rate (mBq·m⁻²·s⁻¹) | References               |
|-------------------|-------------------------------------|--------------------------|
| Vilnius, Lithuania | 11.6–82.7                           | Jasaitis & Girgiždys, 2007 |
| Syria             | 20–2100                             | Shweikani & Hushari, 2005 |
| Czech             | 3.5–208.3                           | Vasidov, 2014            |
| Japan             | 120–160                            | Vasidov, 2014            |
| Beijing, China    | 3.2–112.0                           | Zhang et al., 2015       |
| Xinjiang, China   | 28.41–65.02                         | Present study            |

Notes:

¹H*(10) without deducting the contribution of cosmic rays.

²The absorbed dose rate in air reported in the references is all calculated by theoretical formula, and the value is equal to the absorbed dose rate in air caused by outdoor terrestrial radiation.

³H*(10) after deducting the contribution of cosmic rays.
This research presents the investigation results of the radiation status of a uranium tailings pond and its surrounding area in the Northwest of China. Inside the tailings pond, the average activity concentration of soil radionuclide $^{238}$U, $^{226}$Ra, $^{232}$Th, and $^{40}$K are $42.21 \pm 9.25$ Bq·kg$^{-1}$, $43.83 \pm 12.66$ Bq·kg$^{-1}$, $35.24 \pm 3.28$ Bq·kg$^{-1}$, and $619.16 \pm 73.56$ Bq·kg$^{-1}$, the average $H^*(10)$ is $63.32 \pm 6.46$ nSv·h$^{-1}$, and the average radon exhalation rate is $35.12 \pm 6.14$ Bq·m$^{-2}$·s$^{-1}$. In the area around the tailings pond, the average activity concentration of $^{238}$U, $^{226}$Ra, $^{232}$Th, and $^{40}$K are $43.07 \pm 13.22$ Bq·kg$^{-1}$, $47.11 \pm 14.78$ Bq·kg$^{-1}$, $31.36 \pm 9.67$ Bq·kg$^{-1}$, and $643.49 \pm 71.56$ Bq·kg$^{-1}$, the average $H^*(10)$ is $65.07 \pm 8.46$ nSv·h$^{-1}$, and the average radon exhalation rate is $45.79 \pm 12.91$ Bq·m$^{-2}$·s$^{-1}$.

Radionuclide activity concentration and ambient dose equivalent rate are within the range of background range of China, in which the range of radionuclide activity concentration is $^{238}$U: 2–690 Bq·kg$^{-1}$, $^{226}$Ra: 2–440 Bq·kg$^{-1}$, $^{232}$Th: 1–360 Bq·kg$^{-1}$, $^{40}$K: 9–1800 Bq·kg$^{-1}$, the range of absorbed dose rate in air caused by outdoor terrestrial radiation is 12.7 to 1300 nGy·h$^{-1}$. The calculated soil radon exhalation rates are within the world average range of soil radon exhalation rate as reported in the UNSCEAR (1982) report, 0.2 to 70 mBq·m$^{-2}$·s$^{-1}$.

Among the four radionuclides, the spatial distribution patterns of $^{238}$U and $^{226}$Ra are similar, while the spatial distribution patterns of $^{232}$Th and $^{40}$K are no obvious relationship in the study area. In the vertical profile within 0 to 30 cm, the activity concentrations of

---

**Figure 5.** Spatial distribution of soil radionuclides inside and around uranium tailings pond, (a): the spatial distribution of $^{238}$U, (b): the spatial distribution of $^{226}$Ra, (c): the spatial distribution of $^{232}$Th, and (d): the spatial distribution of $^{40}$K.

**Figure 6.** (a) is the spatial distribution of $H^*(10)$ (the contribution of cosmic rays has been deducted). (b) is the spatial distribution of the soil radon exhalation rate.

4. Conclusion

This research presents the investigation results of the radiation status of a uranium tailings pond and its surrounding area in the Northwest of China. Inside the tailings pond, the average activity concentration of soil radionuclide $^{238}$U, $^{226}$Ra, $^{232}$Th, and $^{40}$K are $42.21 \pm 9.25$ Bq·kg$^{-1}$, $43.83 \pm 12.66$ Bq·kg$^{-1}$, $35.24 \pm 3.28$ Bq·kg$^{-1}$, and $619.16 \pm 73.56$ Bq·kg$^{-1}$, the average $H^*(10)$ is $63.32 \pm 6.46$ nSv·h$^{-1}$, and the average radon exhalation rate is $35.12 \pm 6.14$ Bq·m$^{-2}$·s$^{-1}$. In the area around the tailings pond, the average activity concentration of $^{238}$U, $^{226}$Ra, $^{232}$Th, and $^{40}$K are $43.07 \pm 13.22$ Bq·kg$^{-1}$, $47.11 \pm 14.78$ Bq·kg$^{-1}$, $31.36 \pm 9.67$ Bq·kg$^{-1}$, and $643.49 \pm 71.56$ Bq·kg$^{-1}$, the average $H^*(10)$ is $65.07 \pm 8.46$ nSv·h$^{-1}$, and the average radon exhalation rate is $45.79 \pm 12.91$ Bq·m$^{-2}$·s$^{-1}$.

Radionuclide activity concentration and ambient dose equivalent rate are within the range of background range of China, in which the range of radionuclide activity concentration is $^{238}$U: 2–690 Bq·kg$^{-1}$, $^{226}$Ra: 2–440 Bq·kg$^{-1}$, $^{232}$Th: 1–360 Bq·kg$^{-1}$, $^{40}$K: 9–1800 Bq·kg$^{-1}$, the range of absorbed dose rate in air caused by outdoor terrestrial radiation is 12.7 to 1300 nGy·h$^{-1}$. The calculated soil radon exhalation rates are within the world average range of soil radon exhalation rate as reported in the UNSCEAR (1982) report, 0.2 to 70 mBq·m$^{-2}$·s$^{-1}$.

Among the four radionuclides, the spatial distribution patterns of $^{238}$U and $^{226}$Ra are similar, while the spatial distribution patterns of $^{232}$Th and $^{40}$K are no obvious relationship in the study area. In the vertical profile within 0 to 30 cm, the activity concentrations of
radionuclides $^{238}$U, $^{226}$Ra, and $^{40}$K decreased with the increase of soil depth, while the activity concentration of $^{210}$Po in the northeast direction of the study area increased with the increase of soil depth.

These investigation results revealed that the decommissioning governance of the uranium tailings pond is a good effect, the tailing pond operates normally, and no migration or diffusion of radionuclides in the pond has been found.

Acknowledgments

This work is supported by the National Natural Science Foundation of China, under the Project No.32060292. The authors are thankful to the Radiation Environment Supervision Station of Xinjiang, China and the Urumqi Customs Technology Center, China for providing facilities and support.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Natural Science Foundation of China [32060292].

ORCID

Guangwen Feng http://orcid.org/0000-0002-3379-7728

References

Aladeniyi, K., Olowookere, C., & Oladele, B. B. (2019). Measurement of natural radioactivity and radiological hazard evaluation in the soil samples collected from Owo, Ondo State, Nigeria. Journal of Radiation Research and Applied Sciences, 12(1), 200–209. https://doi.org/10.1080/16878507.2019.1593675

Antovič, N. M., Bošković, D. S., Srkota, N. R., & Antovič, I. M. (2012). Radioactivity in soil from Mojkovac, Montenegro, and assessment of radiological and cancer risk. Nuclear Technology and Radiation Protection, 27(1), 57–63. https://doi.org/10.2298/NTRP1201057A

Baeza, A., Del Rio, M., Miro, C., & Paniagua, J. M. (1992). Natural radioactivity in soils of the Province of Caceres (Spain). Radiation Protection Dosimetry, 45(1-4), 261–263. https://doi.org/10.1093/rpd/45.1-4.261

Carvalho, F. P., Madruga, M. J., Reis, M. C., Alves, J. G., Oliveira, J. M., Gouveia, J., & Silva, L. (2007). Radioactivity in the environment around past radium and uranium mining sites of Portugal. Journal of Environmental Radioactivity, 96(1–3), 39–46. https://doi.org/10.1016/j.jenvrad.2007.01.016

Craff, E. S., Abu-Qare, A. W., Flaherty, M. M., Garofolo, M. C., Rincavage, H. L., & Abou-Donia, M. B. (2004). Depleted and natural uranium: Chemistry and toxicological effects. Journal of Toxicology and Environmental Health - Part B: Critical Reviews, 7(4), 297–317. https://doi.org/10.1080/10937400490452714

Dinis de, M. L., & Fiúza, A. (2013). Occupational exposure during remediation works at a uranium tailings pile. Journal of Environmental Radioactivity, 119 ( 5 ), 63–69. https://doi.org/10.1016/j.jenvrad.2012.08.009

Durusoy, A., & Yildirim, M. (2017). Determination of radioactivity concentrations in soil samples and dose assessment for Rize Province, Turkey. Journal of Radiation Research and Applied Sciences, 10 (4 ), 348–352. https://doi.org/10.1016/j.jrras.2017.09.005

El-Gamal, H., Farid, M. E. A., Abdel Mageed, A. I., Hasabelnaby, M., & Hassanien, H. M. (2013). Assessment of natural radioactivity levels in soil samples from some areas in Assiut, Egypt. Environmental Science and Pollution Research, 20(12), 8700–8708. https://doi.org/10.1007/s11356-013-1844-1

Gabdo, H. T., Ramli, A. T., Saleh, M. A., Sanusi, M. S., Garba, N. N., & Aliyu, A. S. (2015). Radiological hazard associated with natural radionuclide concentrations in the northern part of Pahang state Malaysia. Environmental Earth Sciences, 73(10), 6271–6281. https://doi.org/10.1007/s12665-014-3850-0

IAEA. (2013). Technical reports series No.474 measurement and calculation of radon releases from norm residues. Austria.

Jagetiya, B. L., & Purohit, P. (2006). Effects of various concentrations of uranium tailings on certain growth and biochemical parameters in sunflower. Biologia, 61(1), 103–107. https://doi.org/10.2478/s11756-006-0015-y

Jasaitis, D., & Girgiždys, A. (2007). Natural radionuclide distribution and radon exhalation rate from the soil in vilnius city. Journal of Environmental Engineering and Landscape Management, 15 (1), 31–37. https://doi.org/10.3846/16486897.2007.9636905

Jónás, J., Somlai, J., Csordás, A., Tóth-Bodrogi, E., & Kovács, T. (2018). Radiological survey of the covered and uncovered drilling mud depository, Journal of Environmental Radioactivity, 188, 30–37. https://doi.org/10.1016/j.jenvrad.2017.10.020

Jónás, J., Somlai, J., Tóth-Bodrogi, E., Hegedüs, M., & Kovács, T. (2017). Study of a remediated coal ash depository from a radiological perspective. Journal of Environmental Radioactivity, 173, 75–84. https://doi.org/10.1016/j.jenvrad.2016.11.010

Kessaratikoon, P., Jeeawongsakul, J., Boonkrongcheep, R., & Pholithum, S. (2019). Radiological hazard assessment and excess lifetime cancer risk evaluation in surface soil samples collected from Ban Chang and Nikhom Phathana districts in Rayong province, Thailand. Journal of Physics: Conference Series, 1380(1), 012104. https://doi.org/10.1088/1742-6596/1380/1/012104

Landa, E. R. (2004). Uranium mill tailings: Nuclear waste and natural laboratory for geochemical and radioecological investigations. Journal of Environmental Radioactivity, 77(1),1-27. https://doi.org/10.1016/j.jenvrad.2004.01.030

Laxman Singh, K., Sudhakar, G., Swaminathan, S. K., & Muralidhar Rao, C. (2015). Identification of elite native plants species for phytoaccumulation and remediation of major contaminants in uranium tailing ponds and its affected area. Environment, Development and Sustainability, 17(1), 57–81. https://doi.org/10.1007/s10668-014-9536-7

Liu, Y., Zhou, W., Liu, H., Wei, Q., Gao, B., & Chen, G. (2020). Spatial variability and radiation assessment of the radionuclides in soils and sediments around a uranium tailings reservoir, south of China. Journal of Radioanalytical and Nuclear Chemistry, 324(1), 33–42. https://doi.org/10.1007/s10967-020-07077-w
Lou, Y., Liu, Y., Peng, G., Zhao, G., Zhang, Y., & Yang, Z. (2018). Radioactivity risk assessment of radon and gamma dose at one uranium tailings pond in China. *IOP Conference Series: Earth and Environmental Science*, 108, 032018. https://doi.org/10.1088/1755-1315/108/3/032018

Momčilović, M., Kovačević, J., & Dragović, S. (2010). Population doses from terrestrial exposure in the vicinity of abandoned uranium mines in Serbia. *Radiation Measurements*, 45(2), 225–230. https://doi.org/10.1016/j.radmeas.2010.01.035

Momčilović, M., Kovačević, J., Tanić, M., Đorđević, M., Baćić, G., & Dragović, S. (2013). Distribution of natural radionuclides in surface soils in the vicinity of abandoned uranium mines in Serbia. *Environmental Monitoring and Assessment*, 185(2), 1319–1329. https://doi.org/10.1007/s10661-012-2634-9

Ndontchuen, M. M., Mekongtsø Ngulem, E. J., Simo, A., Njingga, R. L., & Joël, G. S. C. (2014). Gamma emitting radionuclides in soils from selected areas in Douala-Bassa Zone, Littoral region of Cameroon. *ISRN Spectroscopy*, 2014, 1–8. https://doi.org/10.1155/2014/245125

Ouyang, J., Liu, Z., Zhang, L., Wang, Y., & Zhou, L. (2020). Analysis of influencing factors of heavy metals pollution in farmland-rice system around a uranium tailings dam. *Process Safety and Environmental Protection*, 139, 124–132. https://doi.org/10.1016/j.psep.2020.04.003

Portnov, V. S., Yurov, V. M., Maussymbayeva, A. D., Kassymyrov, S. S., & Zhollmagambetov, N. R. (2017). Assessment of radiation risk at the population from pits. *Dumps and Tailings Dams of Uranium Mines*. International *Journal of Mining, Reclamation and Environment*, 37(3), 205–211. https://doi.org/10.1080/17480930.2016.1268801

Qin, G., Liu, Y., Wang, Q., Li, F., Li, W., & Wu, H. (2020). Investigation and analysis of environmental radioactivity levels at typical uranium mines in the south of China. *Radiation Protection Dosimetry*, 189(3), 337–346. https://doi.org/10.1093/rpd/ncaa047

Qu, L., Yao, D., Cong, P., & Xia, N. (2008). Radioactivity concentrations in soils in the Qingdao area, China. *Annals of the New York Academy of Sciences*, 1140, 308–314. https://doi.org/10.1196/annals.1454.038

Sanada, Y., Yoshimura, K., Urabe, Y., Iwai, T., & Katengeza, E. W. (2020). Distribution map of natural gamma-ray dose rates for studies of the additional exposure dose after the Fukushima Dai-ichi Nuclear Power Station accident. *Journal of Environmental Radioactivity*, 223–224

Shilfa, S. N., & Jumpeno, B. Y. E. B., Nurokhim, & Kusdiana, 2020. Ambient dose measurement from high natural background radiation (HNRB) in Botting Utara Village, Mamuju-Indonesia. *IOP Conference Series: Journal of Physics: Conference Series*, 1436, 012027. https://doi.org/10.1088/1742-6596/1436/1/012027

Shweikani, R., & Hushari, M. (2005). The correlations between Radon in soil and its exhalation and concentration in air in the southern part of Syria. *Radiation Measurements*, 40(2-6), 699–703. https://doi.org/10.1016/j.radmeas.2005.06.025

Sivakumar, R. (2014). An assessment of natural radioactivity levels and radiation hazards in the soil of Coonoor, South India. *Environmental Earth Sciences*, 72(12), 5063–5071. https://doi.org/10.1007/s12665-014-3375-6

Turhan, S., & Varinlioglu, A. (2012). Radioactivity measurement of primordial radionuclides in and dose evaluation from marble and glazed tiles used as covering building materials in Turkey. *Radiation Protection Dosimetry*, 151(3), 546–555. https://doi.org/10.1093/rpd/ncs041

UNSCEAR (1982). *Ionizing radiation: Sources and biological effects*. UNSCEAR Report to the General Assembly. United Nations.

UNSCEAR (2000). *Sources and effects of ionizing radiation, volume I: Sources*. UNSCEAR Report to the General Assembly. United Nations.

UNSCEAR (2008). *Sources and effects of ionizing radiation, volume I: Sources*. UNSCEAR Report to the General Assembly. United Nations.

UNSCEAR (2013). *Sources, effects and risk of ionizing radiation, volume I. UNSCEAR Report to the General Assembly*. United Nations.

Vasidov, A. (2014). Field measurement of radon exhalation rate from the soil by CR-39 detector. *Journal of Radioanalytical and Nuclear Chemistry*, 302(2), 919–923. https://doi.org/10.1007/s10967-014-3644-6

Wang, Z. H., He, J., Du, Y., He, Y., Li, Z. Q., Chen, Z. H., & Yang, C. W. (2012). Natural and artificial radionuclide measurements and radioactivity assessment of soil samples in eastern Sichuan province (China). *Radiation Protection Dosimetry*, 150(3), 391–397. https://doi.org/10.1093/rpd/nrc413

Zhang, L., Guo, Q., & Sun, K. (2015). Continuous measurement of radon exhalation rate of soil in Beijing. *Journal of Radioanalytical and Nuclear Chemistry*, 303(2), 1623–1627. https://doi.org/10.1007/s10967-014-3783-9

Zhuo, W., Iida, T., & Furukawa, M. (2006). Modeling radon flux density from the earth’s surface. *Journal of Nuclear Science and Technology*, 43(4), 479–482. https://doi.org/10.1080/18811248.2006.9711127

Zhao, W. H., Guo, Q. J., Chen, B., & Cheng, G. (2008). Estimating the amount and distribution of radon flux density from the soil surface in China. *Journal of Environmental Radioactivity*, 99(7), 1143–1148. https://doi.org/10.1016/j.jenvrad.2008.01.011

Zong, M. R., Dong, F. Q., Liu, M. X., Yang, G., Zhang, Q., Hou, L., & Luo, Z. (2017). A detailed investigation on the environmental effect of an uranium mine in Western China including γ-ray radiation formation and microbe distribution. *Journal of Nanoscience and Nanotechnology*, 17(9), 6614–6619. https://doi.org/10.1166/jnn.2017.14530